CHALMERS
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A study of naturalistic driving data

Master's Thesis in Infrastructure and Environmental Engineering

Jakob Imberg, Andréa Palmberg

Department of Applied Mechanics
CHALMERS UNIVERSITY OF TECHNOLOGY
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Cover:
Screenshot from a video from the euroFOT project. The picture shows the forward camera view when a driver approaches one of the curves included in this study.

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Abstract

Traffic accidents are commonly found on horizontal curves. It is therefore important to design horizontal curves that elicit safe driving behavior. This thesis investigates how curve geometry influences the driver behavior in horizontal curves by using naturalistic driving data. Seven curves were selected, all on rural two-lane roads with a posted speed limit of 70 km/h. The curve geometry factors studied were radius, presence and lengths of spiral transitions and lengths of approach and exit tangent. Regression analyses were used to analyze how these factors influenced the driver behavior in terms of speed and maximum lateral acceleration. The speed behavior was also analyzed by studying speed profiles.

The study showed that all studied factors influenced the driver behavior in the selected curves. The speed increased for larger radii, and longer approach tangent resulted in higher speed at the beginning of the curvature. Longer transition resulted in higher speeds at the center of the curve, and did not affect the maximum lateral acceleration – indicating a changed trajectory. All but one of the selected curves did not fulfill the existing recommendations on curve design provided by the Swedish Transport Administration. The speed profiles showed that the median speed exceeded the posted speed limit in all curves except one. Driving at higher speeds than what a curve is designed for could increase risks. The study also found that speed patterns in curves seemed to be independent of the choice of speed.

Key words: Curve Geometry, Driver behavior, Horizontal curves, Naturalistic driving data

Hur kurvgeometri påverkar förarbeteende i horisontalkurvor
En studie av naturalistisk kördata
Examensarbete inom Masterprogrammet Infrastruktur och Miljöteknik
Jakob Imberg, Andréa Palmberg
Institutionen för Tillämpad Mekanik
Avdelningen för Fordonssäkerhet
Accident prevention gruppen
Chalmers tekniska högskola

Sammanfattning

Trafikolyckor är vanligt förekommande i horisontalkurvor. Det är därför viktigt att utforma kurvor som framkallar ett säkert körbeteende. Denna avhandling undersöker hur kurvgeometri påverkar körbeteende i horisontalkurvor, genom användning av naturalistisk kördata. Sju kurvor valdes, alla på tvåfiliga landsbygdsvägar med en hastighetsgräns på 70 km/h. De kurvgeometriska faktorerna som undersöktes var radie, förekomst och längd på klotoider samt tangentlängder. För att analysera hur dessa faktorer påverkar körbeteendet i form av hastighet och maximal lateral acceleration användes regressionsanalyser. Hastighetsbeteende studerades även med hjälp av hastighetsprofiler.

Studien visade att alla studerade faktorer påverkade körbeteendet i de valda kurvorna. Hastigheten ökade för större radier, och längre tillfartstangent resulterade i högre hastighet i början av kurvaturen. Längre klotoider medförde högre hastigheter i mitten av kurvorna, och påverkade inte den maximala laterala accelerationen – vilket indikerade på ändrad position. Alla utom en av de valda kurvorna uppfyllde inte de nuvarande kraven för utformning av horisontalkurvor från Trafikverket. Trots detta visade hastighetsprofilerna att medianhastigheten översteg vägens hastighetsbegränsning i alla kurvor utom en. Att köra med högre hastighet än vad en kurva är utformad för innebär förhöjda risker. Studien visade även att hastighetsprofilerna i kurvorna verkade opåverkade av val av hastighet.

Nyckelord: Horisontalkurvor, Naturalistisk kördata, Kurvgeometri, Körbeteende

Contents

Preface

This report is a result of a master thesis work of 30 ECT, which has been conducted during the spring term 2015 at SAFER Vehicle and Traffic Safety Center at Chalmers. The master's thesis is the final part of our civil engineering studies at Chalmers University of Technology.

First of all we would like to thank our supervisor Selpi for her support and valuable input throughout the thesis work. We would also like to thank our examiner Robert Thomson for his valuable inputs to the thesis. This work used the SAFER infrastructure of naturalistic driving data. Without the access to this data, the project could not have been conducted. We would like to thank all people at SAFER for contributing to an enabling environment and for providing us new knowledge in the field of traffic safety.

Finally we would like to thank our respectives and friends for being helpful and supportive during the studies at Chalmers University of Technology.

Göteborg June 2015-07-03

Jakob Imberg, Andréa Palmberg

1 Introduction

Traffic accident is one of the leading causes to death in the world, with more than one million victims and additionally 50 million injuries annually (World Health Organization, 2013). Traffic accidents do not only cause death, injuries and emotional stress to those affected, but also direct and indirect costs for the society. In Sweden, around 3000 persons are seriously injured in traffic accidents annually, and 300 people are killed (Trafikanalys, 2014). For year 2005, the traffic accidents were estimated to cost 16.9 billion Swedish crowns (Myndigheten för samhällsskydd och beredskap, 2008). Hence, there are both ethical and economic reasons to improve traffic safety. The Swedish government has for these reasons stated Vision zero, a vision implying that no accidents with fatal outcome or serious injuries will occur on the Swedish roads (OECD, 2008).

Many accidents occur on horizontal curves, Zegeer et.al (1990) found that the accident rate is up to four times higher for curves compared to tangents. The causes are both vehicular, driver and road environment (Rumar, 1985). Previous studies have consistently found driver errors to be the most common factor involved in the cause of traffic accidents (Haldorsen, 2014; Nofal, et al., 1996; Rumar, 1985). A key factor identified was road alignment that complicated the drivers' road perception (Rumar, 1985). This implies that driver behavior must be taken into account in the road design in order to decrease the accident frequency and severity (Wegman, 2003; Theeuwes, et al., 2012).

Several studies have found that the road safety can be increased by designing roads that are non-surprising and forgiving (Bonneson, et al., 2006; European Commission, 2014). The ideas of these roads are that on unexpected situations occur, and that mistakes made by drivers can be avoided or corrected. Another concept for designing safe roads is "safety-conscious design" (Wegman, 2003). The concept aims to design roads that elicit an appropriate driver behavior by a consistent design that characterize the road's function. On such roads drivers should be able to drive in approximately in the same manner during the whole trip (Lannér, et al., 2000). For a road to be considered consistent, some have suggested a maximum speed difference of 5 km/h between straight segments and curves (Fitzpatrick, et al., 2000). For successive curves, the differential can be maximum 10 km/h instead.

For already existing roads, it is hard to make geometric changes. Therefore, it is of importance to consider safety already in the planning stage. In order to design safe roads, an understanding of driver behavior in curves is of importance. This thesis therefore studies how curve geometry influences driver behavior in curves, by using naturalistic driving data from Swedish roads. This could for instance be of interest for road engineers, transport agencies and others interested or involved in road design.

Previous studies have investigated driver behavior in horizontal curves. Most of these studies have used driving simulators or instrumented vehicles (Montella, et al., 2015; Zakowska, et al., 2008; Altamira, et al., 2014). Other methods that have been used are on-pavement sensors and radar guns (Bonneson, et al., 2006; Passetti & Fambro, 1999). Only a few studies have used naturalistic driving data to analyze driver behavior in curves (Othman, et al., 2011). Naturalistic driving data is data collected from everyday driving, and represents continuous driver behavior under real traffic conditions on existing roads.

The naturalistic driving data used in this study was collected as part of the euroFOT project, 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 year 2010 and 2011. Advanced logging equipment was installed in the cars, which included GPS and video equipment to record the driver, pedals and the rear and front view. It also comprised can-bus signals about speed, acceleration, lateral acceleration etc.

1.1 Objectives

The aim of the thesis is to study how curve geometry influences driver behavior in curves, by using naturalistic driving data. To achieve this, the following objectives are set:

- Provide a state-of-the-art review on road alignment and the effect on driver behavior
- Provide a state-of-the-art review on driver behavior in curves
- Describe the driver behavior in curves in terms of speed and maximum lateral acceleration based on naturalistic driving data
- Investigate how the driver behavior in curves is affected by radii, tangent lengths, presence and length of spiral transitions, radius of previous curve and driver

1.2 Scope

The study is limited to seven curves in Gothenburg and Kungälv in Sweden, all on 70 km/h two-lane rural highways with a road width of approximately 6 m. The study only considers naturalistic driving data from cars driven in Sweden (collected as part of the EuroFOT project. Only data collected from passenger cars is used, and the driver factors studied are speed and maximum lateral acceleration. Vehicular factors and personal trait are not considered. Only data from free flow conditions, no overtaking activities, no cruise control in use and no trailer connected are used. Regarding curve geometry, the factors taken into account are limited to radius, length, presence and length of spiral transition curves, travel direction, tangent lengths and radius of previous curve. Therefore, factors such as cross fall, super-elevation and pavement conditions are outside the scope.

2 Literature study

In order to analyze driver behavior in curves, knowledge about how curves are designed is essential. Therefore, a state-of-the-art review was performed about curve design in Sweden. A state-of-the-art review was also made about previous studies of driver behavior in curves, and about how different factors connected to the curve geometry affect driver behavior.

2.1 Curve geometry

Horizontal curves consist of three elements which together can form a variety of curves. The elements are as follows; tangents, circular arcs and spiral transitions. The appearance of curves with only circular arcs and curves with both circular arcs and spiral transitions differs, which can be seen in Figure 1.

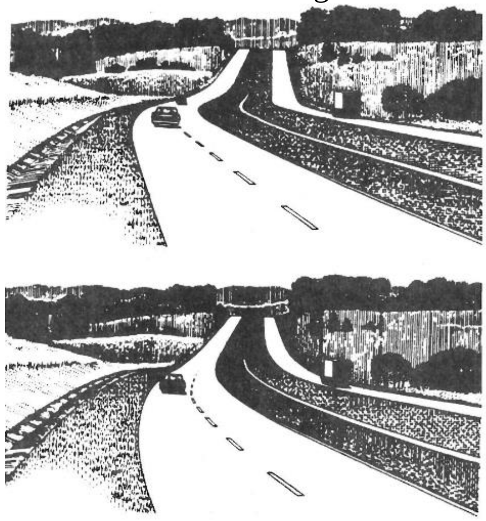


Figure 1: Top: simple circular curve without spiral transitions, bottom: curve with spiral transitions. Images are from exhibit 3-32 in (American Association of State Highway and Transportation Officials, 2001) reprinted here with permission from American Association of State Highway and Transportation Officials.

Different combinations of circular curves exist, and are as follows; simple, compound and reverse curves (McGinnis, u.d). The different types can be seen in Figure 2. A simple circular curve is illustrated in Figure 3. The circular arc starts at the tangent to curve point (TC) and ends at the curve to tangent point (CT) (Banks, 2002). The tangents meet at the point of intersection (PI). The circular curve can be described by its length (L), radius (R), external distance (E), semi tangent distance (T) and deflection angle (I).

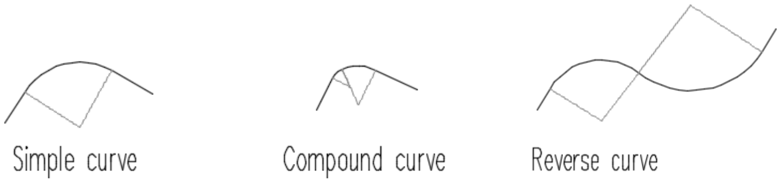


Figure 2: Different types of circular curves.

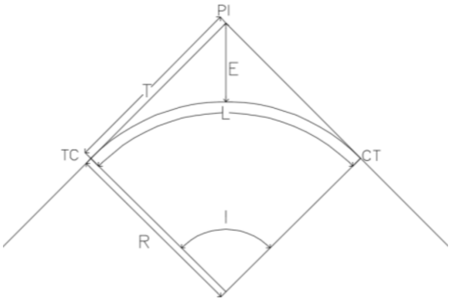


Figure 3: Nomenclature for simple circular curve.

Different types of transition curves also exist, and they are either empirical or mathematical (Meyer & Gibson, 1980). The most common one is the spiral transition, which is a curve that can be described mathematically. The purpose of spiral transitions is to generate a gradual change in curvature and lateral acceleration, and thereby increase the comfort (Stewart & Cudworth, 1990 & Lannér, et al., 2000). Spiral transitions are today commonly used on roads as transitions between tangents and circular arcs. Spiral transitions can be used in different ways in horizontal curvature, and the reasons for its wide usage have been found to be; aesthetic features (Lannér, et al., 2000; Banks, 2002), driving comfort (Passetti & Fambro, 1999; Lannér, et al., 2000; Zakowska, et al., 2008) and natural transition stretch for super elevation (Banks, 2002). In a simple spiral curve, the spiral transition is placed between the tangent and the circular arc in horizontal curves, see Figure 4 left. At the tangent, the radius of the spiral transition is infinite. The radius decreases towards the circular curve to meet its curvature (Council, 1992). In a combining spiral curve, two circular arcs with different curvature are connected by a spiral transition, see Figure 4 middle (Meyer & Gibson, 1980). A third type of spiral curve is when two spiral transitions connect two tangents, see Figure 4 right.

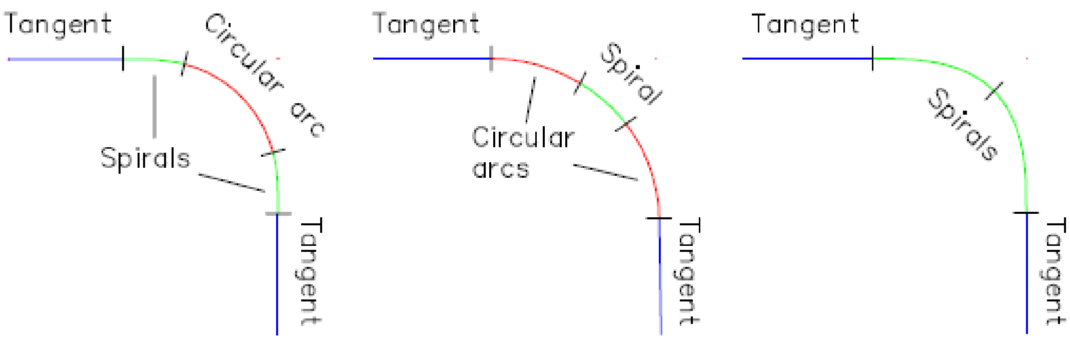


Figure 4: Different types of curves with spiral transitions.

Figure 5 illustrates a simple spiral transition curve. The spiral transition begins at the tangent to spiral point (TS) and ends at the spiral to curve point (SC), where a circular arc begins (Banks, 2002). The spiral has a spiral angle (Θs) and a spiral length (Ls). The final radius of the spiral transition curve is the same as the radius of the circular arc (Rc). Spiral transition curves are often explained by their parameter (A). The parameter depends on the radius of the circular arc (Rc), and the length of the spiral (Ls) according to formula (1).

$$A^2 = R_c * L_s \tag{1}$$

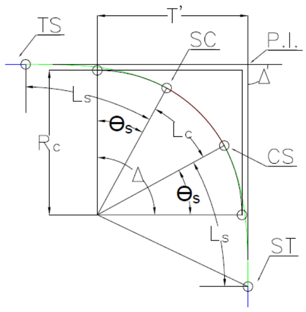


Figure 5: Nomenclature for spiral transition.

If spiral transition curves are to be inserted in a circular curve, the tangents have to be relocated in order for the radius of the circular arc to remain the same (Meyer & Gibson, 1980). The curve will therefore move inwards, which is illustrated in Figure 6. In the figure, curve number 1 is a circular arc, starting in the inner tangent points (TP1) (Lannér, et al., 2000). Curve number 2 is a circular arc with a larger radius than curve number 1, starting in the outer tangents (TP2). The third curve has the same radius as curve number 1, and consists of both a circular arc and two spiral transitions. This curve starts at the outer tangents (TP2), and is shifted inwards compared to curve number 1.

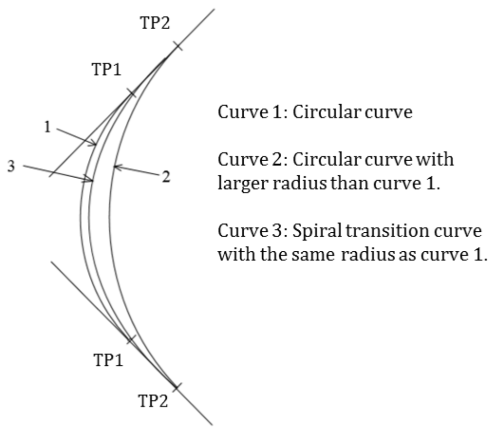


Figure 6: Different curve figurations. Image is from (Lannér, et al., 2000), reprinted here with permission from Lannér.

2.1.1 Swedish design standards for horizontal curves

The government agency in charge of the Swedish road network is the Swedish Traffic Administration (Trafikverket). In cooperation with the Swedish councils and communities, they establish documents with regulations for the geometric design of roads and streets in Sweden (Swedish Transport Administration, 2015). The current documents have been used since 2012. The previous version was established in year 2004. The documents include methods and recommendations for road design based on environmental, socioeconomic, functional and political goals.

The overall requirements for Swedish road and street design are that the road design should encourage road users to adapt a safe driver behavior and to choose a suitable speed (Swedish Transport Administration, 2012a). The proceeding stretch of the road should be visually clear, to avoid unexpected design. Horizontal curves should be designed to be comfortable to drive in, have enough visibility and esthetically fit into the landscape (Lannér, et al., 2000). Small radii and short curves should be avoided in the design.

In order to reduce the number and severity of traffic accidents the Swedish Transport Administration has set a goal that 80 percent of the traffic should keep the posted speed limit in year 2020 (Swedish Transport Administration, 2014). A study from year 2013 concluded that 47 percent of drivers drove faster than the posted speed limit on Swedish national roads (Swedish Transport Administration, 2014). The posted speed limit should normally be the same as the design speed (Swedish Transport Administration, 2012b), which is the speed for which the road is designed to provide safe and comfortable driving. The design speed is for instance used to determine sight distance, super elevation and radius of curves. Higher speeds cause higher side friction demand and longer stopping distance, which requires curves with larger radius and higher super elevation in order to provide safe roads.

The Swedish Transport Administration's requirements of minimum radius for horizontal curves can be seen in Table 1. The desirable minimum radius applies to new constructions. For reconstruction of existing roads, values of minimum acceptable radius are used.

Table 1: Minimum radius for horizontal curves with a super elevation of at least 4 percent (Swedish Transport Administration, 2012c); (Swedish Transport Administration, 2004). The guidelines for 60 and 80 km/h are from year 2012, while the guidelines for 70 and 90 km/h are from year 2004.

Design speed [km/h]	**Desirable minimum radius for new constructions [m]**	**Minimum acceptable radius [m]**
60	140	100
70	340	210
80	400	300
90	520	400

The Swedish Transport Administration has also set guidelines for the arc length of horizontal curves (Swedish Transport Administration, 2012d). The arc length should be larger than one ninth of the radius, and should not be larger than the radius itself. Desirable arc length is also dependent on the speed; the length should be equal to a minimum of five seconds driving with the posted speed (Swedish Transport Administration, 2012d). For roads with a design speed of 70 km/h the desirable minimum arc length is about 100 m and it should not be shorter than about 60 m.

The Swedish Transport Administration (2012c) recommends the usage of transition curves for radii smaller than the minimum resulting radius (R_r) shown in Table 2. The reason is to provide driving dynamics. However, spiral transitions can be used even for curves with larger resulting radius than shown in Table 2, of aesthetic reasons. The resulting radius for compound curves can be calculated by equation (2) (Swedish Transport Administration, 2012d).

$$R_r = 1/(\left(\frac{1}{R_1}\right) - \left(\frac{1}{R_2}\right)) \qquad (2)$$

For simple curves the resulting radius (R_r) is equal to the radius of the curve (R_1).

There are also requirements for the spiral parameter (A) that have to be fulfilled. When transition curves are used, it is important that the curvature of the following circular arc is prominent (Swedish Transport Administration, 2012c). The minimum allowed spiral parameter can be seen in Table 2. For small radii (R < 300 m), the parameter also has to be smaller than the radius of the circular arc and it is recommended to be in the interval $\frac{2R}{3} > A > \frac{R}{3}$ (Swedish Transport Administration, 2012d). For large radii (R > 300 m), it is recommended to be in the interval $\frac{R}{2} > A > \frac{R}{3}$.

*Table 2: Minimum curve radius without transition and minimum spiral parameter (Swedish Transport Administration, 2012c, 2004). The guidelines for 60 and 80 km/h are from year 2012, while the guidelines for 70 and 90 km/h are from year 2004. *Not defined in the guidelines, interpolated from minimum spiral parameter for design speed of 60 and 80 km/h.*

Design speed [km/h]	**Minimum resulting radius without spiral transition [m]**	**Minimum spiral parameter A [m]**
60	305	130
70	400	155*
80	500	185
90	650	210*

2.2 Driver behavior in horizontal curves and influence of road geometry

Driver behavior is complex and a driver's actions are dependent on several factors, for instance personality trait (Kong, et al., 2013), road alignment, road environment and weather (Fitzpatrick, et al., 2000). In this section, the driver behavior in horizontal curves will be described in terms of speed, longitudinal acceleration and deceleration and lateral acceleration.

2.2.1 Data collection methods and scope of previous studies

Previous research has studied driver behavior in curves, with different aims and data collection methods. The most common methods in the reviewed literature are driving simulators and instrumented vehicles. However, sensors, radar guns and naturalistic driving data have also been used to study driver behavior in curves. Most of the previous studies about driver behavior are based on data collected under favorable weather conditions and during daytime. A collection of previous studies can be seen in Table 3.

Table 3: Previous studies of driver behavior in curves. S: Speed, AD: Longitudinal Acceleration and Deceleration, L: Lateral acceleration. TRH: Two-lane Rural Highway, RH: Rural Highway.

Study	Country	Parameter	Tools	Road type, Speed [km/h]	Conditions	Radii [m] Deflection angle [°]	Curve lengths [m]	Spiral	Tangent lengths [m]
Present (this thesis)	SWE	S, AD, L	Naturalistic driving data, FOT data	TRH 70km/h	All weather conditions, All light conditions, Free flow	110-500 m 30-55.5°	50-349m	Yes	100-710m
(Montella, et al., 2015)	ITA	S, AD	Simulator	TRH	No sight obstructions, dry weather, daylight	125-800m 45°	98-630 m	No	800 m
(Altamira, et al., 2014)	ARG	S, AD	GPS-logger and camera (field study)	TRH	Free flow, daylight, dry weather	25-1000m	-	No	≤ 400m
(Pérez-Zuriaga, et al., 2013)	ESP	S, AD	GPS on private cars (field study)	TRH 60-80 km/h	Free flow, dry weather conditions, daylight	52-519m 10.269 - 110.376°	93-333m (including spiral lengths)	Yes, A=49-231	6-1548m
(Othman, 2011)	SWE	S, L	Naturalistic driving data	70-110 km/h	-	<=400-1350 m	0-122 m	No	-
(Quaium, 2010)	USA	S	Measures	TRH 56-88 km/h	Day and night separately	97-566m 21-92°	246-1378m	No	-
(Hu & Donnell, 2010)	USA	AD	Controlled field study with instrumented vehicle	TRH 65 km/h	Nighttime	31-464m	48-186m		0-884m
(Zakowska, et al., 2008)	ITA	S	Simulator	50, 70, 100 km/h	Good and poor visibility	300, 500, 1000/-	157-524m	Yes	300, 400, 500m
(Helmers & Törnros, 2006)	SWE	S	Simulator	TRH 70km/h	Good and poor visibility	100, 200, 400m	0-240m	Yes, L: 0R, 0.2R, 0.4R, 0.6R	600m
(Nie, 2006)	CAN	S	Controlled field study with instrumented vehicle	TRH and other roads	Free flow, daytime, dry weather	180-1189 m	40-1074m	Yes, L:10-160m	30-115m (preceding)
(Syed, 2005)	CAN	L	Controlled field study with instrumented vehicle	TRH 80-90 km/h	Free flow, differed weather conditions	300-1200m	100-1000m (including spiral lengths)	Yes	-
(Van Winsum & Godthelp, 1996)	NLD	L	Simulator	TRH	Free flow, daytime, dry weather	40, 80, 120, 160m (left turn only) 90°	-	No	-
(Glennon, et al., 1985)	USA	L	Sire-based observations, radar guns	TRH	-	135-462 m 3.8-12,9 °	-	-	-
(Ritchie, 1972)	USA	S, L	Controlled field study with instrumented vehicle	RH	Daytime, dry weather	-	-	No	-

2.2.2 Speed

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

Othman (2011) found in a study of naturalistic driving data that the speeds on icy or wet roads were lower compared to bare roads. Othman also found that the speed limits rarely were exceeded on wet and icy roads. In the study, dry roads were defined as no wiper activity. However, roads can be wet even though it is not raining or snowing at that moment. Wallman et al (1997) estimated the speed behavior on winter roads, and found that drivers choose a speed of 75 to 90 percent of their speed on bare roads when they travel on winter roads. The average speed during winter was estimated to be at least 11 km/h lower than during summer conditions. In the study by Wallman et al, a higher speed reduction was found for situations with precipitation than for situations when the road surface was slippery. However, the speed reduction was found to be more dependent on the visual appearance of the road than on the actual road friction. The visual conditions are different for day- and nighttime. However, according to both Quaium (2010) and Donnell et al (2006) the speeds during day- and nighttime do not differ considerably.

When it comes to factors connected to the road geometry, several studies have pointed out radius or degree of curvature 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. How the operating speed was found to decrease with radius in the study by Montella et al (2015) is illustrated in Figure 7. In a study by Quaium (2010) the speed was found to increase with the posted speed limit, super elevation and radius, and to decrease with deflection angle. Othman (2011) found that the choice of speed was more dependent on radius than on the posted speed limit.

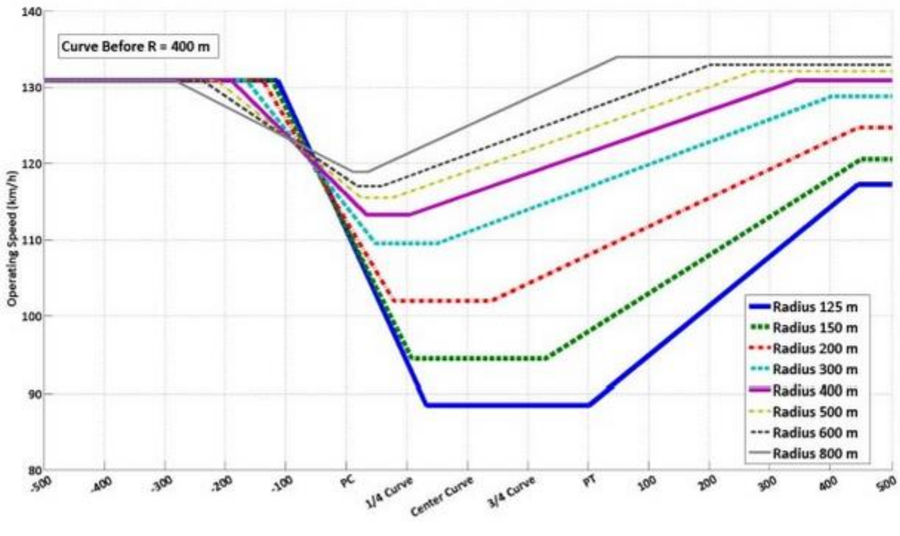


Figure 7: Operating speed at different positions in curves with varying radii. Image is from Figure 3 (Montella, et al., 2015), reprinted here with permission from Montella.

The radius of the curve does not only affect the speed in the curve, but also the speed at the approach tangent. Altmira et al (2014) made continuous speed measurements on a two-lane rural highway by the use of an instrumented vehicle and test drivers. The result showed that the speed changes at the approach tangent were mostly dependent on the radius of the following curve. The same result was found in the simulator study by Montella et al (2015). The speed at the exit tangent is also affected by the radius, smaller radius result in lower speed.

Helmers & Törnros (2006) performed a simulator study for rural two-lane highways, for curves with radii of 100, 200 and 400m and spiral-lengths varying between 0 and 0.6 times the radius of the curve. The spiral transitions were found to increase the speed on both the approach tangent and the center point of curves. The speed increased with the length of the spiral transition. A simulator study by Zakowska et al (2008) agrees that spiral transitions result in higher speed in curves. Another parameter influencing the speed in curves is the travel direction. In a study using naturalistic driving data, Othman (2011) noted higher speeds in inner curves compared to outer curves.

2.2.3 Longitudinal acceleration and deceleration

The acceleration and deceleration rate is affected by radius, gradient and tangent length, and has been found to increase in curves compared to tangents (Altamira, et al., 2014; Montella, et al., 2015). Hu and Donnell (2010) developed a model based on field experiments on 16 horizontal curves. The model indicated that acceleration and deceleration depend on curve direction and curve length additionally.

Small radii lead to high deceleration values when approaching curves, according to both Altmira et al (2014) and Hu and Donell (2010). The model developed by Hu and Donnell (2010) indicated higher deceleration rates when approaching curves for large differences in radii between successive curves. The model also showed an increased deceleration when entering a curve for drivers departing the former curve with a high acceleration, which most probably is due to higher speed at the tangent. High speed at approach tangents can occur if the tangent is long, and therefore long tangents lead to increased deceleration at the curve entrance. Lower deceleration values were found for curves with large radii compared to curves with small radii. Also, the radius of the upstream curve affects the deceleration. For a curve with larger radius than the upstream curve, the deceleration is lower than if the curve would have a smaller radius. The effect of the characteristics of the upstream curve is reduced if the horizontal curve length is increased, since drivers have enough distance between the curves to base their behavior on road geometry. Further on, long curve lengths were found to increase the rate at which drivers decelerated when approaching curves. For a curve shorter than the previous one, the deceleration was found to be higher. The study by Hu and Donnell (2010) also found that higher deceleration when entering a curve resulted in lower speed in the curve.

According to Montella et al (2015) smaller radius results in a shift of the point of deceleration towards the center of the curvature. For curves with larger radii, the deceleration ends earlier, this can be seen in Figure 8. In a study by Altmira et al (2014), the length necessary for deceleration was found to decrease with increased radii, independent on approach speed. According to a study performed on GPS-instrumented vehicles on curves with different radii and tangent lengths, deceleration starts approximately 70 meters before transition curves and ends at second half of the transition curve (Pérez-Zuriaga, et al., 2013). Higher deceleration values were found for smaller 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 found to be more affected by radius than speed. By studying curves with radii up to 1000 m and tangents with a maximum length of 400 meters, the deceleration length was found to vary between 50 and 230 meters. The deceleration length was found to increase for gradients of 2-5 percent compared to gradients of less than 2 percent. Deceleration was in the study defined as values lower than -0.1 m/s2.

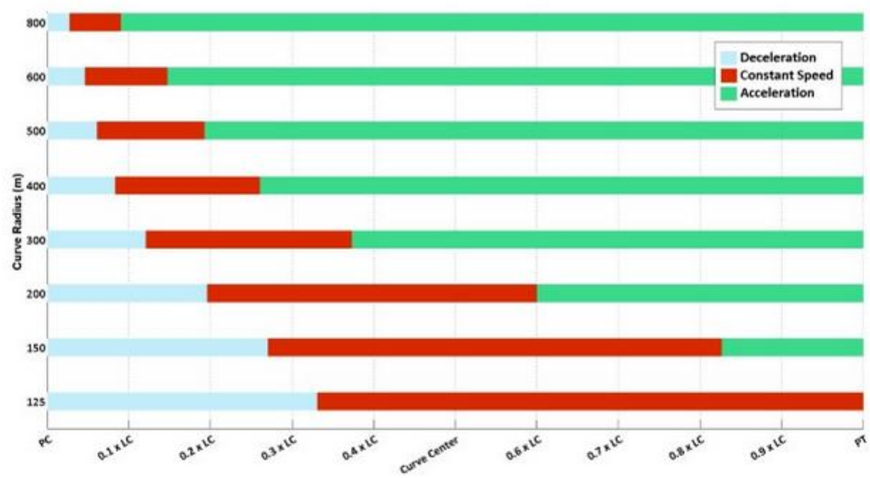


Figure 8: Deceleration and acceleration in curves with varying radii. Image is from Figure 4 (Montella, et al., 2015), reprinted here with permission from Montella.

The model developed by Hu and Donell (2010) indicated 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, see Figure 8. Acceleration lengths were seen to vary between 150 and 270 meters, in the study performed by Altmira et al (2014).

Hu and Donnell (2010) found high acceleration values for long curves, which most probably is due to long available stretch to accelerate on and therefore higher speed. The model also indicated lower rates of acceleration when drivers depart curves with large radii, which can be related to a higher speed 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) used speed differentials to analyze driver behavior in curves. Individual speed differential (ΔV) is calculated by subtracting each individual's speed on the curve with the speed on the preceding tangent. Pérez-Zuriaga et al (2013) concluded that the individual speed differential $\Delta_{85}V$ is a more accurate method than subtracting V_{85} on the curve with V_{85} on the tangent, to determine the speed differential. They also found that $\Delta_{85}V$ was high for sharp curves and flattened out for curves with radius larger than about 200 m. The study was performed with instrumented vehicles on curves with radius lower than 600 m and with long approach tangents.

2.2.4 Lateral acceleration

The lateral acceleration have by several authors 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; Van Winsum & Godthelp, 1996). 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). Appropriate super elevation result in a gradual increase of lateral acceleration when driving through a curve (Glennon, et al., 1985). If the super elevation is deficient, the demand for side-friction increases which leads to higher risk for accidents (Othman, 2008; Zegeer, et al., 1992).

According to a study of naturalistic driving data by Othman (2011), the highest lateral acceleration occurs in the entrance of a curve compared to the middle- and the end point. Regardless of radius, the lateral acceleration decreases towards the same value at the end point of a curve. Othman also found that the lateral acceleration is higher on inner curves than on outer curves. The same conclusion was drawn by Syed (2005), in a study on instrumented vehicles in Canada. In a simulator study by Helmers & Törnros (2006) the effect of spiral transitions on the maximal lateral acceleration within curves was studied. The result indicated that spiral transitions only affected the maximum lateral acceleration in the curve with the smallest radius (100m). The maximal lateral acceleration was in this curve reduced for spiral length of 0.6 times the radius of the curve.

3 Methodology

The methodology is divided into three parts; selection of curves, selection of trips and data analysis. The first part describes the desirable characteristics of the curves, and how the selection was made. The second part defines the required prerequisites of trips from which data were to be used for the analysis. The last part, data analysis, describes how the collected data was analyzed.

3.1 Selection of curves

With the literature study as a base, curves on roads with similar characteristics as in previous studies were selected to be able to compare the results. The drivers participating in the euroFOT project were travelling mainly in Gothenburg, Sweden. This limited a large amount of the data to roads close to the city.

With these limitations, simple curves preceded and followed by tangents were selected on two-lane, rural roads in Gothenburg and the surrounding municipalities with speed limits of 70 to 90 km/h. It was necessary that no traffic islands or major intersections were located adjacent the curves, since they could influence the driver behavior. By studying the National Road Database for Sweden, NVDB[1], it could be seen that the majority of rural two-lane roads in Gothenburg and the surrounding municipalities had a speed limit of 70 km/h, and only a few roads had a speed limit of 80 or 90 km/h.

Approximately 30 curves were selected as a first sample. A database query was run to find the number of passes through these curves. The GPS signal was used to find the trips that passed the curves. It was necessary to use a GPS interval in the query to ensure that all trips that passed were identified. Some curves were excluded from the sample due to few passes, few different drivers or domination of only one driver. After the exclusion, only curves in Gothenburg and Kungälv remained.

To get information about curve geometry in terms of radius, length of curve and presence and length of spirals, the Swedish Transport Administration, Kungsbacka municipality and Trafikkontoret in Gothenburg were contacted about road maps. Primary maps were provided from Kungsbacka municipality. Primary maps are detailed maps provided for urban areas, and includes for instance buildings, height curves, roadsides and trees. However, the Swedish Transport Administration and Trafikkontoret in Gothenburg did not respond. Since no maps for roads in the Gothenburg area could be provided, Autodesk AutoCAD Civil 3D[2] was used to estimate the curve characteristics. A satellite map from Bing was used as background, and the prerequisites of the curves were approximated by using built in tools to fit a curve to the center-line of each curve on the map. Estimations of approach and exit tangent lengths were made by measuring the length of the straight segment between the selected curve and the curve before and after respectively. The estimations in CAD using a satellite map were compared to estimations on the primary maps for three curves in Kungsbacka municipality. The curve characteristics were conforming,

[1] National Road Database, The Swedish Transport Administration's database for the road network. Link: nvdb2012.trafikverket.se

[2] Software for civil engineering design

and therefore assumed to be adequate. The CAD drawings of the selected curves can be seen in Appendix A: Curve drawings & visibility.

After the estimations of the curve geometry, some more curves were excluded since they were compound curves instead of simple curves; after this step seven curves remained with radii from 110 m to 500 m, all on roads with a speed limit of 70 km/h. The curves are numbered one to seven, from the smallest to the largest radius.

The characteristics of these seven curves are given in Table 4. The table includes information about the curve design in terms of length, presence and lengths of spiral transition curves, lengths of approach and exit tangents, deflection angle and radius of previous curve. Radii of the previous curves were estimated in AutoCAD in a similar way as for the selected curves, and varied from 100 m to 800 m. For curve number 1 inner the radius of the previous curve was estimated to be 300 m; however, a traffic island is present in that curve. The radius of 300 m was still used in the analysis.

The curve lengths vary from 50 to 349 meters, and the deflection angle from 30 and 55.5 degrees. Only one curve, number 7, is circular without spiral transition curves. Curve number 5 and 6 have a spiral transition curve only on one side of the circular arc. The other curves have spiral transitions with lengths of 25, 40, 50 and 80 meters. The lengths of the approach tangents vary from 100 to 710 meters, with a majority shorter than 200 m.

The visibility differs between the curves and also between the travel directions in each of the curves. To give an understanding of the visibility conditions, images from a forward video from the euroFOT-data is shown for each curve and travel direction in Appendix A: Curve drawings & visibility.

Additional information about gradient, cross fall, annual average daily traffic (AADT[3]), road width and curvature was collected from the system PMSV3[4] provided by the Swedish Transport Administration, see Appendix B: Curve characteristics. The data was only available for curve number 1, 2, 4, 6 and 7, and the years at which the data had been measured differed between travel direction and different curves. The data from PMSV3 showed that the road widths for the selected curves are 6-6.3 meters, and the annual average daily traffic (AADT) 3800 to 4750. Curve number 1 and 2 had only a small gradient. The gradient for curve 4 to 6 respective for curve number 7 is shown in Figure 9 and Figure 10.

[3] Annual Average Daily Traffic, the total volume of vehicle traffic on a road for one year divided by 365 days

[4] Pavement Management System volume 3, The Swedish Transport Administration's database for road data. Link: pmsv3.trafikverket.se

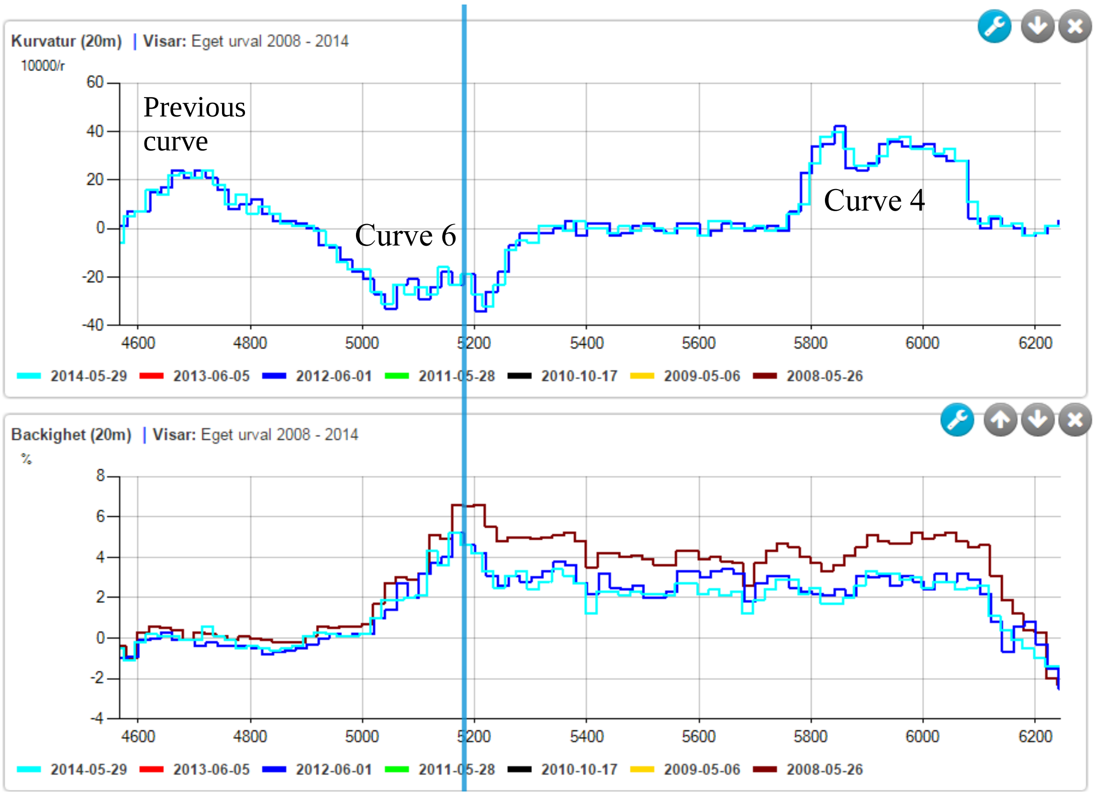


Figure 9: Output from PMSV3. Curvature [10000/radius] and gradient [%] from the approach tangent of curve number 6 inner to the exit tangent of curve number 4 outer. The colors represent the year of measurement.

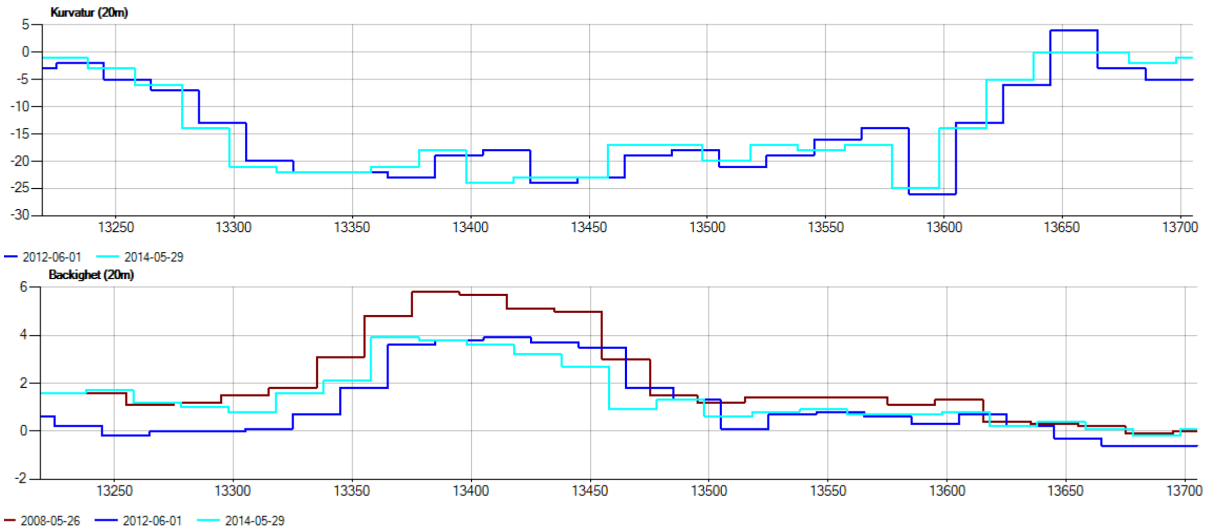


Figure 10: Output from PMSV3. Curvature [10000/radius] and gradient [%] from the approach tangent to the exit tangent of curve number 7 inner. The colors represent the year of measurement.

Table 4: Geometry of selected curves estimated by using AutoCAD Civil 3D.

Curve	R [m]	Curve length [m]	Deflection angle [°]	R of curve before [m]	Spiral length in [m]	Spiral length out [m]	Approach tangent length [m]	Exit tangent length [m]	Construction year (output from PMSV3)
1 inner	110	53	53.5	300	50	50	230	100	1977
1 outer				100	50	50	100	230	
2 inner	120	50	36	110	25	25	240	100	1977
2 outer				160	25	25	100	240	
3 inner	290	156	41	800	50	50	100	180	-
3 outer				385	50	50	180	100	
4 inner	300	254	55.5	470	50	25	160	480	1980
4 outer				410	25	50	480	160	
5 inner	385	164	30	290	80	0	425	180	-
5 outer				730	0	80	180	425	
6 inner	410	284	42.5	450	0	40	130	480	1980
6 outer				300	40	0	480	130	
7 inner	500	349	40	350	0	0	710	100	1991
7 outer				470	0	0	100	710	

3.2 Selection of trips

Trips that passed each of the selected curves were collected from the euroFOT database using a database query. The data includes several video sources, GPS and CAN-bus signals. For each trip data was processed to select comparable and unaffected driving conditions. Only trips with the following prerequisites were selected;

- Free flow conditions
- No trailer connected
- Adaptive cruise control off

Driver accepts the data to be used for future analysis (i.e., outside of the EuroFOT project)Trips in which drivers used mobile phone or had passengers in the car were not excluded from the study, since they represent everyday driving. Trips with all light and weather conditions were chosen to represent Swedish road conditions and everyday driving. This choice also resulted in more data to get a larger sample for the analysis.

The database query could not exclude trips in which the regular cruise control (not same as adaptive cruise control) was used, trips in which overtaking was performed in the curve, or trips with no free flow conditions due to bicyclists etc. CAN-bus signals were plotted in Matlab[5] and videos were watched to identify trips that did not fulfill the requirements and were then manually removed.

The number of trips used for the analysis can be seen in Table 5, as well as number of unique drivers, age distribution and gender. The number of passes in each curve varies, from 56 passes in curve number 7 outer to 461 in curve number 5 outer. The number of unique drivers varies from 11 in curve number 2 outer to 87 in curve number 5 outer. The trips in curve number 1 and number 2 are dominated by three drivers while the trips in curve number 3 and number 5 are more evenly distributed between the drivers. The distribution of drivers and trips for each curve can be seen in Figure 11. The figure was created in IBM SPSS Statistics[6] based on the driver ID:s for each of the trips used in the analysis. The age range of the drivers is 18-62 years, and the median is between 45 and 49 years for the different curves. The distribution between trips made by female and male drivers differs between the curves.

[5] Software for programming, computation, data analysis and visualization
[6] Software for statistical analyses

Table 5: Information about trips and drivers for the selected curves.

Curve		Trips	Unique drivers	Age range	Median age	Percentage of trips by females/males
1	Inner	203	14	18-57	45	52/48
	Outer	223	14	18-55	45	56.5/43.5
2	Inner	241	15	18-55	45	61/39
	Outer	219	11	18-55	45	55/45
3	Inner	281	65	25-62	47	26.5/73.5
	Outer	272	63	18-61	47	27.5/73.5
4	Inner	459	32	18-59	49	20/80
	Outer	280	31	18-61	49	23.5/76.5
5	Inner	362	78	18-62	47	25/75
	Outer	461	87	18-62	48	26/74
6	Inner	270	28	18-61	49	15/85
	Outer	423	30	18-59	48	20/80
7	Inner	61	31	34-60	46	34.5/64.5
	Outer	56	28	19-60	46	24/76

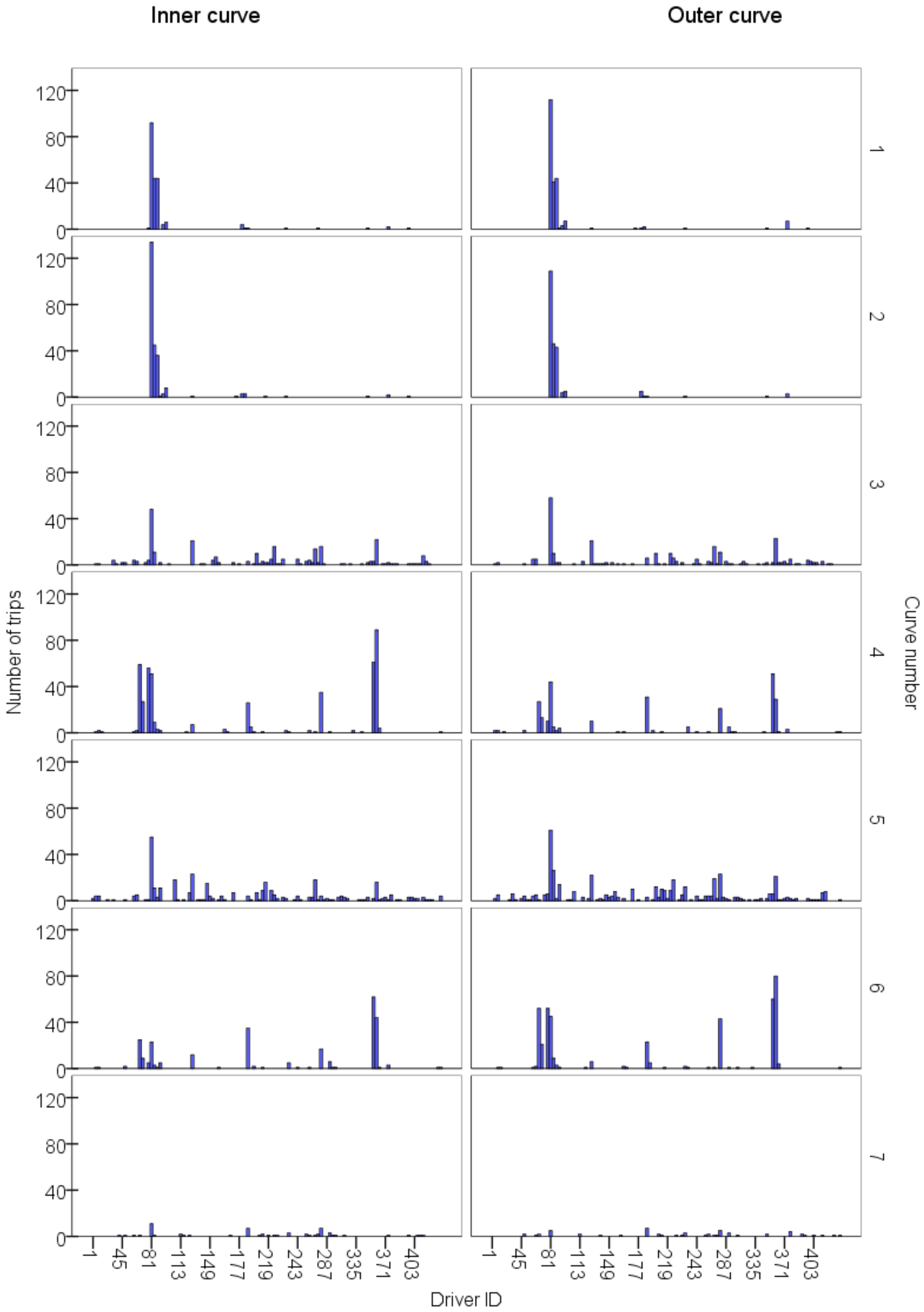


Figure 11: Driver and trip distribution for each curve. Created in SPSS Statistics.

3.3 Data analysis

Naturalistic driving data from euroFOT contains continuous data measured 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. Therefore, representative positions were chosen based on the curve geometry. The chosen positions are illustrated in Figure 12. The indexes of the points are based on travel direction. When approaching the curve, all points are indexed with “in”. After reaching the middle point of the curvature, the indexes change to “out”. All sections start at the approach tangent 100 m from where the curvature start, and ends at the exit tangent 100 m from where the curvature ends. This length was used since the shortest tangent was 100 m. The blue lines represent tangents, the green line a spiral transition and the red line a circular curve. (*T_in/T_out*) are start and end point on the tangents. (*S_in/S_out*) and (*C_in/C_out*) are points between tangent and curvature. If there is a spiral transition, (*S_in/S_out*) is the point between tangent and spiral. If no spiral is present, (*S_in/S_out*) is the same point as (*C_in/C_out*), which is the location where the curvature with constant radius begins. (*C*) is the center point of the curve. To better receive changes in the driver behavior, a point between each of the previous mentioned points were used as well. These are middle points called (*TM_in/TM_out*) and (*CM_in/CM_out*).

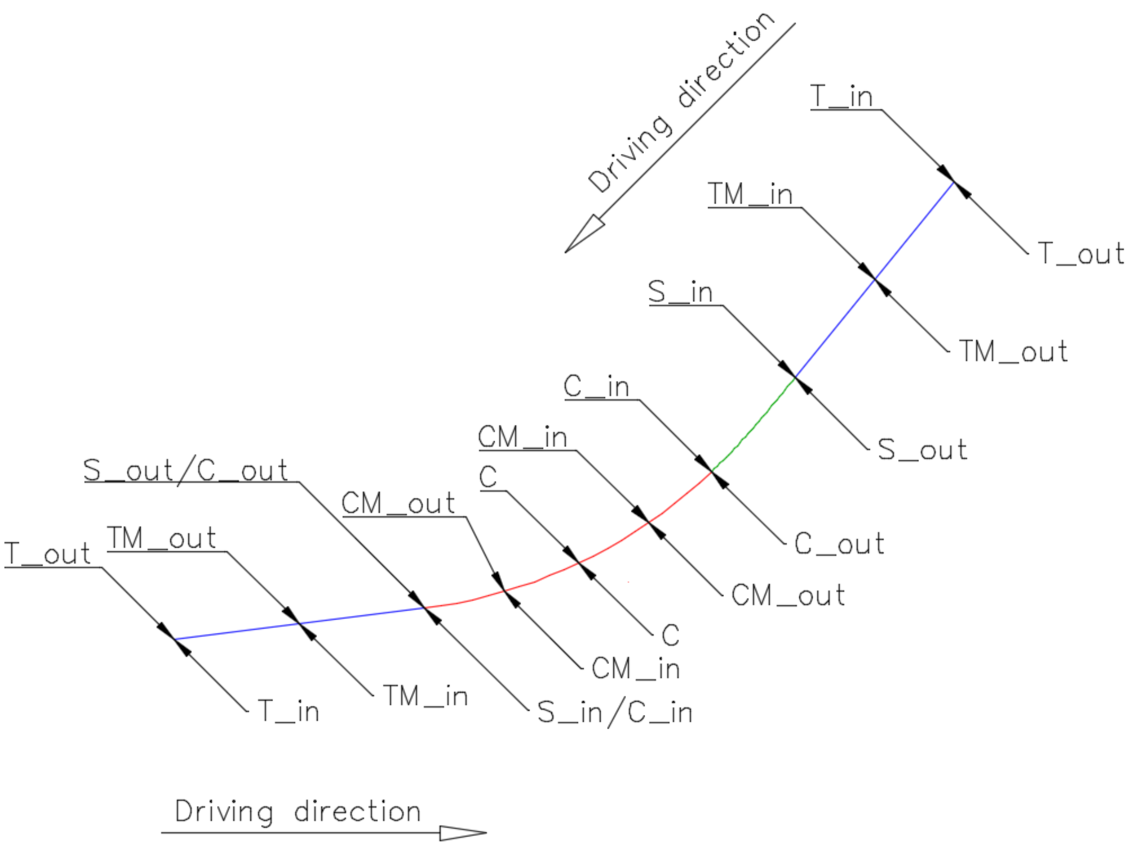


Figure 12: Points based on curve geometry. Created in AutoCAD Civil 3D.

A map tool in AutoCAD Civil 3D was used to get the GPS coordinates for the different points described above, and to define a GPS interval around each of the positions in all curves, see example in Figure 13. A Matlab script was run to extract speed for each position for the selected trips, resulting in 0-2 data points per GPS interval. The very few trips with no speed data within the interval were excluded. For the trips with 2 data points, the speed from one point was used.

Figure 13: Example of a GPS interval for a point. Captured from Bing map in AutoCAD Civil 3D.

The trajectory for the selected trips passing curve number 4 and number 6 can be seen in Figure 14. The plot was created in MathWorks Matlab, based on data from car data collected in Sweden as part of the euroFOT project. The red lines shows the trajectory for trips driving in curve number 4 inner and number 6 outer, and the black lines shows the trajectory for trips in the other direction. As the figure shows, the trajectories are separated for the north south direction, but not for the east west direction. The trajectories crosses each other in the east west direction, which makes it difficult to analyze trajectories in curves, therefore it has not been included in this study.

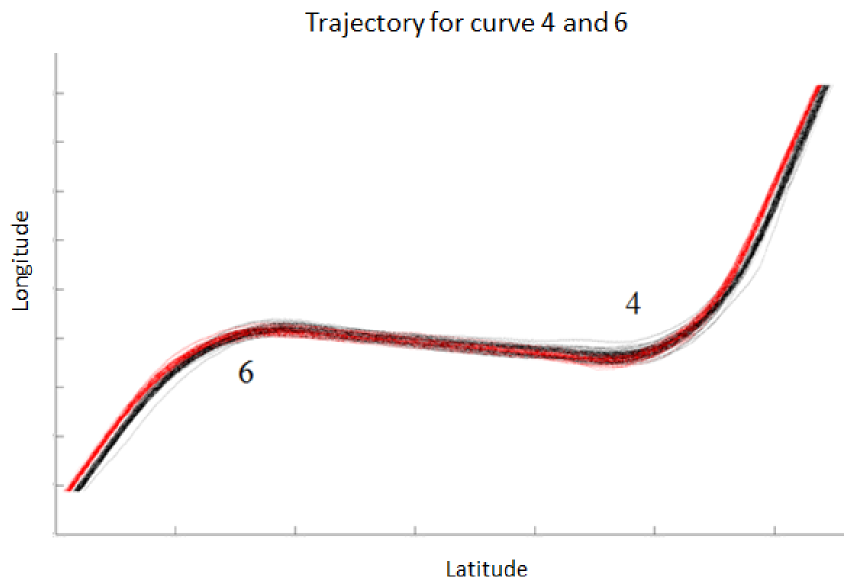


Figure 14: Trajectory plot for curve number 4 and 6 using GPS-signal. Trips going in curve number 6 inner and curve number 4 outer are plotted with black lines. Trips going in the other direction are plotted with red lines. Created in Matlab.

A table containing all trips and data about the driver, road characteristics and speed for the 11 points in each curve were generated in Matlab. By using continuous data for each trip, the maximum lateral acceleration within the curvature was generated.

Previous studies have used speed differentials to describe driver behavior in curves. Speed profiles for different drivers and speed profiles in the curves were generated in Excel to analyze patterns. Also the speed differentials in (*ΔV_in*) and out of the curves (*ΔV_out*) were calculated for each trip. *ΔV_in* was calculated by subtracting the lowest speed in the curvature with the highest speed on the two points on the approach tangent. *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 analysis were performed in SPSS to find factors affecting the speed at the beginning (*C_in*) and center (*C*) of curves, speed differentials and maximum lateral acceleration in the curvature.

Table 6: Dependent and independent variables used in the analysis. RC: Radius of curve, RPC: Radius of previous curve, LAT: Length of approach tangent, LAS: Length of approach spiral transition, LET: Length of exit tangent, LES: Length of exit spiral transition. shows the independent variables that were used for the different dependent variables. The stepwise method was chosen, with an entry probability of 0.05, removal probability of 0.10 and a 95 percent confidence interval. Driver A was excluded from the analysis, since the driver mainly drove in curve number 3 and 5 and showed a different behavior than other drivers in terms of very high speeds. Regression analysis including Driver A was also performed to compare the results.

Table 6: Dependent and independent variables used in the analysis. RC: Radius of curve, RPC: Radius of previous curve, LAT: Length of approach tangent, LAS: Length of approach spiral transition, LET: Length of exit tangent, LES: Length of exit spiral transition.

Dependent variables	Independent variables
Speed at C	R_C, R_{PC}, L_{AT}, L_{AS}
Speed at C_in	R_C, R_{PC}, L_{AT}, L_{AS}
ΔV_in	R_C, R_{PC}, L_{AT}, L_{AS}
ΔV_out	R_C, L_{ET}, L_{ES}
Max. lateral acc.	R_C, R_{PC}, L_{AT}, L_{AS}

4 Results

The result from the analysis of driver behavior in the selected curves is shown in this chapter. The chapter is divided into three sections: *Geometry of selected curves and design standards*, *Speed profiles and speed differentials* and *Relation between driver behavior and road geometry*. In the first one, the geometry of the selected curves is compared to the current Swedish design standards. In the second section speed profiles for the different curves are provided. The third section describes how factors connected to curve geometry affect the driver behavior in the selected curves.

4.1 Geometry of selected curves and design standards

This section describes how the radius, curve length and spiral length of the selected curves relates to the Swedish existing design standards. In Table 7 the geometry of the selected curves can be seen as well as the current design standards. It can be seen that curve number 1, 2, 3 and 4 have radii smaller than the desirable minimum radius. The radii of curve number 1 and 2 are additionally lower than the minimum acceptable radius.

The desirable minimum arc length for roads with a speed limit of 70 km/h is 100 m, and the minimum acceptable 60 m. Both curve number 1 and 2 have shorter curve lengths than the minimum acceptable, and the other curves have longer curve lengths than the minimum desirable length.

For curve on roads with speed limit 70 km/h, spiral transitions should be used if the radius is smaller than 400 m, which includes all curves except number 6 and 7. The only curve without any spiral transitions is curve number 7. Curve number 1 to 4 have spiral transitions on both sides of the circular curve, and curve number 5 and 6 on only one side. The minimum spiral parameter was calculated for the selected curves by using formula 1 on page 4 with the radius and length of spiral transition as parameters. It was found that only the spiral parameter for curve number 5 was larger than the requirement.

Table 7: Geometry of the selected curves and Swedish design standards. Green indicates that the requirements are fulfilled, orange indicates that the requirements are partly fulfilled and red indicates that the requirements are not fulfilled.

Curve	Radius [m]	Desirable min R / Min acceptable R [m]	Circular curve length [m]	Desirable min arc length / Min acceptable arc length [m]	Spiral lengths [m]	Min spiral length [m]
1	110	340/210	53	100/60	50/50	218
2	120		50		25/25	200
3	290		156		50/50	83
4	300		254		25/50	80
5	385		164		0/80	62
6	410		284		0/40	-/59
7	500		349		0/0	-

4.2 Speed profiles and speed differentials

The average speed at the center point of the curves is shown in Table 8. The average was calculated of the15:th, median and 85:th percentile speed for the inner and outer travel direction. The average speed can be seen to increase with the radius, for all curves except curve number 7. For the average of the median speed, the speed limit (70 km/h) is held only in curve number 1.

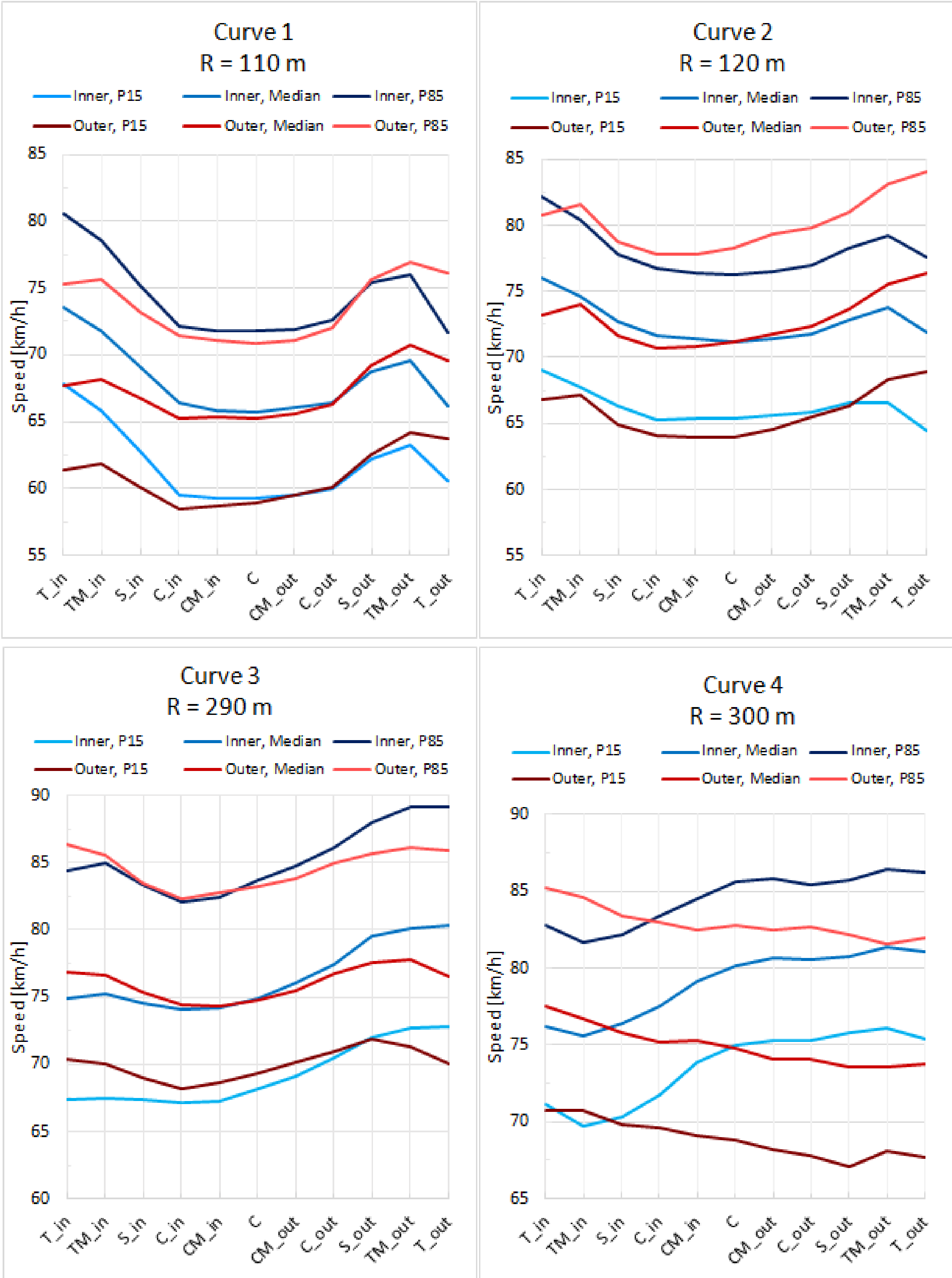
Table 8: Average speed between the speed in inner curve and the speed in outer curve at the center point of the curve.

Curve number	Radius [m]	Average speed between speed inner and outer at the center point of the curve [km/h]		
		15:th percentile	Median	85:th percentile
1	110	59	66	72
2	120	65	72	77
3	290	68	75	83
4	300	72	77	84
5	385	72	78	87
6	410	76	83	88
7	500	67	75	85

The 15:th percentile, median and 85:th percentile speed for the eleven points is shown for each curve in Figure 15. In the graphs, the speed in inner curves is shown by a blue line, and the speed in outer curves with a red line. Note that the distances between each of the points differ in reality.

The 15:th percentile, median and 85:th percentile speed pattern for each curve is similar. The speed profile for curve number 5 is smooth, and the speed difference between the tangent before and after the curve is less than 5 km/h. The speed profile is similar for both inner and outer. For curve number 1, 2 and 3, a speed reduction can be noticed within curvature. The lowest speed is found at point *C_in*. For these curves, the speed profiles for inner and outer appear mirrored, and no distinct differences in speed can be seen between inner and outer curve. The same appears for curve number 5.

For curve number 4, 6 and 7 the speed pattern between inner and outer differs. In curve number 4 the speed is increased throughout the whole curvature for the inner direction. For the other direction, the speed is reduced instead. The speed differential between the tangents is larger for the inner curve than for the outer curve. For curve number 6, a small increase in speed can be seen at *C_in* for the outer curve. At *CM_in*, the speed becomes constant. For the other direction, a speed reduction begins at *C_in* instead, and the speed becomes constant at *C_out*. Curve number 7 shows an increase in speed between point *C* and *CM_out* for the outer direction, and a decrease between *CM_in* and C in the inner curve.


Curve 1
R = 110 m
Inner, P15
Inner, Median
Inner, P85
Outer, P15
Outer, Median
Outer, P85
Speed [km/h]
T_in
TM_in
S_in
C_in
CM_in
C
CM_out
C_out
S_out
TM_out
T_out
Curve 2
R = 120 m
Curve 3
R = 290 m
Curve 4
R = 300 m

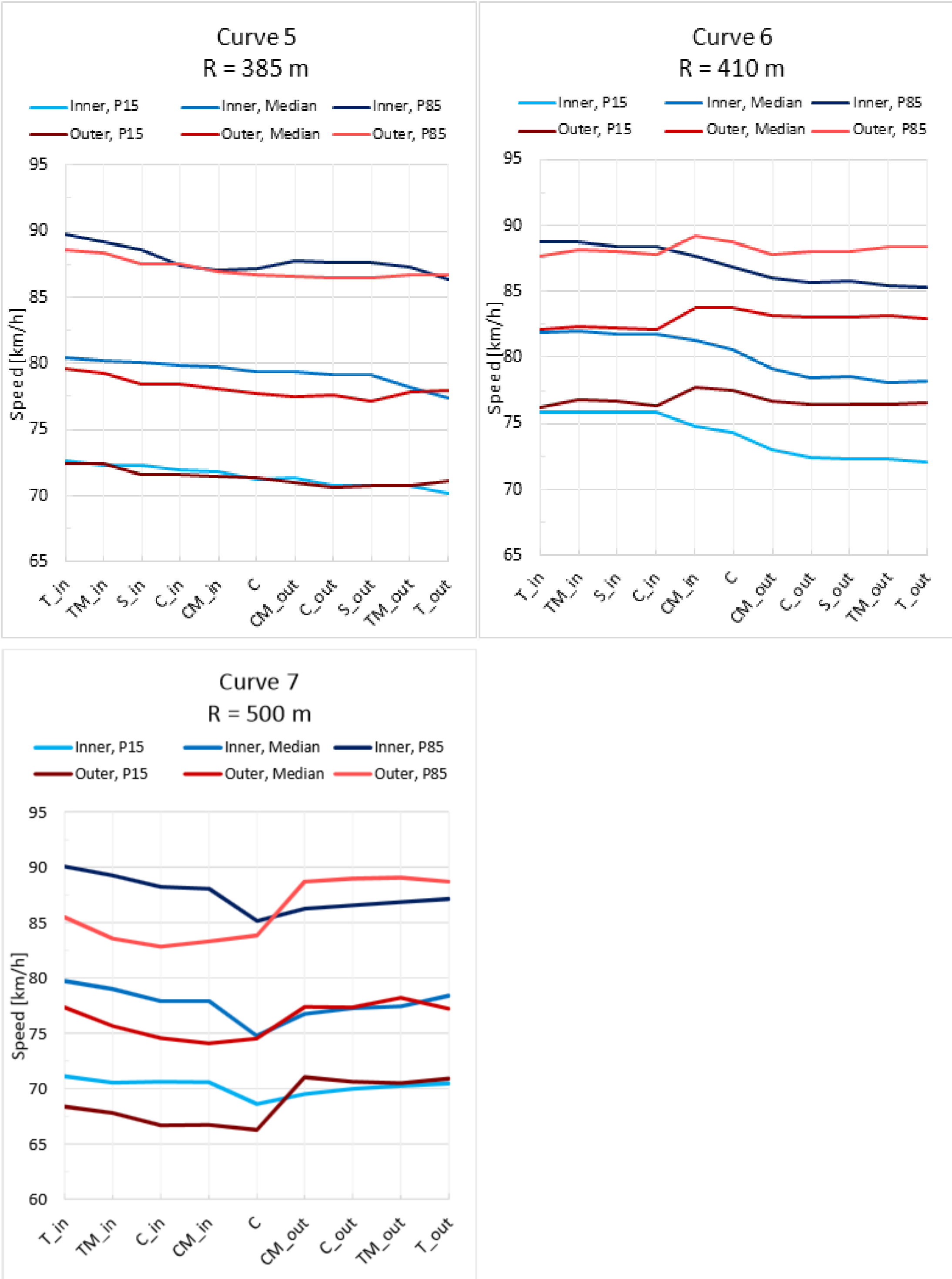


Figure 15: Speed profiles for inner (blue) and outer (red) curve, for 15:th, median, 85:th percentile speed.

The 15:th, median and 85:th percentile speed at the tangent between curve number 4 and 6 are shown for both directions in Figure 16 and Figure 17. The first and last two points are approximately the same points as *TM* and *T* in the two curves respectively. At the tangent between curve number 4 inner and 6 outer there is a negative gradient of approximately 4 percent, see Figure 9 on page 16. The speed profile shows a small increase in speed on this tangent, and the highest speed is found close to curve number 6. For the other direction, see Figure 17, there is a constant positive gradient on the tangent. The speed is seen to increase slightly towards the middle of the tangent, to therefore decrease slightly before curve number 4.

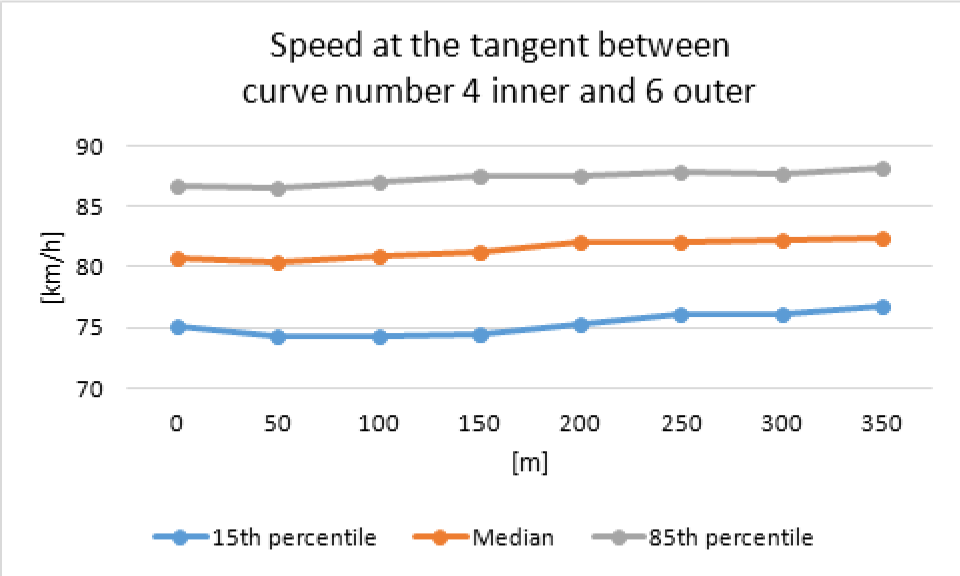


Figure 16: 15:th, median and 85:th percentile speed at the tangent between curve number 4 inner and number 6 outer.

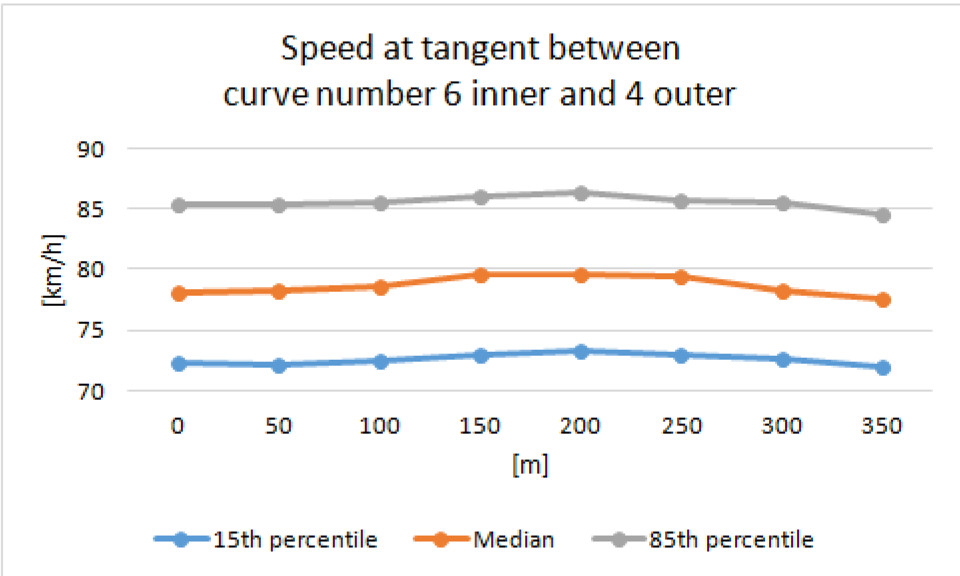


Figure 17: 15:th, median and 85:th percentile speed at the tangent between curve number 6 inner and number 4 outer.

By plotting the speed profiles for individual drivers driving through the same curve and in the same travel direction several times, it can be seen that the speed pattern correlates well to the speed patterns in Figure 15. The size of the speed range differs between different drivers and curves, see examples in Figure 18 and Figure 19. The 15:th, median and 85:th percentile speed also differs between different drivers and curves. For instance, driver A consistently drives faster than all other drivers. By watching videos of most of the trips in which driver A drives slower than the driver's usual speed in that curve. It could be seen that in most cases, the driver either had a child in the car or used a mobile phone. Regardless of the high speed, the speed profile is similar to speed profiles for drivers driving at lower speed.

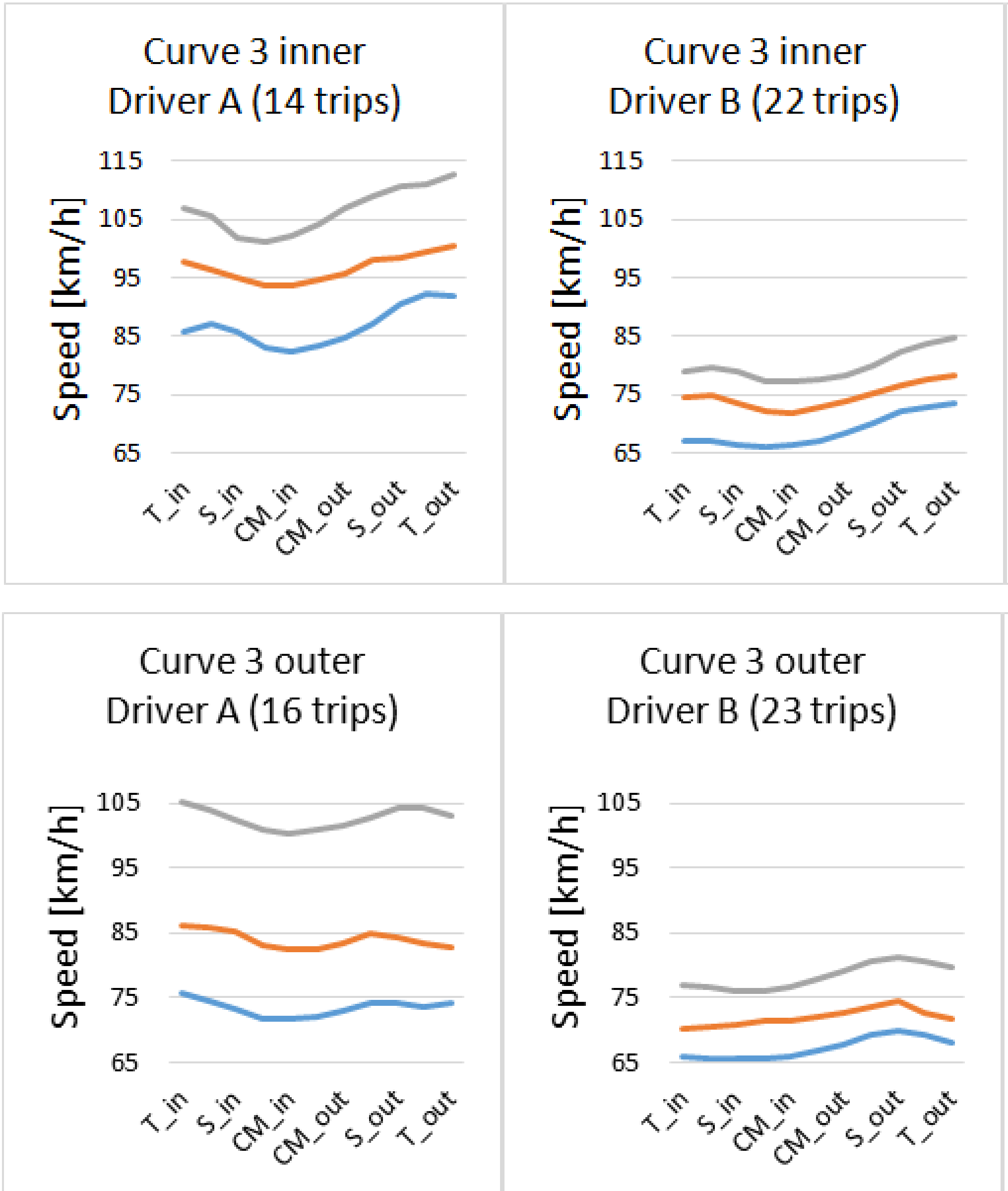


Figure 18: Speed profiles for curve number 3 for driver A and B.

For most drivers the speed pattern was similar. However; for curve number 6 outer, the speed profiles for different drivers were found to differ slightly, see Figure 19. Driver D decreases the speed out of the curvature, while driver C slightly increases the speed.

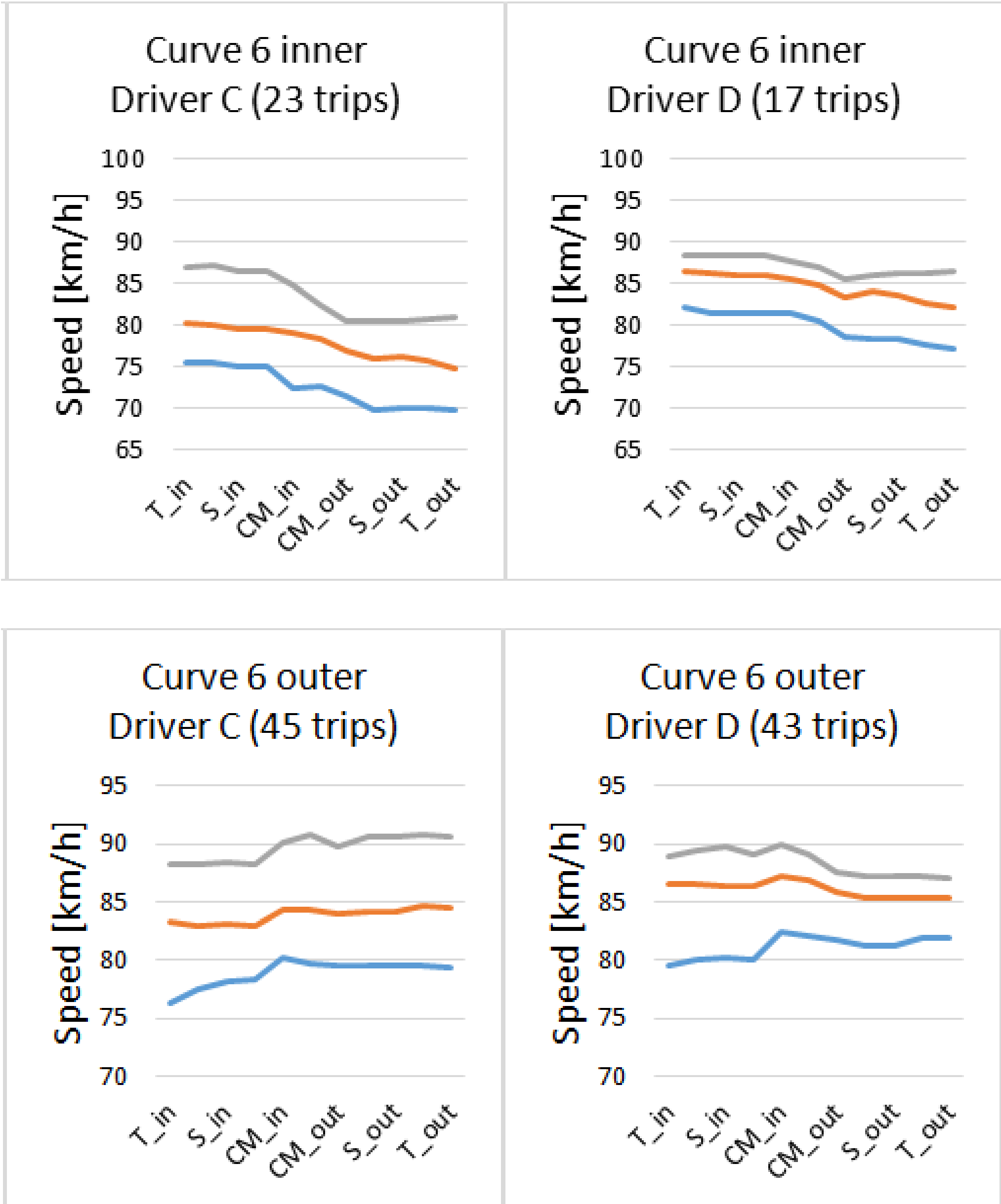


Figure 19: Speed profiles for curve number 6 for driver C and D.

Figure 20 show histograms of the speed differential in respective out for curve number 1 to 7. The height of the staples represents the frequency. Due to few trips in curve number 7, the staples are lower compared to the other curves.

By studying the speed differential in, the speed reduction appears higher on curve number 1 and 2 compared to the other curves. For curve number 1, the range is wide and the staples evenly distributed. With increasing radius, the speed differential moves towards the 0 value. For curve number 3, 4, 5 and 6 there are more trips with a positive speed differential in than in the other curves.

The speed differential out is similar for curve number 1, 2 and 3. The speed differential decreases with increasing curve radius. For curve number 5 and 6, the speed differential is concentrated around the 0 value.

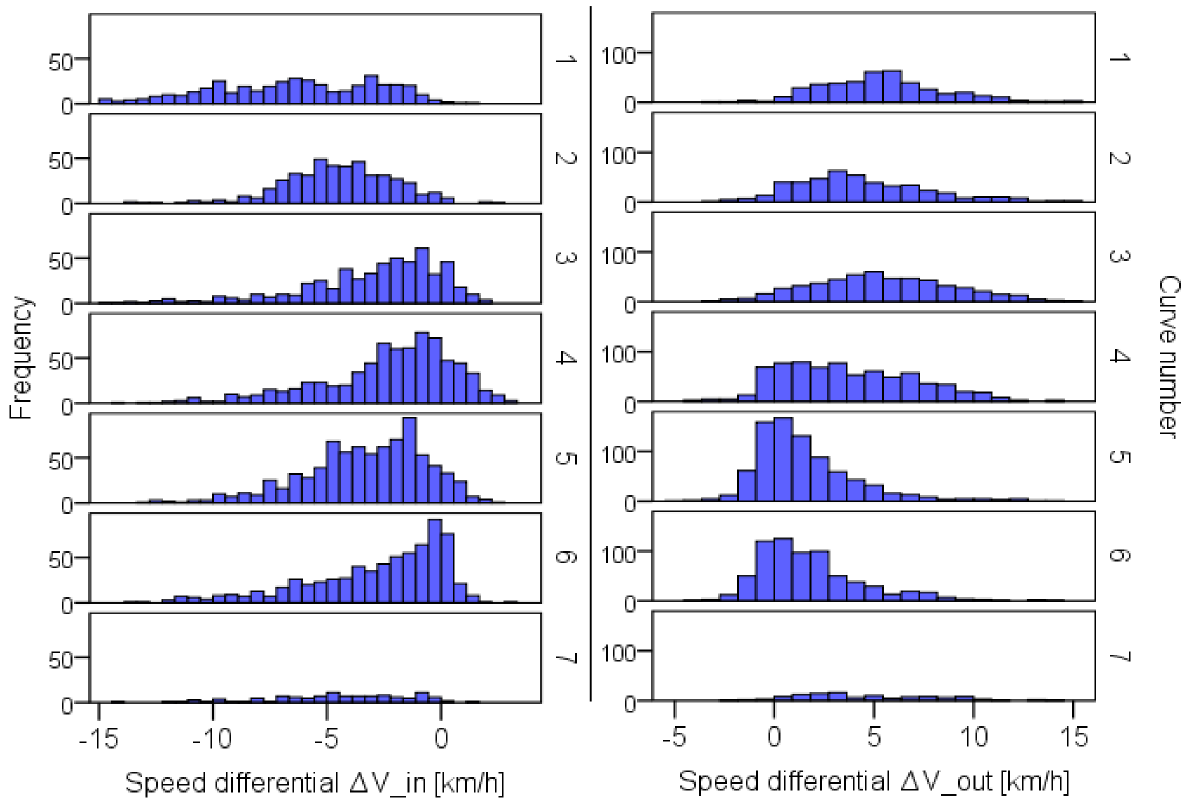


Figure 20: Histograms showing the speed differentials in respective out for the selected curves. Created in SPSS Statistics.

4.3 Relations between driver behavior and curve geometry

In this section, result about how factors related to the curve geometry affect the driver behavior in curves is discussed.

4.3.1 Results from graphs

Figure 21 shows the median speed at the point where the approach tangent ends and the spiral transition curve begins, *S_in*, for different lengths of the approach tangents. Each color represents one curve for both travel directions. For all curves except curve number four, the speed is lower in the direction with the shortest length of the approach tangent. For curve number four, the speed is lower for the longer tangent instead. In the figure, it can also be seen that the speed increases with larger radii except for curve number 7 with the largest radii.

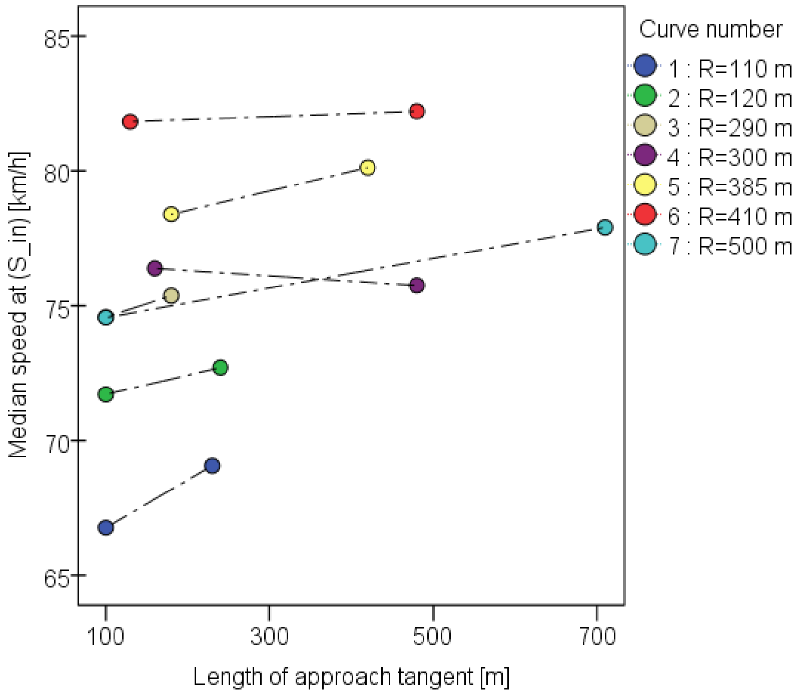


Figure 21: Median speed at the start-point of the curvature (S_in), for different lengths of approach tangent. Created in SPSS Statistics.

In Figure 22 the median speed at the end of the curve (*S_out*) is shown for different lengths of the exit tangent. Curve number 1, 2, 3 and 4 consistently show higher speed at *S_out* for longer tangent lengths. However, curve number 5 and 6 indicate the opposite pattern and for curve number 7 no change can be detected. The median speed at *S_out* increases with the radii of curve number 1, 2, 3, 5 and 6. For curve number 4 the speed at *S_out* differs a lot between the different tangent lengths.

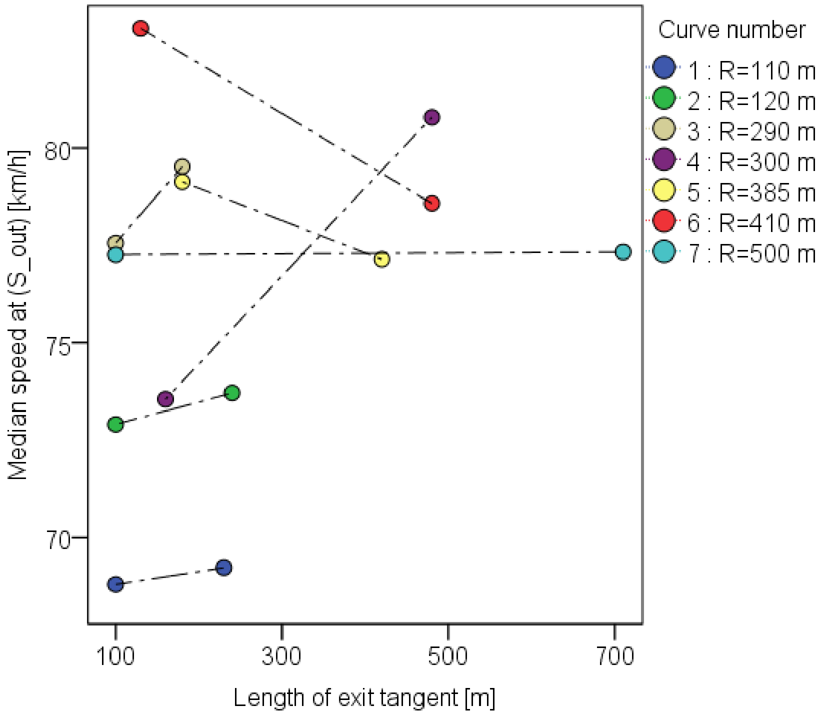


Figure 22: Median speed at the end-point of the curvature (S_out), for different lengths of exit tangent. Created in SPSS Statistics.

4.3.2 Results from regression analysis

The regression analysis was done to study the influence of tangent length, radius of curve, presence and length of spiral transitions and radius of the previous curve on speed at point *C_in* and *C,* speed differentials and maximum lateral acceleration. A 5 percent significance level was set as the criteria for including an independent variable in the model. The result is briefly presented in this section, tables from the regression analysis can be found in Appendix D: Regression analysis.

A summary of the result from the regression analysis is shown in Table 9. The influence of an independent variable is calculated by multiplying the coefficients with the length of the corresponding independent variable. The calculated coefficients and the constant are summarized to get the value of the dependent variable.

As mentioned in the methodology, driver A was excluded from the first regression analysis. The result when including driver A did not differ considerably compared to excluding the driver, except for the dependent variable *Speed at C_in*. When including driver A, the result showed that the only factor influencing the speed at the beginning of the curve was the curve radius. The result when excluding driver A showed that more variables influenced the speed at that point.

Table 9: Summary of result from regression analysis in SPSS.

	Speed at C_in (without driver A) [km/h]	Speed at C_in (with driver A) [km/h]	Speed at C [km/h]	ΔV_in [km/h]	ΔV_out [km/h]	Maximal lateral acceleration [m/s^2]
Constant	63.787	63.902	62.874	-7.430	6.229	3.062
Radius of previous curve	Not significant	Not significant	-0.004	-0.004	Not included	-0.001
Approach tangent length	0.002	Not significant	-0.003	-0.006	Not included	0.000
Approach spiral length	Not significant	Not significant	0.050	0.055	Not included	Not significant
Curve radius	0.039	0.041	0.046	0.016	-0.012	-0.003
Exit spiral length	Not included	Not included	Not included	Not included	-0.006	Not included
Exit tangent length	Not included	Not included	Not included	Not included	0.004	Not included

How the studied factors influenced the speed, speed differential and maximal acceleration is described below:

Radius of previous curve

- Larger radius of previous curve results in slightly lower speed at *C*
- The radius of the previous curve does not influence the speed at *C_in*
- Larger radius of the previous curve results in larger speed differential when entering the curve

- Larger radius of previous curve decreases the maximum lateral acceleration in the curve

Approach tangent length

- Longer approach tangent results in higher speed at the start of the constant curvature (*C_in*), but lower speed in the center of the curve (*C*). However, the influence on speed is relatively low
- Longer approach tangent results in larger speed differential when entering the curve
- The influence of the approach tangent length on the maximum lateral acceleration is negligible

Approach spiral length

- The speed *C* increases with longer approach spiral transition
- The speed at *C_in* is independent on the length of the approach spiral transition
- Longer approach spiral transition results in smaller speed differentials when approaching the curve
- The maximum lateral acceleration in the curve is unaffected by the length of approach spiral transition

Curve radius

- The speed at *C* and *C_in* increases with the radius of the curve.
- Larger radius results in smaller speed differential in and out of the curve
- The maximum lateral acceleration increases with smaller radius

Exit spiral length

- Longer exit spiral transitions results in smaller speed differentials when leaving the curve

Exit tangent length

- Longer exit tangent results in larger speed differential when leaving the curve

5 Discussion

In this chapter the selection of curves and trips is discussed, as well as the result from the speed profiles and how curve geometry affects driver behavior in curves. The result is also compared to previous studies presented in the literature study. Also, limitations of the study are discussed, and ideas about further studies outlined.

5.1 Naturalistic driving data

The study was limited to the car data collected in Sweden as part of the euroFOT project. The age, gender and range of drivers could therefore not be influenced. However, it would have been possible to only select trips made by specific drivers. The driving routes could also not be influenced, whereupon only curves close to Gothenburg were selected to get a large number of passes. This limited the number of curves that could be used, and also the amount of data. Another limitation with using naturalistic 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 which would result in more comparable curves. Also, it would result in more curves to analyze.

However, the advantages with the naturalistic driving data are that it is collected from everyday driving and on existing roads. The participants drive more naturally compared to when using simulators or instrumented vehicles. Everyday driving results in that most drivers drive many times through specific curves. Therefore, it is possible to study how the same driver behaves in the same curve at different times. However, it is not possible to study the driver behavior when driving in a curve for the first time. Even though one could see that a driver had not driven in a specific curve during the euroFOT project, the driver could have driven there before.

Compared to methods measuring data at points, data from euroFOT is continuous. This makes it possible to study detailed driving behavior. However, this study only uses continuous data for maximum lateral acceleration. The speed data was studied for eleven points along the curves, which made it possible to couple the driver behavior to curve geometry.

5.2 Selected curves and trips

Seven curves with different characteristics were selected in the study. How well the geometry of the selected meet the current recommendations set by the Swedish Transport Administration is discussed, as well as how the selection affects the result. How the selection of passes through these curves affects the result is also considered.

The existing design standards from year 2012 do not include design recommendations for roads with speed limit of 70 km/h. However, in the previous documents from year 2004 this is included. It is therefore assumed that the standards from year 2004 are valid for roads with a speed limit of 70 km/h.

5.2.1 Curves

The choice to only select curves on two-lane rural roads was made to get a result comparable with previous studies. However, it resulted in a selection of curves that all have a posted limit of 70 km/, and which limits the study to only one type of road. For the analysis it would have been preferable to analyze more curves, which would result in a more reliable result. However, as mentioned above the study was limited to the data available in the euroFOT car data from Sweden.

In order to get a result comparable to other studies, this study used curves in between tangents. This made it possible to determine how tangent lengths affect the driver behavior. To ensure that drivers anticipated curves at a desired speed, it was desired that the drivers had obtained constant speed before the curve. However, many curves on two-lane rural highways in Sweden only have short or no tangents between adjacent curves. If curves with short or no tangents should have been included in the analysis, a larger number of curves could have been selected. Since a large part of the Swedish road network seems to be designed with short or no tangents between adjacent curves, future studies should also include that type of curves to get a larger and more representative sample.

The study did not take factors related to the vehicle, personal trait and road factors such as pavement conditions, friction and superelevation into account. These factors could influence the driver behavior. For instance, insufficient superelevation results in increased lateral acceleration. To include this factor would be of interest. Information about superelevation was not found for all curves in this study, which made it hard to include. However, the factors taken into account in the study are considered to have the major influence on the driver behavior.

No drawings could be found for the selected curves; therefore estimations of curve geometry were made from a satellite map. There could be errors in the satellite map, resulting in an estimated curve geometry differing from the reality. Also, there could be errors in the alignment created in AutoCAD. The radii of the curves used in the analysis were the circular radii estimated from the map, and the same radius was used for both travel directions. However, the driving path radius most probably differs from the estimated radius. A previous study by Bonneson et al (2007) found that the driving path radius is the same as or slightly higher than the radius of the curve.

The selected curves were both simple circular curves, curves with spiral transition one side of the circular arc, and curves with spiral transitions on both sides of the circular arc. This made it possible to study the effect of spiral transitions; however, it resulted in less comparable curves. Since most Swedish two-lane rural roads have a speed limit of 70 km/h, and since different types of curves were chosen for the analysis, it is believed that the selected curves give a good representation of the curves in Sweden. The chosen curves have radii from varying from 110 to 500 m, which made it possible to study the effect of radius on driver behavior. Also, curve number 1 & 2, 3 & 4, and 5 & 6 respectively had similar radii. Since the radii is pairwise similar, it was possible to compare how other factors than radii affected driver behavior for these curves, for instance tangent length.

Curve number 1 and number 2 (radii 110 and 120 m) have radii lower than what is acceptable according to the design standards. Additionally, curve number 3 and number 4 (radii 290 and 300 m) have radii smaller than the desirable radius. This indicates a presence of curves on the Swedish roads with lower standards than the existing recommendations. No construction years were found for curve number 3 and 5, but the curves 1, 2, 4, 6 and 7 were constructed between year 1977 and year 1991.

The design standards were probably different then compared to the existing standards. This gives an indication that it is more desirable today to use larger radii on curves on two-lane rural highways in Sweden compared to earlier.

Regarding the arc length of the selected curves, all curves except curve number 1 and 2 fulfill the recommendation. Curves number 1 and 2 are shorter than the minimum acceptable length together with the fact that their radii are lower than the minimum acceptable radius, indicates that they are not well designed compared to the current standards. Therefore, the results from these two curves are very interesting to compare with the results from curves that actually fulfill the current recommendations.

The result showed that among the selected curves that have spiral transitions, only curve number 5 inner has a spiral length longer than the minimum according to the recommendations. The spiral transition is missing in curve 5 outer. On the other hand; the radius is only slightly smaller than what is recommended without spiral transition. Curve number 6 does not need spirals according to the current recommendations. However, it has a spiral on one side which is shorter than the minimum requirement. Consequently, the only curve that actually fulfills the recommendations is curve number 7, and curve number 5 and 6 almost fulfills the recommendations.

5.2.2 Trips

The data used in the analysis was collected from naturalistic driving. When manually going through the trips and only selecting trips that fulfilled the requirements set, not all videos for all trips could be watched due to time restrictions. Therefore, in case of malfunction of a signal, the analysis could include trips with non-free flow for instance. However, since there are many trips in each curve, this would most probably not have any significant effect on the result.

To represent everyday conditions trips with passengers in the car, mobile phone in use, all weather conditions and all light conditions were used. These factors could all influence the driver behavior. Previous studies have found lower speeds on wet or icy roads compared to dry roads. Also, the speeds on winter roads have been found to be 75 to 90 percent of the speed on bare roads. However, the speeds during day and nighttime have been found to not differ considerably. Since this study includes winter conditions and precipitation, the speeds that were observed here might be slightly lower than what has been found in previous studies of favorable weather conditions.

The database used does not include information about surface conditions (wet/dry). However, it includes information about wiper activity and main beam. Therefore, it would be possible to distinguish between driver behavior during light and dark conditions, and also during precipitation and dry weather conditions. It would also be possible to distinguish between snow and rain by using information about outside temperature. To compare the driver behavior for different weather and light conditions would be of interest as a further study.

One major difference in this study compared to simulator- and instrumented vehicle studies is that in this study the data is dominated by trips from drivers driving in the same curves many times. For example, three drivers account for 790 trips in curve 1 and 2. The fact that several drivers drove in the same curves many times means that they are familiar with the road and probably have a strategy for how to drive in the curves. A driver anticipating a curve for the first time probably chooses a more defensive driving behavior, and also gets more surprised by unexpected road alignment. It is not known to which extent the familiarity of a road influences the driver behavior. Further studies on how the familiarity of a curve influences the driver behavior would be valuable.

When selecting curves, many curves were excluded due to too few passes. Some of the selected curves had more than 400 trips in one direction, which make it difficult to analyze it together with curves with only a few passes. The selected curve with the fewest trips had more than 50 trips in each direction, while the excluded curves had between 0 and10 trips in each direction. Additionally a few curves with many trips were excluded due to too low range of drivers. There is an increased risk of biased data if one driver totally dominates the trips in a curve. The exclusion resulted in fewer selected curves, with many trips passing in each direction. An option would have been to select many curves with few trips instead of selecting few curves with many trips. However, it would have been difficult to find enough curves since the passes gets fewer the further away the roads are from Gothenburg. With this setup, it would also be hard to analyze driver behavior in single curves since there would not be enough data for it.

To define the eleven points to retrieve data about speed, GPS-coordinates were used. It was found that the GPS precision is poor, as can be seen in Figure 14 on page 22. Since the road width is approximately 6 m, the paths of inner and outer curves cross each other, and since there are many trips that occur to be even outside the road, the error is estimated to be approximately 10 meters. Also, for each of the eleven points, 1 to 2 data points were found within the box. The data was collected once every tenth of a second. When travelling at 70 km/h (~20 m/s) this would mean one data point every 2 meters. Therefore, the error for each point is approximately 2 m. Due to these errors; the data is not collected exactly when the vehicle passes the point of interest. However, speed does not fluctuate much. This implies that the speed most probably is representative for the point anyway.

Regarding the selected trips, curve number 7 has substantially less trips than the other curves. However, the trips are evenly distributed between different drivers; see Figure 11 on page 20. In curve number 3 and 5 there is a large range of drivers, and the trips are evenly distributed. In curve number 4 and 6 there are 7-8 drivers responsible for most trips. In curve number 1 and 2 three drivers dominate the number of trips. Since in most curves there are many trips and many different drivers, different driver behaviors are represented in the data. This reduces the probability of data biased towards certain behavior.

Most of the trips were made by male drivers with a median age of 47-49 years. However, the age range was between 18-62 years, and in curve number 1 and number 2, there were more trips made by female drivers compared to male drivers. It is therefore considered that the study represents many different types of drivers.

5.3 Speed profiles and speed differentials

In this chapter, the result from the speed profiles is discussed, and the average speed between inner and outer curve is compared to the posted speed limit.

5.3.1 Speed compared to posted speed limit

The result showed that in general drivers keep a higher speed than the posted speed limit. 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 favorable weather conditions, as discussed previously. Also, the speed was measured close to and within curves. Most probably, the speed is even higher on tangents. The minimum desirable radius for curves with spiral transitions on roads with a speed limit of 70 km/h is 340 m, on 80 km/h it is 400 m and on 90 km/h roads it is 520 m. This means that, in terms of radius, it would be safe according to the design standards to drive in 80 km/h on curve number 6 and 7. However, the 85:th percentile speed exceeds 80 km/h for all curves except curve number 1 and 2.

The fact that drivers keep higher speeds in the curves than the speed they are designed for could result in safety problems. 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. It is therefore unsafe to travel at higher speed than what the curve is designed for. Higher posted speed limits affect the recommendations for curve design in terms of larger radius, longer spiral transitions and higher super-elevation. The combination of drivers exceeding the speed limit and curves that do not satisfy the design standard makes a serious threat to traffic safety. The extent of these problems and the connection to accident data needs further research.

5.3.2 Speed profiles

By studying the average speed at the center point (*C*) of the curves, the speed was found to increase with the radius of the curve, see Table 8 on page 25. This result is consistent to previous studies by Helmers & Törnros (2006), Montella et al (2015), Quaium (2010) and Othman (2011). However; for the curve with the largest radius, curve number 7, the 15:th, median and 85:th percentile speed was similar to the speed in curve number 3, which has a much smaller radius. By studying the speed profile for curve number 7 it can be seen that the center point is where the lowest speed occurs for both travel directions. However, if the average speed would have been calculated for point *CM_in* or *CM_out* instead, the speed would still not support the pattern of higher speed for higher radius. Most probably, there are other factors affecting the speed more than the radius in this specific curve. This is further discussed later on.

The speed profiles are created for the 15:th, median and 85:th percentile speed for each of the eleven point. This implies that the profile is not created for one representing trip. Therefore, the profile for individual trips might appear different. However, the speed patterns are similar for the 15:th, median and 85t:th percentile in all curves, which indicates that the profiles are valid. Also, the distances between the points where data were collected vary, which is not apparent from the figures. This results in that some parts of the profiles for the curves with short lengths (1 and 2) are stretched. For curve number 7 which is long, some parts are compressed instead. However, the patterns are still the same.

For curve number 1, 2 and 3, the speed profiles show a decrease in speed within the curvature compared to the speeds at the tangents, see Figure 15 on page 26-27. This gives an indication that drivers decrease their speed in curves with small radii. This result is consistent with the previous studies by Helmers & Törnros (2006), Montella et al (2015), Quaium (2010) and Othman (2011). For these three curves, the inner and outer speed profiles appear mirrored, which indicates a similar behavior regardless of travel direction. The different behaviors on the tangents are probably due to different tangent lengths, and different radii of previous and following curves.

Curve number 5 shows a smooth speed profile which is almost identical for both travel directions; see Figure 15 on page 26-27. 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. For curve number 1, 2 and 3 the tangent length appears to influence the choice of speed. In these curves, the speed at the approach tangent is higher in the direction where the approach tangent is longer (230, 240, 280 m compared to 100 m). This correlates to the study by Hu and Donell (2010), in which higher approach speeds were found for longer tangents. The same occurs at the exit tangent, where the speeds are higher on longer tangents. This is also found for curve number 4 and 7. For curve number 6, the approaching speed is approximately the same for both directions. However the speed at the exit tangent is higher for the shorter tangent (130 m) compared to the longer tangent (480 m). Most probably, the speed in this curve is affected by other factors, such as a gradient in the curve.

For the larger radii curves 4, 6 and 7 the speed patterns between inner and outer differs. In one direction the speed increases, and in the other direction the speed decreases instead. By studying the gradient profiles for these curves, see Figure 9 and Figure 10 on page 16, it is shown that all these curves have gradients. The speed profiles for each curve seemed to correlate well to the gradient. When traveling in curve number 6 inner, the drivers reach curve number 4 outer after a tangent stretch of approximately 480 m. The gradient on this tangent is constant and approximately +4 percent. Even though drivers shows a decrease in speed for such gradient when traveling in curve number 4, 6 and 7, they have the same speed at the exit tangent of curve 6 as at the approach tangent at curve 4.

By studying the speed at the tangent stretch between curve number 4 and curve number 6, it could be seen that on the downhill tangent (4 inner to 6 outer) the speed increased slightly. Most probably this is an effect of the gradient. However, this increase is only a few kilometers per hour. The speed differences that appear to be due to gradients in curve number 4, 6 and 7 are higher. This gives an indication of that gradients affect the speed in curves more than it affects the speed at tangents. In the other direction, from curve number 6 inner to curve number 4 outer, the gradient is approximately +4 percent. The speed should therefore be reduced. However, the speed between curve number 6 and the middle of the tangent increases slightly. Between the middle of the tangent and curve number 4 the speed decreases instead. This also indicates that a gradient of 4 percent do not have any significant effect on the speed at tangents.

For curve number 3 and 5, no data about gradient could be found. Curves with known gradient (4, 6 and 7) show a speed profile affected by the gradient, and curve number 3 and 5 do not show such an impact. Therefore, it is assumed that these two curves do not have a distinct gradient.

In most curves, the speed is not held constant between the two points that were analyzed at the approach tangent (*T_in* and *TM_in*), regardless of tangent length. An increase of speed between *T_in* and *TM_in* indicates that the tangent lengths might be too short for the drivers to reach their desirable speed before entering the curve. A decrease of speed may indicate that the two points, *T_in* and *TM_in*, are located too close to the curve to identify constant speed. Previous studies have concluded that drivers start to reduce their speed about 50-230 m before the curvature starts (Montella, et al., 2015; Altamira, et al., 2014). The point *T_in* is located 100 m from where the curvature starts, hence it is expected that drivers reduce their speed at that point. It would have been good to have the points *T_in* and *TM_in* further away from the curvature. However, it was desired to use the same distance between *T_in* and the curvature for all curves to make it comparable. Since the shortest tangents were only 100 m, also the points at the longer tangents were limited to 100 m from the curvature.

5.3.3 Speed profiles for individual drivers

By studying the speed pattern for individual drivers, it could be seen that the pattern mostly were the same for different drivers driving in the same curve and in the same direction, see Figure 18 on page 29. An exception was seen between driver C and D in Figure 19 on page 30. This implies that there are other factors than the curve geometry that can affect the speed pattern as well.

Even though the speed patterns appeared to be similar for different drivers in most cases, the speed range differed. This indicates that the choice of speed is not only dependent on the road geometry, but also on other factors such as the personality. For instance, driver A consistently drives much faster than all other drivers. It was found that in those trips that the driver drove less fast, the driver was influenced by factors such as having a child in the car or using a mobile phone. Therefore, this driver obviously desires to drive at high speeds, but changes behavior during certain circumstances. This behavior was not further studied since it was not included in the aim. However, possible reasons are that the driver gets distracted or consciously drives slower.

Driver A also shows a large speed interval, especially in curve number 3 outer; see Figure 18 on page 29. The difference between the driver's 85:th percentile and 15:th percentile speed is almost 30 km/h. The decrease in speed and the speed profiles are similar, regardless of entrance speed. It is interesting that the driver can manage to drive through the curve at over 100 km/h, but 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 when approaching a curve is a learned behavior that triggers regardless of speed. Another possible reason could also 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.

It is also noticeable that the pattern is the same for driver A and B, who drives at much lower speeds. This indicates that the curve geometry has a large impact on the driver behavior.

5.3.4 Speed differentials

Curve number 7 has few trips compared to the other curves, which makes it difficult to analyze. However, curve number 1 and 2 shows a larger speed differential (speed reduction) when driving in to the curve compared to curve number 3, 4, 5 and 6. This corresponds well with the study performed by Peréz-Zuriaga et al (2013), which concluded a larger speed differential on curves with radius smaller than 200 m. It also correlates well to studies by Altamira (2014) and Hu & Donell (2010), which have found that small radii lead to higher deceleration. Several drivers in curve number 3, 4, 5 and 6 have a speed differential above 0, which means that they have higher speed in the curve than on the approach tangent. This indicates that curve radii above approximately 300 m allow the driver to keep more consistent speed.

The pattern is similar but differs somewhat when driving out of the curve. Curve number 1, 2 and 3 shows a larger speed differential (increase of speed) compared to curve number 5 and 6, while curve number 4 is in-between. It indicates that the speed differential out of a curve increases for curves with a radius smaller than 300 m. A study by Hu & Donell (2010) found a similar result. Several drivers in curve number 4, 5 and 6 have a speed differential below 0, which means that they have lower speed on the exit tangent than in the curve. This could be explained by the gradient in curve number 4 and 6.

5.4 Relations between curve geometry and driver behavior

This chapter is divided into the studied curve geometry factors. How these studied factors affect the speed and maximal acceleration is discussed, and compared to previous studies presented in the literature study.

5.4.1 Radius of curve

The result from the regression analysis shows that the curve radius is the factor that influences the driver behavior in curves most. The speed at *S_in* was found to increase with larger radii for all curves except curve number 7, see Figure 21 on page 32. By studying the speed profile for this curve, it can be seen that the 85:th percentile speed is similar to the larger radii curves 5 and 6, while the median and the 15:th percentile speeds are lower. An explanation for this could be that one of the tangents is very short (100 m) and that there is a gradient, which affects the speed more than the radius in that specific curve. The regression analysis also 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), Quaium (2010) 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 reason for this is possibly that drivers can keep higher speed in curves with large radii, and therefore do not have to decrease the speed as much as in small radii curves.

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 exit 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).

5.4.2 Radius of previous curve

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

In curves with larger radii than the previous curve, lower deceleration was found compared to smaller radii. The influence of the previous curve was also found to be higher for shorter curve lengths. This study found higher speed reduction 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 it also causes lower speed at *C*.

5.4.3 Tangent length

The speed at *S_in* was found to be higher for long approach tangents, see Figure 21 on page 32. This was found for all curves except for curve number 4 which showed a slight decrease in speed instead. Most probably, this is due to the fact that curve number 4 has a gradient which affect the speed more than what the length of the tangent does. The regression analysis showed that longer approach tangent resulted in higher speed also at *C_in*. However, at 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 *S_in* and *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 well 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.

For most curves the speed at *S_out* increases with increased length of the exit tangent. However, curves number 5 and 6 show a decrease instead. The reason for curve number 5 is unknown. However, the long tangent after curve number 6 (inner) has a constant positive gradient which probably leads to lower speed. Additionally the short tangent after curve 6 (outer) is preceded by a negative gradient which helps the drivers to accelerate out of the curve.

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 studies further.

5.4.4 Presence and length of spirals

A simulator study by Zakowska et al (2008) found higher speed in curves with spiral transitions. The simulator study by Helmers & Törnros (2006) also found higher speeds at the approach tangent and at the center point, increasing with the length of the spiral transition. The regression analysis agreed that the speed at the center point (*C*) 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 center 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 center 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 (~100m).

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 center of the curve if the spiral transition is long. Since drivers keep a higher speed 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.

5.5 Design of curves

Previous studies have found that road safety can be increased by designing roads with a consistent design. On such roads, drivers should be able to drive at approximately the same manner during the whole trip. Consistent curve design can be defined by a maximum speed difference of 5 km/h between tangent and curve (Fitzpatrick, et al., 2000). This is obtained in curve number 5, which shows a smooth speed profile which is almost identical for both travel directions. The radius of curve number 5 is 385 m, and the tangent lengths 180 and 480 m respectively. A spiral with the length of 80 m is connected to the longer tangent. Of the selected curves, this is one of the two curves that best meets the current requirements set by the Swedish Transport Administration regarding curve radius, spiral parameter and arc length. Since no other curves fulfilled the requirements, except curve number 7, no conclusion can be drawn about fulfilling the requirements result in a safe curve design or not. Also, other factors such as crossfall and superelevation were not considered.

The result showed that gradients in curves have a major effect on the driver behavior. The curve geometry is designed based on the posted speed limit. If this is exceeded, the safety decreases as mentioned before. Curves with gradients showed an increased speed in the downhill direction. Therefore, to increase safety it might be preferable to design such curves for a higher speed. However, the result showed that the desirable speed by drivers increased for larger radii. Therefore; if curves with gradients would be designed for a higher speed, drivers might choose to exceed the posted speed limit even more.

Since this study does only study the speed at different points along curves, nothing can be said about how spiral transitions affect the continuous speed in curves, the trajectory or the perception of the curvature. However, it was found that spiral transitions elicited higher speed at the center of the curve. Higher speeds results in increased risk, for instance one needs longer distance to stop. This can be an argument for that spiral transitions decrease the safety. On the other hand, it was shown that the maximum lateral acceleration was unaffected; hence a spiral transition assists the driver when driving through a curve. A question that rises is if this is valid only for alert drivers, who can perceive that the curve becomes sharper when the spiral switch into a circular curve. Further studies analyzing drowsy drivers' perception of spiral transition curves would be valuable and taking into account the safety aspects when drivers have reduced driving ability.

6 Conclusions

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. All studied factors affected the driver behavior in curves. Of these, radius was the most influencing factor. Larger radius results in higher speeds, lower speed differentials and decreased maximum lateral acceleration. Longer approach spiral transition results in higher speeds at the center of the curve, and do not affect the maximum lateral acceleration – indicating a changed trajectory. Longer exit spiral transition results in lower acceleration when leaving a curve. The radius of the previous curve has a low influence compared to the geometry of the curve. For longer approach tangents, the speed at the beginning of the curve is increased. However, the speed reduction is larger resulting in lower speed at the center of the curve. Longer exit tangent results in larger acceleration.

Additionally, it was found that many curves do not fulfill the current design recommendations. Also, the majority of drivers drove faster than the posted speed limit in the curves, which can increase risk.

7 Further studies

This study used data for all weather- and light conditions. It would be of interest to study how the driver behavior changes based on these conditions by using naturalistic driving data. To take more factors into account, and also include more curves would give a broader knowledge of how driver behavior is affected by curve geometry. Such factors could be vertical alignment, crossfall, superelevation and pavement conditions. It would also be of interest to study more driver behavior parameters such as yaw rate, steering angle, lateral jerk or trajectory to give a broader understanding.

Along with most previous studies, this study focused on curves separated by tangents. Further studies analyzing compound curves and curves with short or no tangents are necessary to give a broader knowledge. Also, it would be of interest to study different types of roads and speed-limits.

It was found that only two of the selected curves fulfilled the existing documents for curve design. How curves generally are designed in Sweden and how the documents are interpreted would be of interest to study. Such study could be used as a base for what type of curves that are significant to study.

This study only connected curve geometry and driver behavior. To include a safety aspect in terms of accident data would be of interest to study. For instance, the curve geometry and driver behavior could be studied in curves where many accidents occur.

Most drivers in this study drove through the same curves many times. A driver that is familiar with a road may probably take higher risks, but is at the same time aware of the road geometry and difficulties along the road. How this affects the driver behavior would be valuable to study, i.e. how the familiarity of a curve influences the driver behavior.

Since spiral transition curves were found to elicit higher speed at the same time as the maximum lateral acceleration did not increase, the spiral transition most probably change the trajectory. This would therefore be of interest to study further. However, the GPS signals were found to be in poor quality to be used for such purpose. Further studies analyzing drowsy drivers' perception of spiral transition curves would also be valuable and taking into account the safety aspects when drivers have reduced driving ability.

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Appendix A: Curve drawings & visibility

Images of the selected curves are shown in this appendix, with the road geometry drawn in AutoCAD Civil 3D with a satellite map from Bing as background. The tangents are marked by blue lines, spiral transitions by green and circular curves by red lines. The positions of the eleven points can be seen as white markings on the lines. In the figures adjacent curves and crossings can be seen as well. Example images from forward videos from euroFOT from May and June year 2010 are also shown, to give an understanding of the visibility conditions in the selected curves.

Curve 1

Inner:

Outer:

Curve 2

Inner:

Outer:

Curve 3

Inner:

Outer:

Curve 4

Inner:

Outer:

Curve 5

Inner:

Outer:

Curve 6

Inner:

Outer:

Curve 7

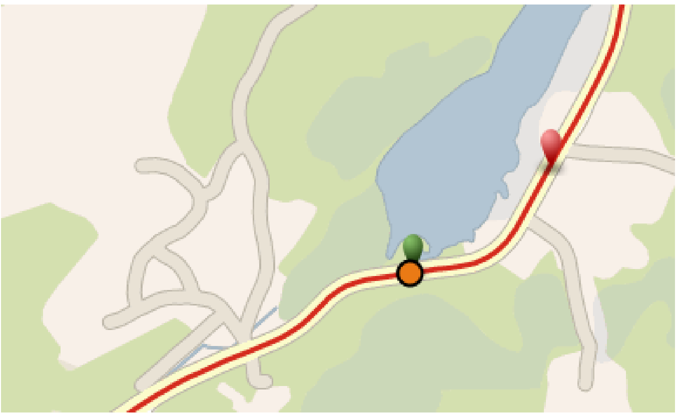
Inner:

Outer:

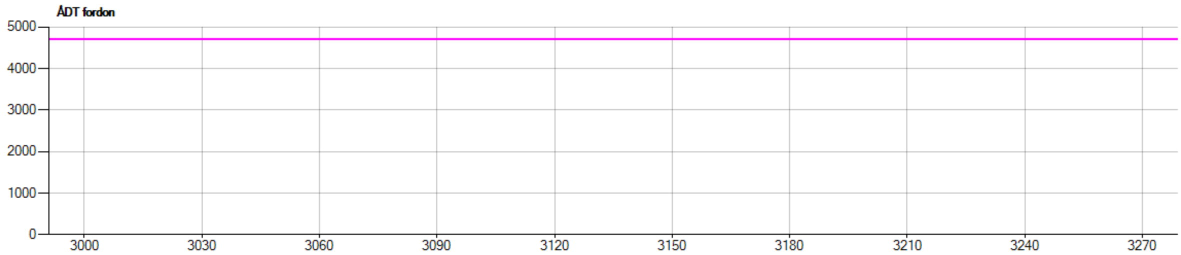
Appendix B: Curve characteristics

Curve characteristics in terms of curvature, gradient, annual average daily traffic (AADT) and road width are shown for the selected curves 1, 2, 4, 6 and 7 respectively and also for the stretch between curve number 4 and 6. For curve number 3 and 5 no data was available. The data was collected from the system PMSV3 provided by the Swedish Transport Administration. The system can be used to collect measured and calculated data about paved roads in Sweden. The data was only collected for one direction in each curve, since there were no or only old data available for the other direction. The data were collected in different years, when possible data is shown for year 2008, 2012 and 2014. However, for some curves the most recent data is from year 2003. The direction is shown in the map for each curve. The green point at the maps is the starting point, and the red one represents the ending point. The first two graphs show the AADT and road width in meters respectively. The following graphs show the curvature (defined as 10000/radius) and gradient in percentage. The measurements were taken every 20 meters, and the different colors represent different measuring years.

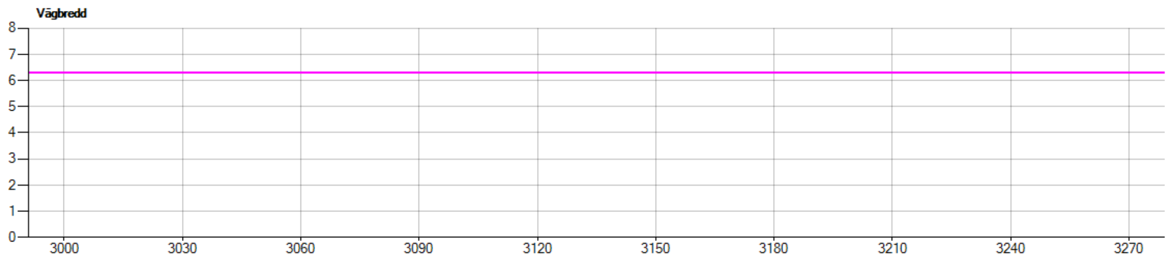
Curve 1



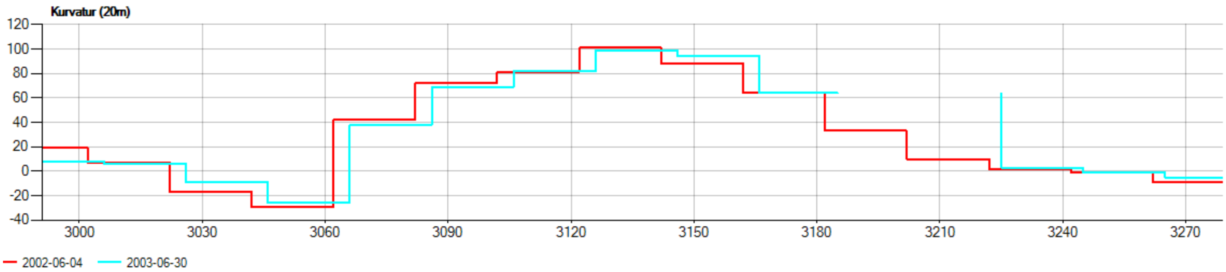
AADT:



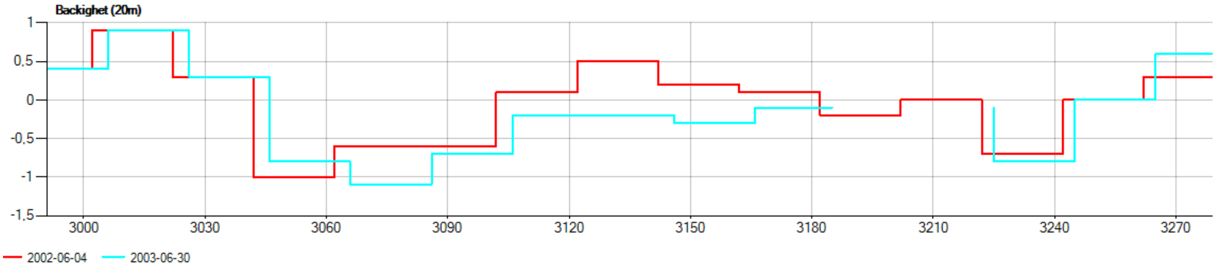
Road Width:



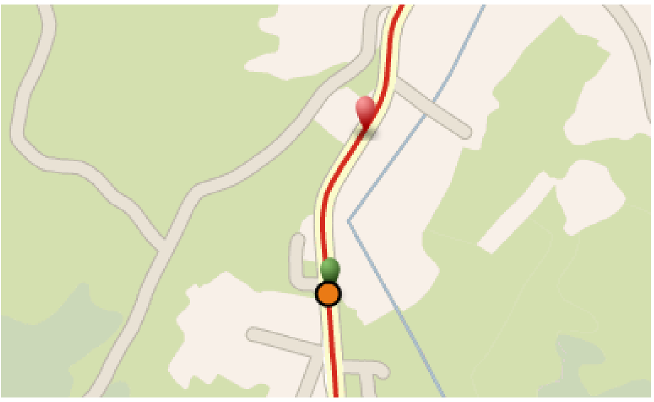
Curvature:



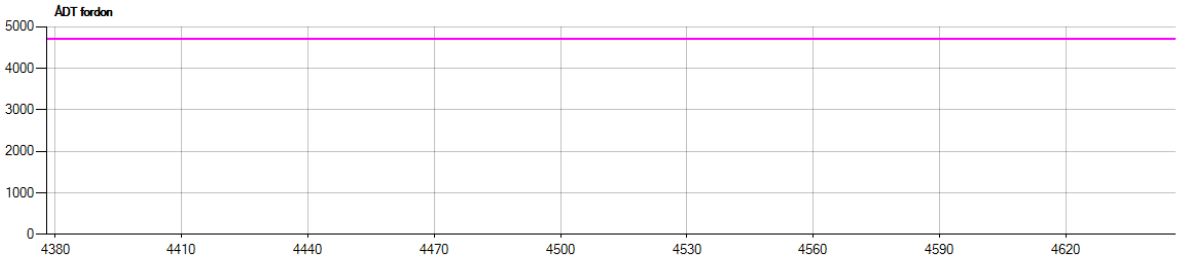
Gradient:



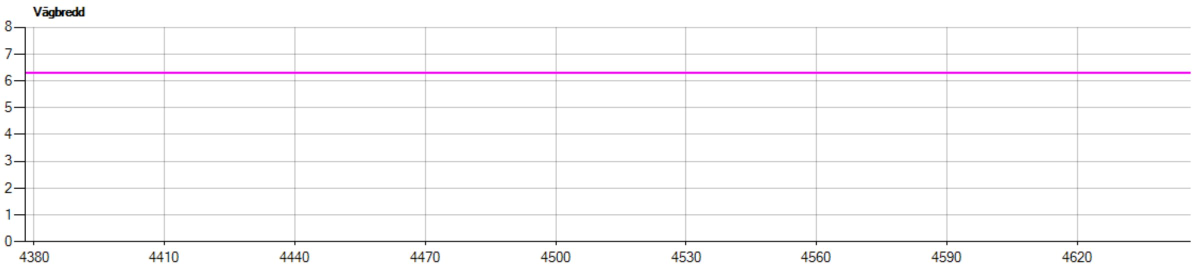
Curve 2



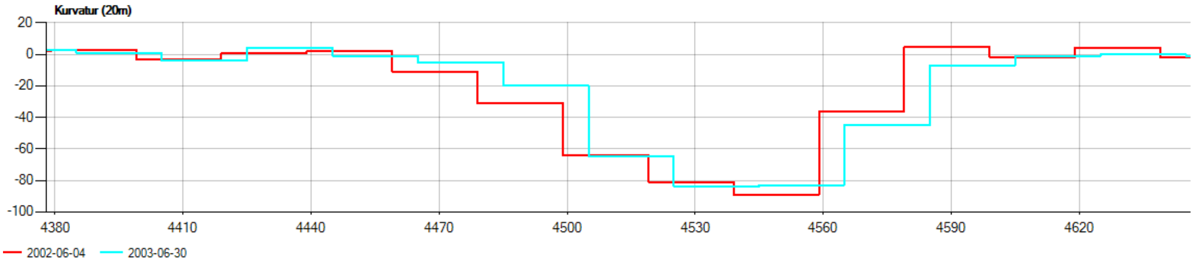
AADT:



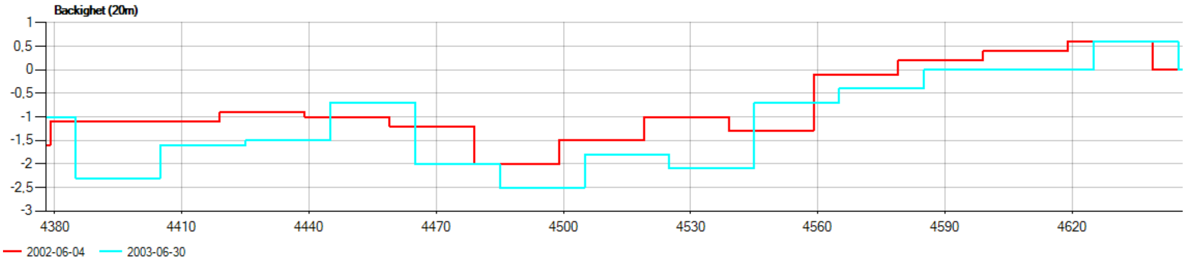
Road width:



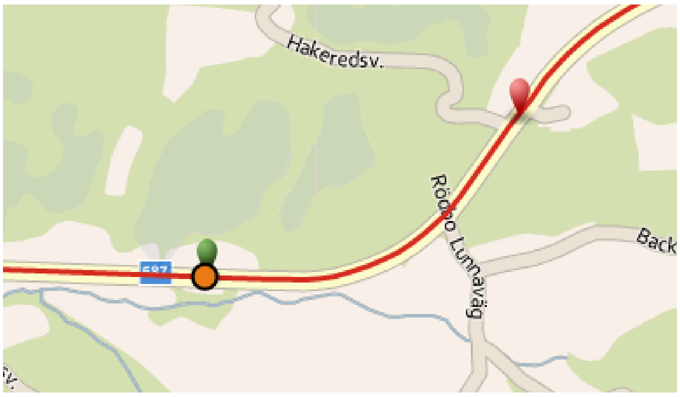
Curvature:



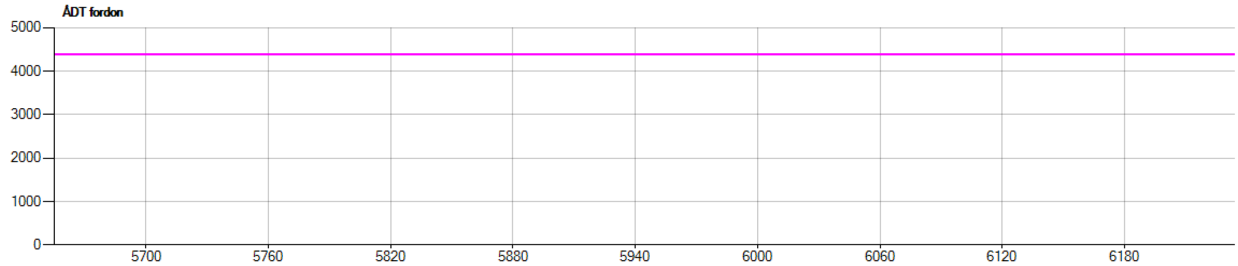
Graident:



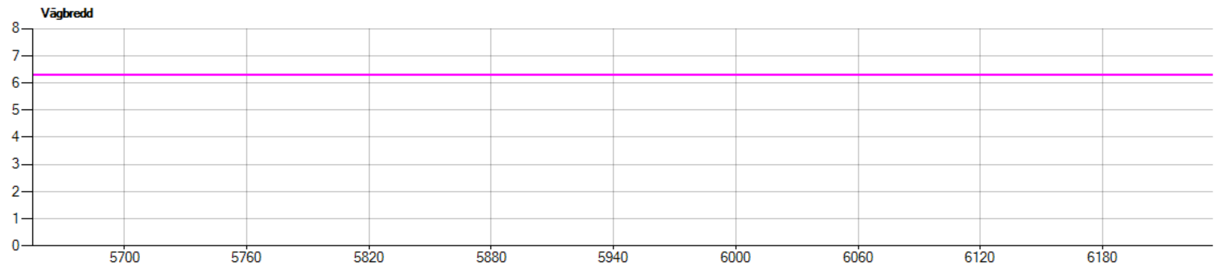
Curve 4



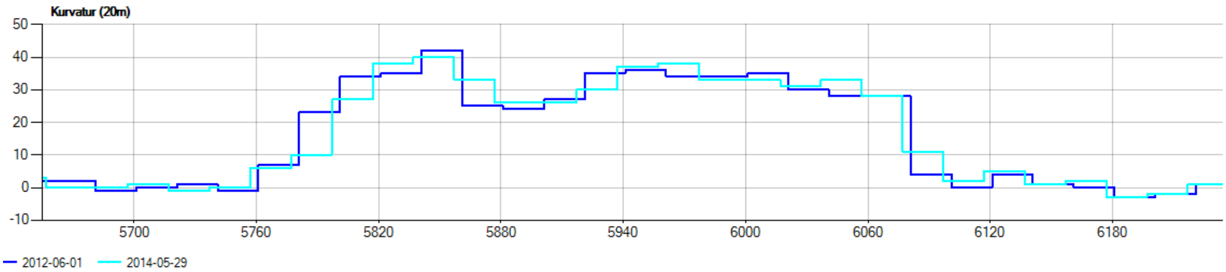
AADT:



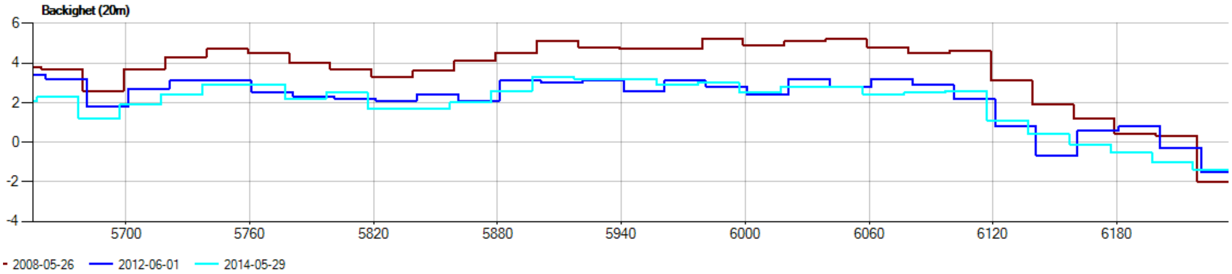
Road width:



Curvature:

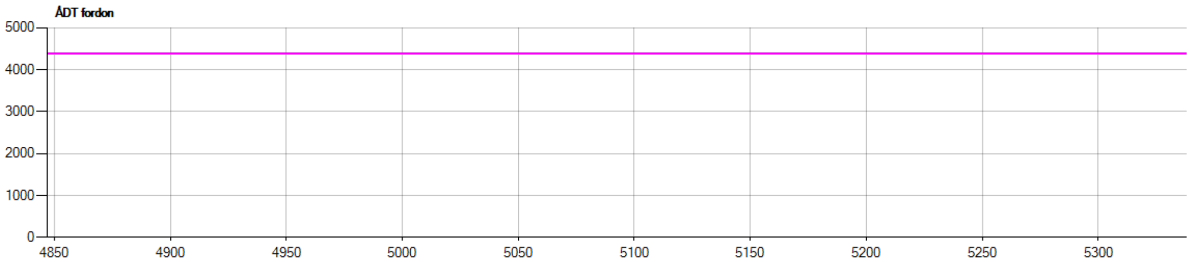


Gradient:

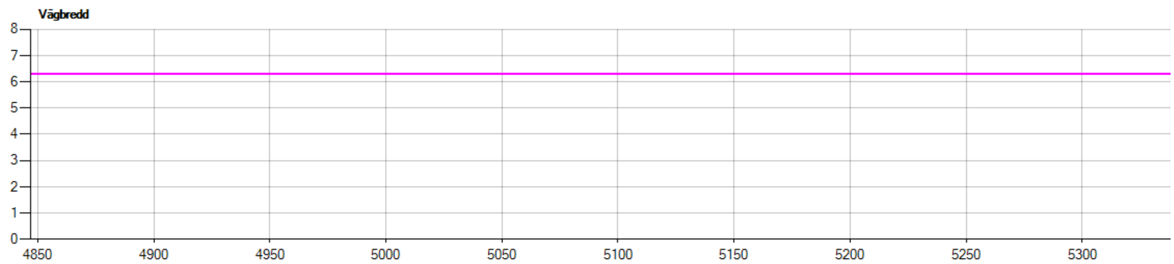


Curve 6

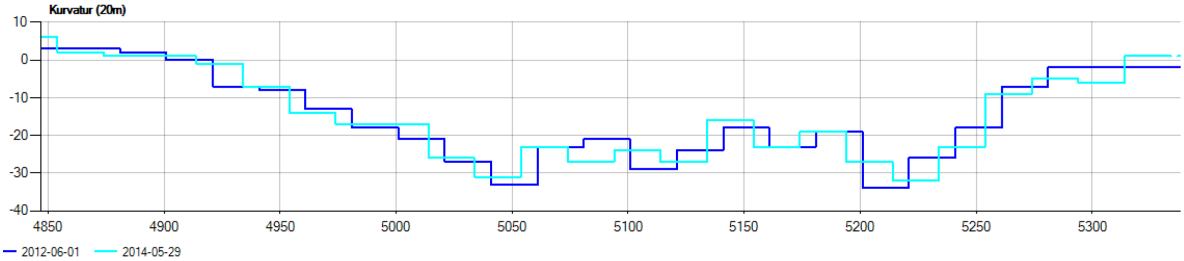
AADT:



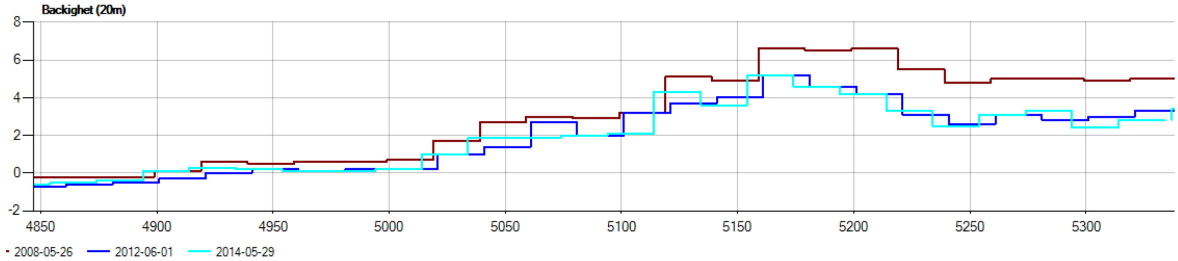
Road width:



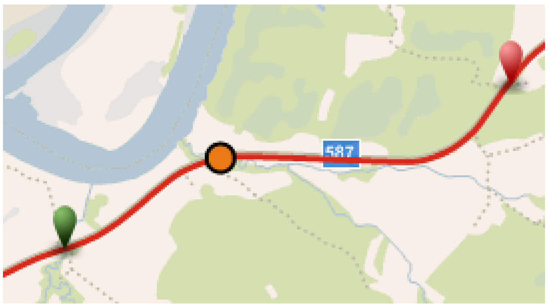
Curvature:



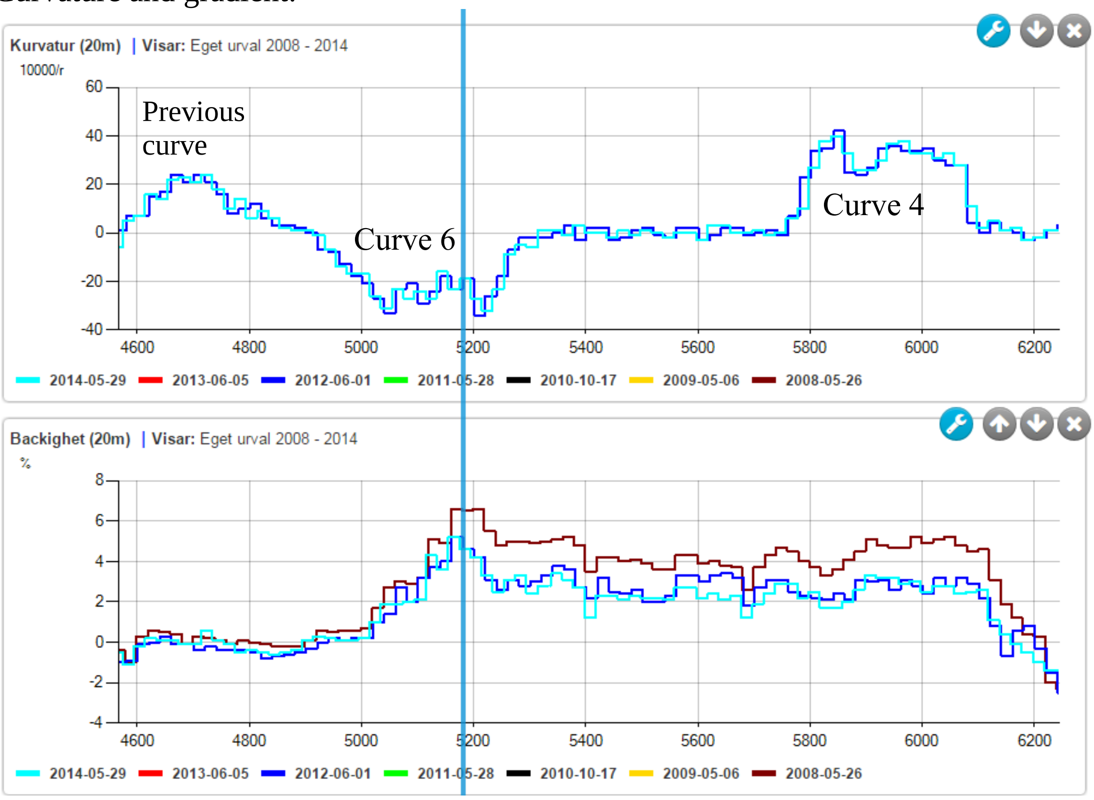
Gradient:



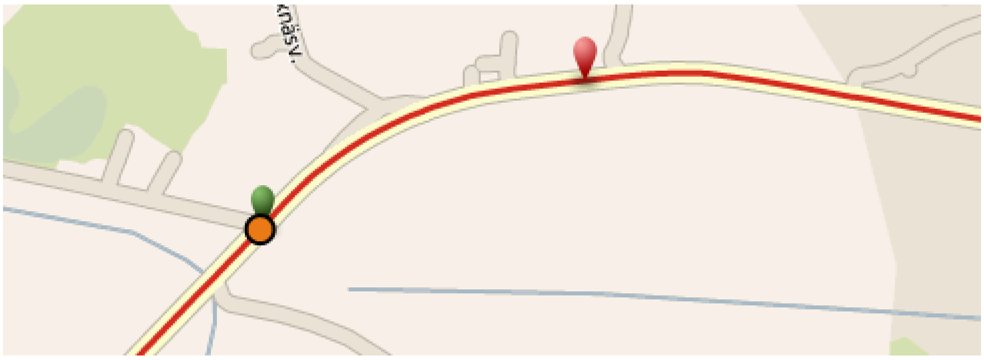
Curve 4 to 6



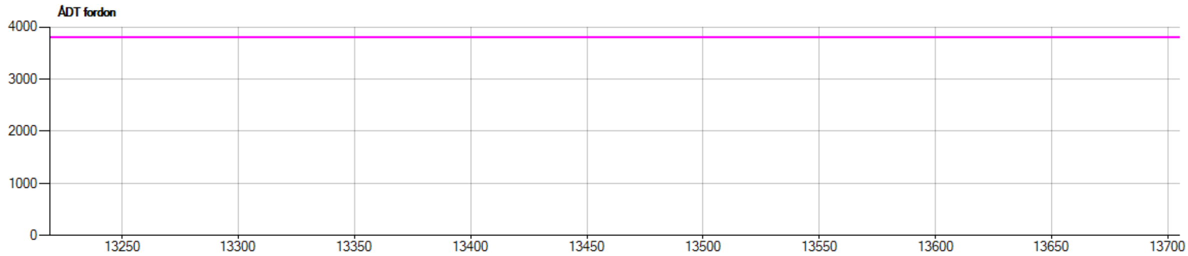
Curvature and gradient:



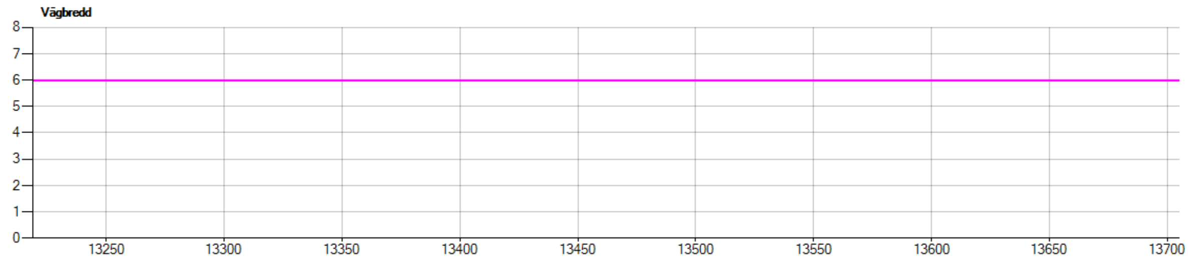
Curve 7



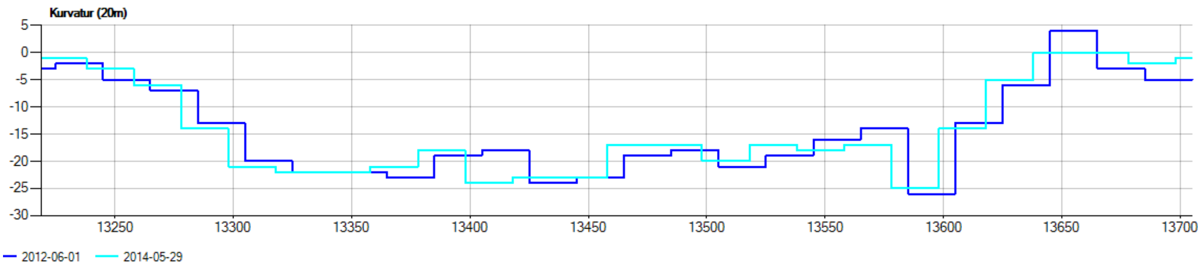
AADT:



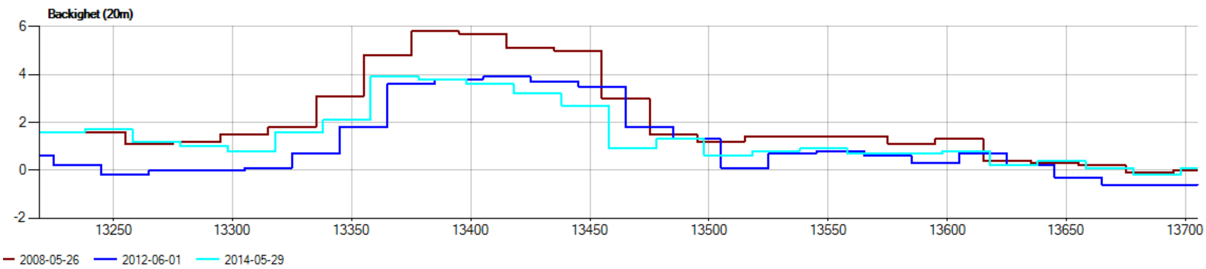
Road width:



Curvature:

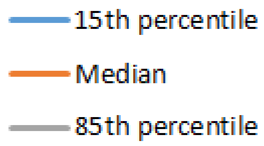


Gradient:

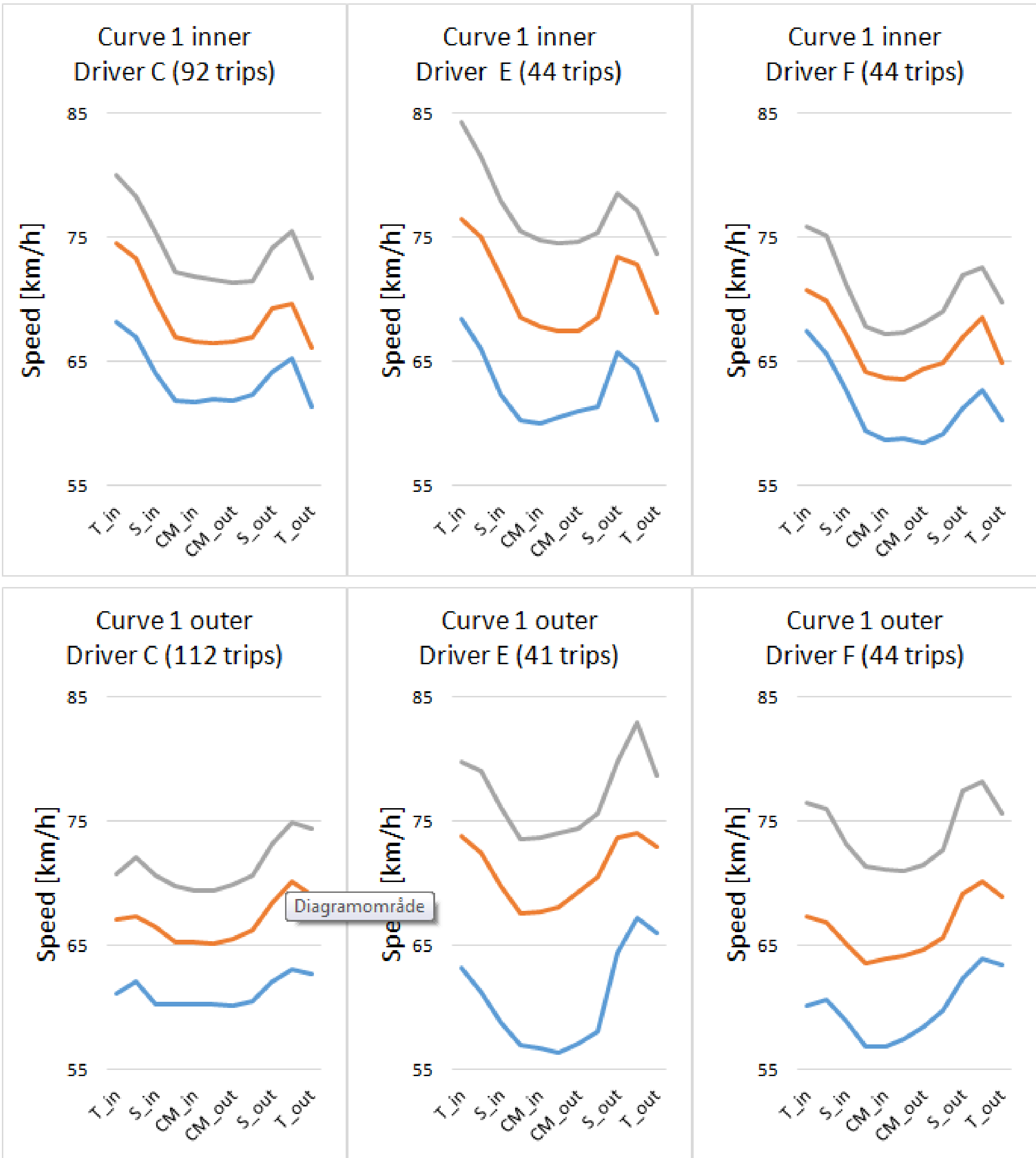


Appendix C: Speed profiles

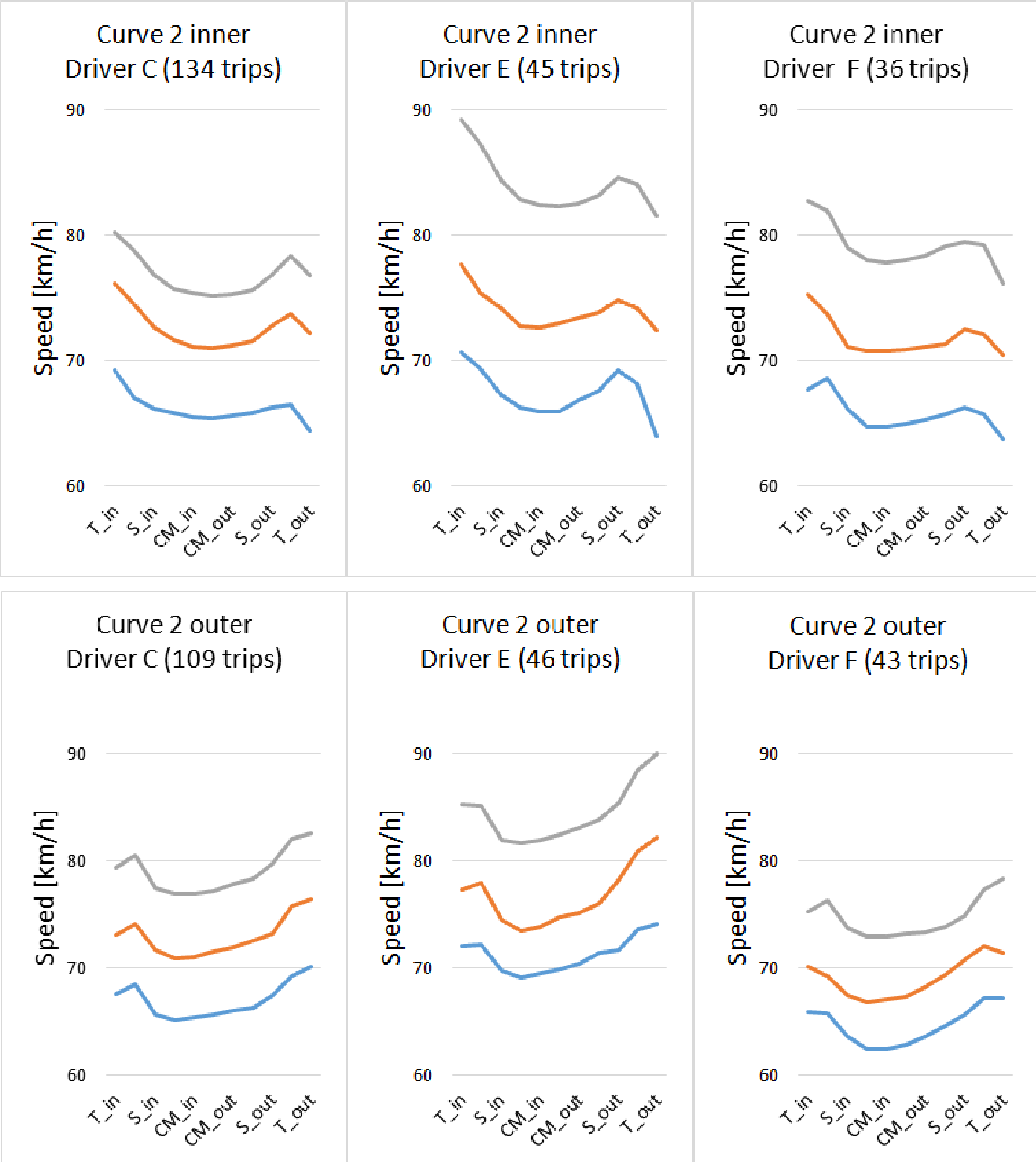
In this appendix speed profiles for curve number 1-6 are shown for drivers who drive in the same curve several times. The speed is presented as 15:th, median and 85:th percentile speed.



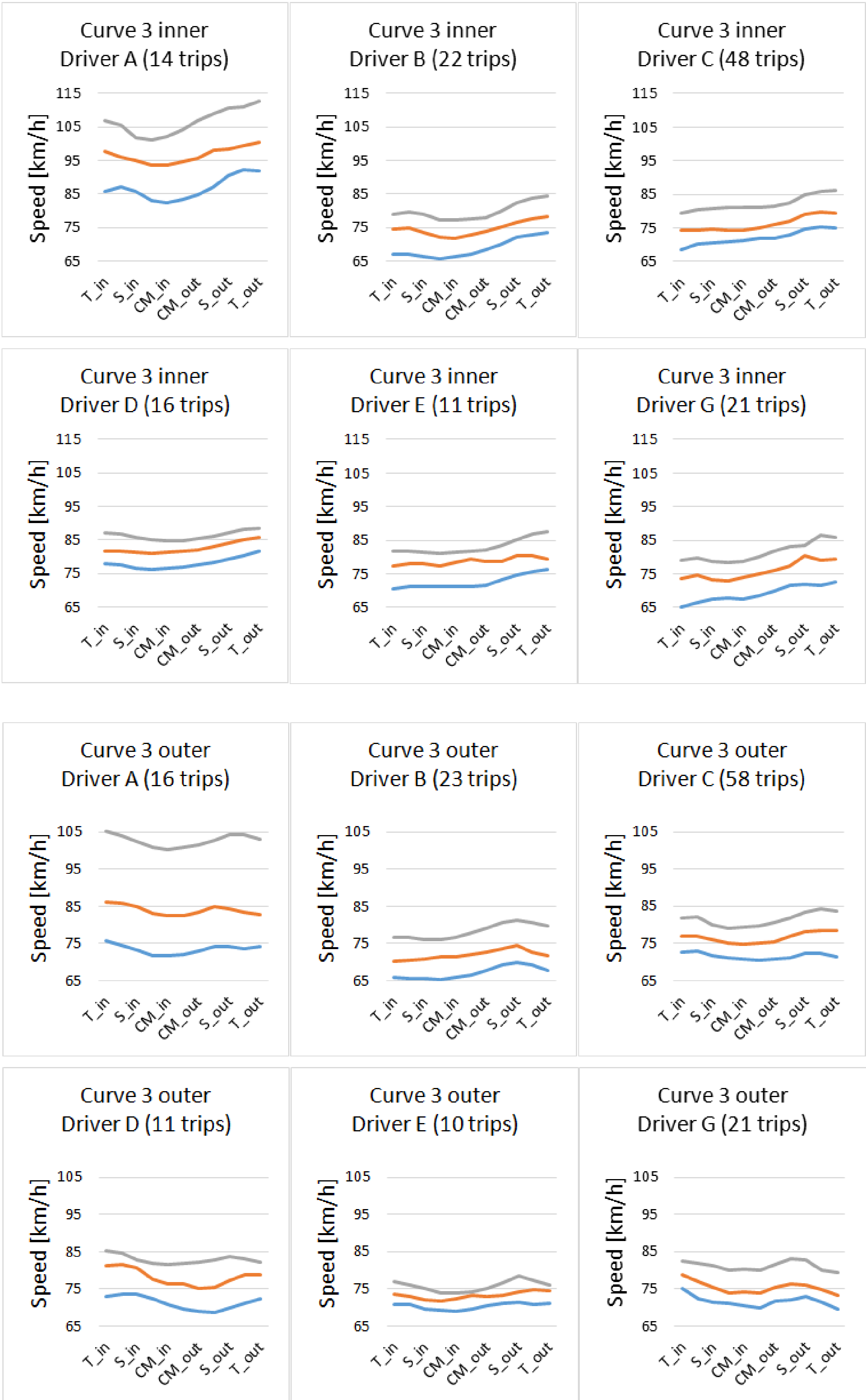
Curve 1



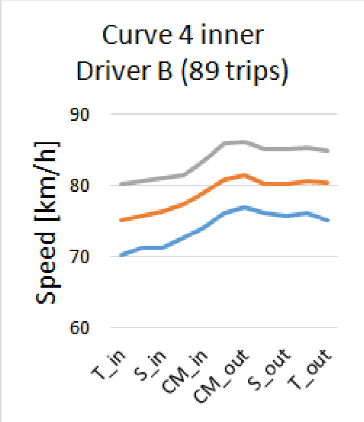
Curve 2

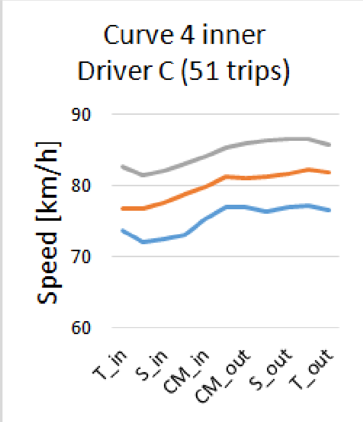

Curve 2 inner
Driver C (134 trips)
Curve 2 inner
Driver E (45 trips)
Curve 2 inner
Driver F (36 trips)
Curve 2 outer
Driver C (109 trips)
Curve 2 outer
Driver E (46 trips)
Curve 2 outer
Driver F (43 trips)
Speed [km/h]
90
80
70
60
T_in
S_in
CM_in
CM_out
S_out
T_out

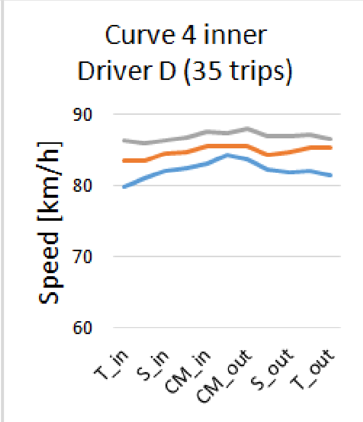
Curve 3

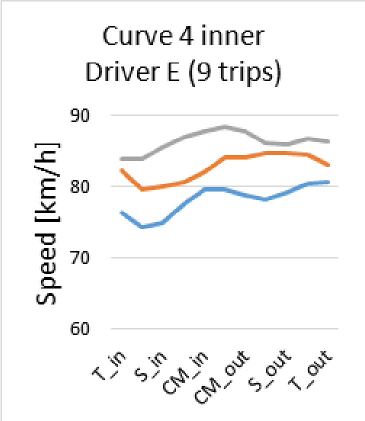

Curve 3 inner
Driver A (14 trips)
Curve 3 inner
Driver B (22 trips)
Curve 3 inner
Driver C (48 trips)
Curve 3 inner
Driver D (16 trips)
Curve 3 inner
Driver E (11 trips)
Curve 3 inner
Driver G (21 trips)
Curve 3 outer
Driver A (16 trips)
Curve 3 outer
Driver B (23 trips)
Curve 3 outer
Driver C (58 trips)
Curve 3 outer
Driver D (11 trips)
Curve 3 outer
Driver E (10 trips)
Curve 3 outer
Driver G (21 trips)
Speed [km/h]
115
105
95
85
75
65
T_in
S_in
CM_in
CM_out
S_out
T_out

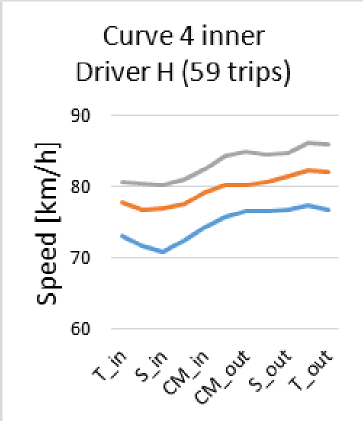
Curve 4

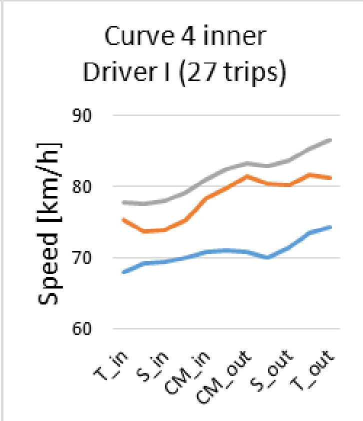

Curve 4 inner
Driver B (89 trips)
Speed [km/h]
90
80
70
60
T_in
S_in
CM_in
CM_out
S_out
T_out

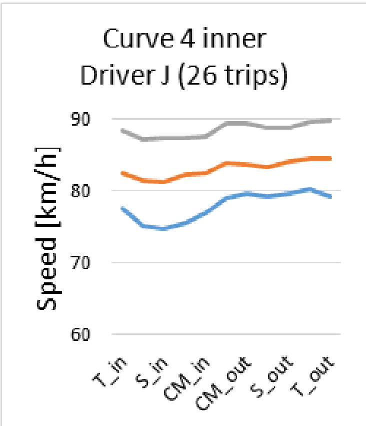

Curve 4 inner
Driver C (51 trips)
Speed [km/h]
90
80
70
60
T_in
S_in
CM_in
CM_out
S_out
T_out

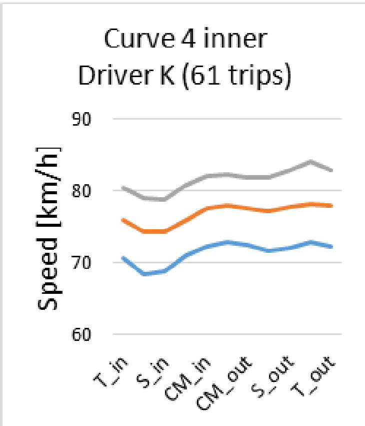

Curve 4 inner
Driver D (35 trips)
Speed [km/h]
90
80
70
60
T_in
S_in
CM_in
CM_out
S_out
T_out

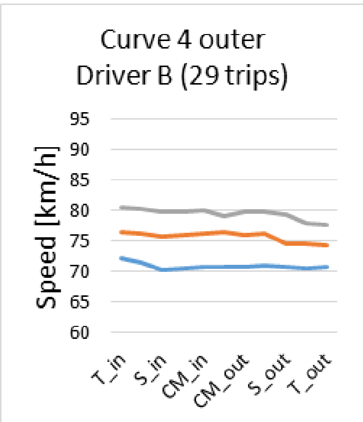

Curve 4 inner
Driver E (9 trips)
Speed [km/h]
90
80
70
60
T_in
S_in
CM_in
CM_out
S_out
T_out

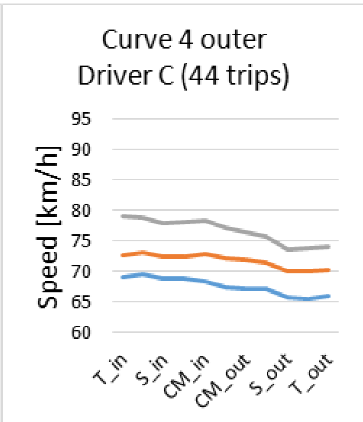

Curve 4 inner
Driver H (59 trips)
Speed [km/h]
90
80
70
60
T_in
S_in
CM_in
CM_out
S_out
T_out

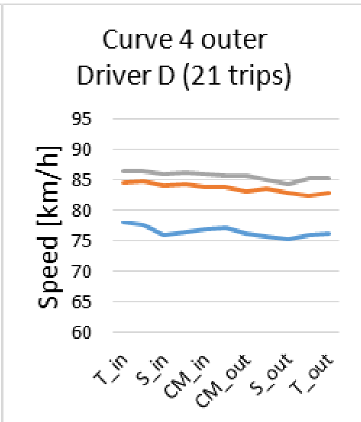

Curve 4 inner
Driver I (27 trips)
Speed [km/h]
90
80
70
60
T_in
S_in
CM_in
CM_out
S_out
T_out

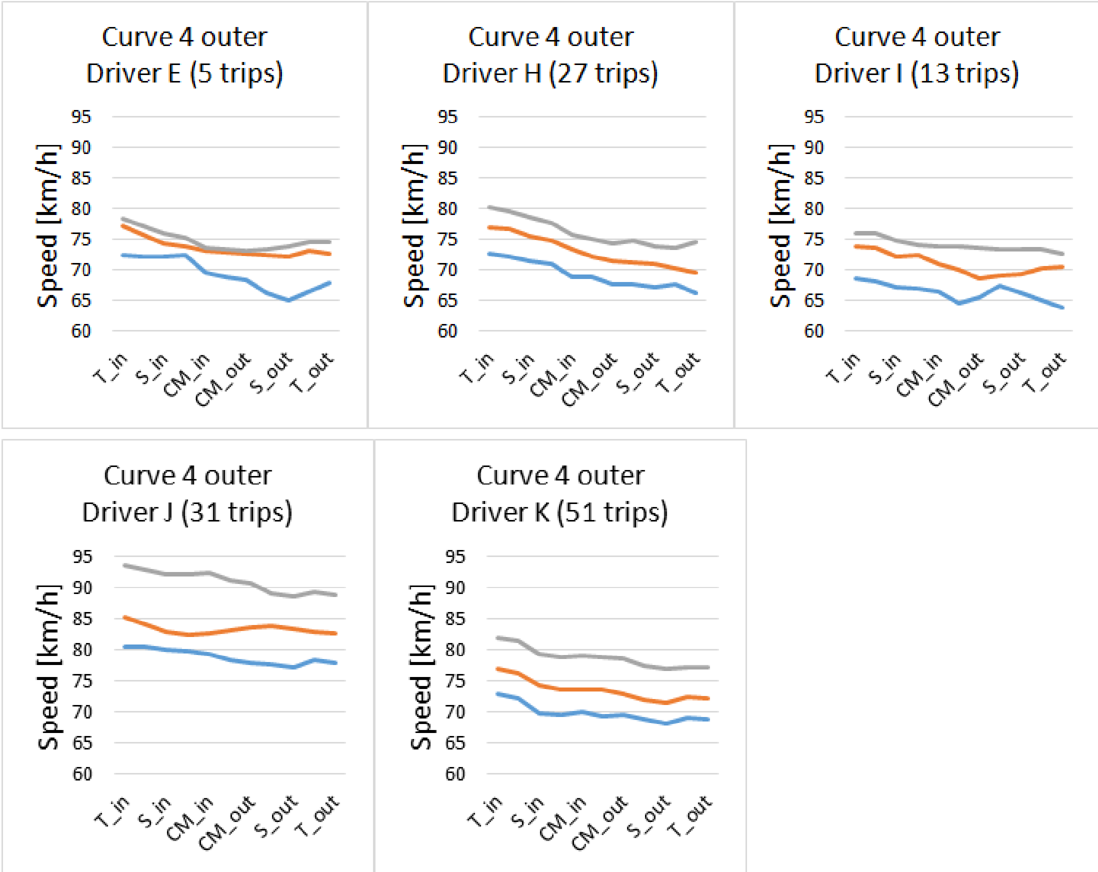

Curve 4 inner
Driver J (26 trips)
Speed [km/h]
90
80
70
60
T_in
S_in
CM_in
CM_out
S_out
T_out


Curve 4 inner
Driver K (61 trips)
Speed [km/h]
90
80
70
60
T_in
S_in
CM_in
CM_out
S_out
T_out


Curve 4 outer
Driver B (29 trips)
Speed [km/h]
95
90
85
80
75
70
65
60
T_in
S_in
CM_in
CM_out
S_out
T_out

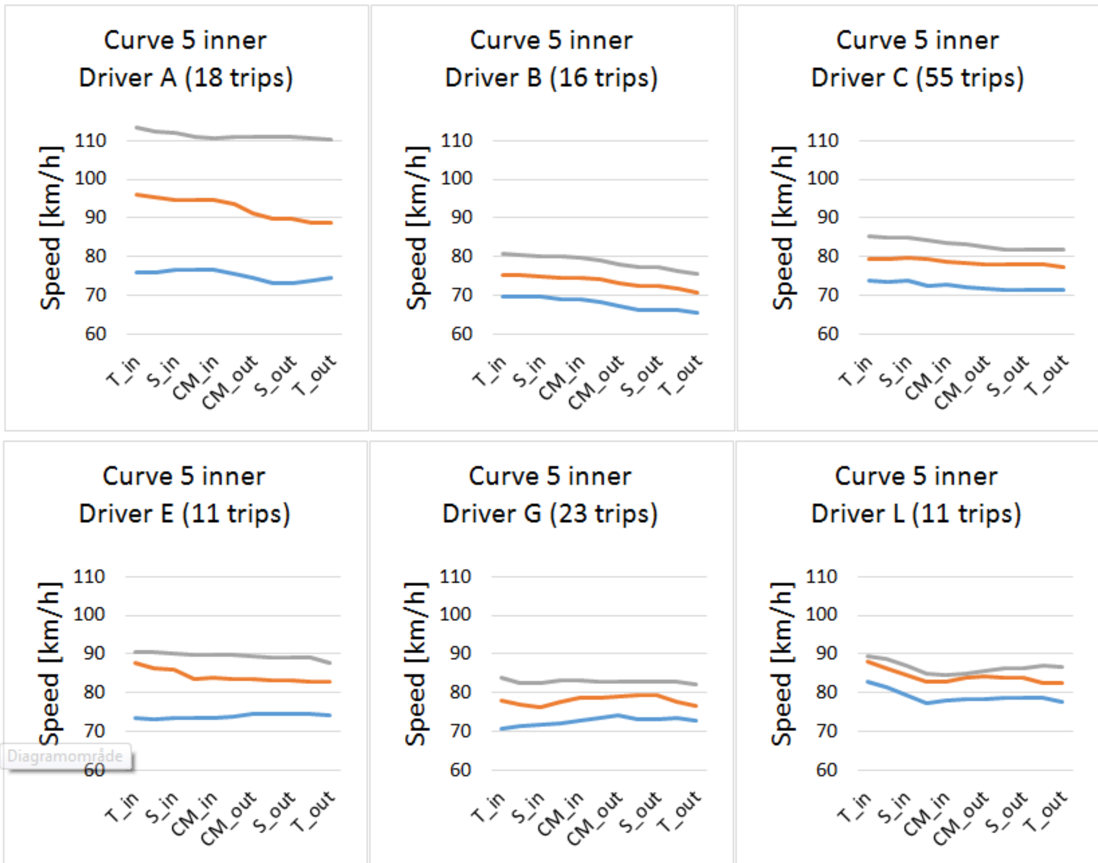

Curve 4 outer
Driver C (44 trips)
Speed [km/h]
95
90
85
80
75
70
65
60
T_in
S_in
CM_in
CM_out
S_out
T_out


Curve 4 outer
Driver D (21 trips)
Speed [km/h]
95
90
85
80
75
70
65
60
T_in
S_in
CM_in
CM_out
S_out
T_out

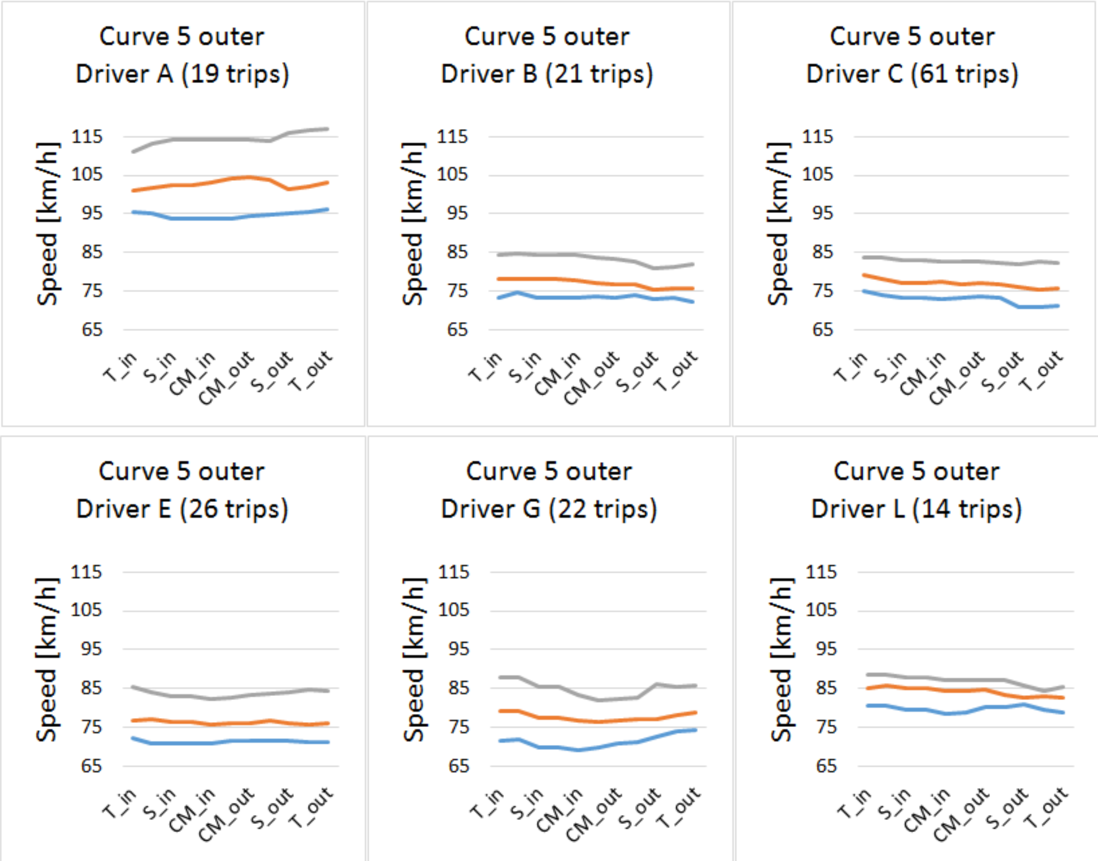


Curve 4 outer
Driver E (5 trips)
Curve 4 outer
Driver H (27 trips)
Curve 4 outer
Driver I (13 trips)
Curve 4 outer
Driver J (31 trips)
Curve 4 outer
Driver K (51 trips)
Speed [km/h]
95
90
85
80
75
70
65
60
T_in
S_in
CM_in
CM_out
S_out
T_out

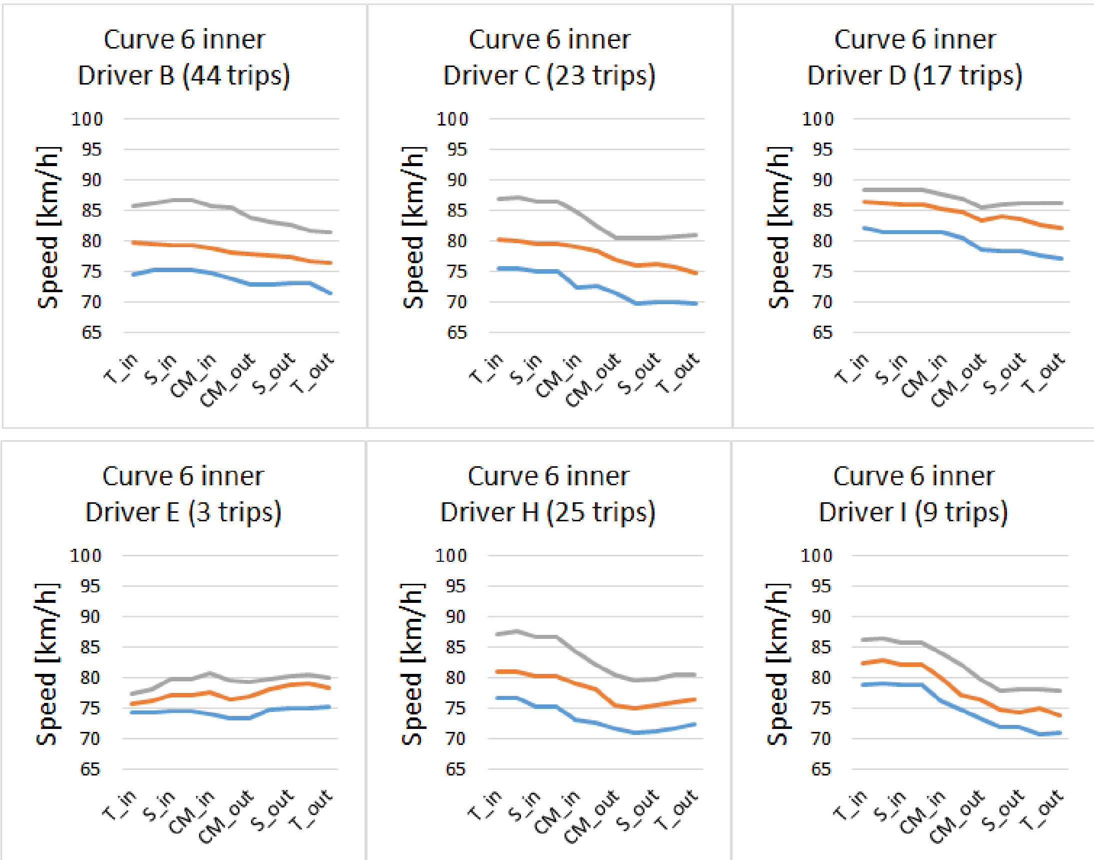
Curve 5

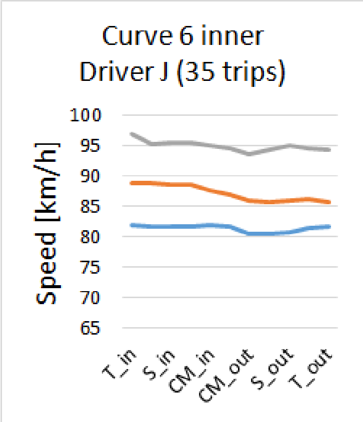


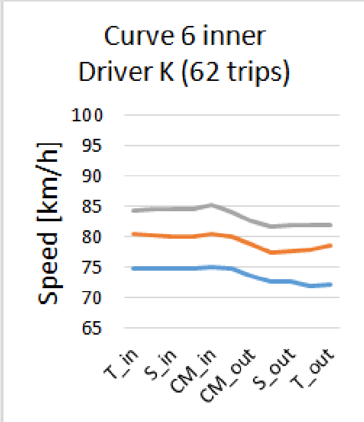
Curve 5 inner
Driver A (18 trips)
Curve 5 inner
Driver B (16 trips)
Curve 5 inner
Driver C (55 trips)
Curve 5 inner
Driver E (11 trips)
Curve 5 inner
Driver G (23 trips)
Curve 5 inner
Driver L (11 trips)
Speed [km/h]
110
100
90
80
70
60
T_in
S_in
CM_in
CM_out
S_out
T_out

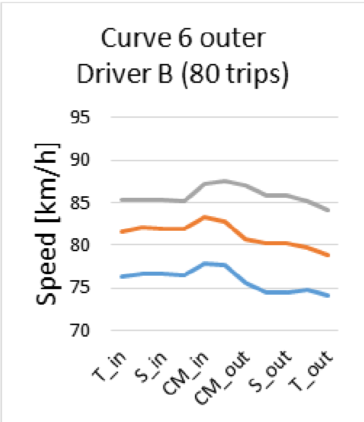

Curve 5 outer
Driver A (19 trips)
Curve 5 outer
Driver B (21 trips)
Curve 5 outer
Driver C (61 trips)
Curve 5 outer
Driver E (26 trips)
Curve 5 outer
Driver G (22 trips)
Curve 5 outer
Driver L (14 trips)
Speed [km/h]
115
105
95
85
75
65
T_in
S_in
CM_in
CM_out
S_out
T_out

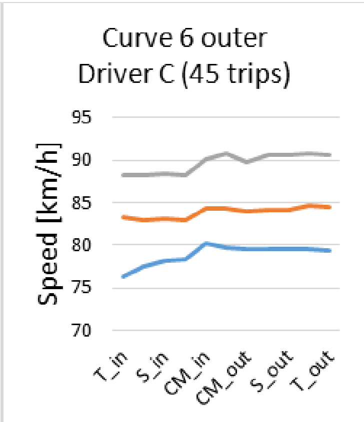
Curve 6

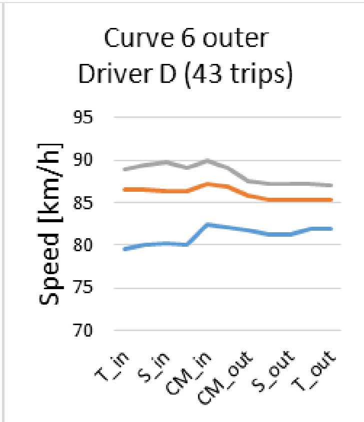

Curve 6 inner
Driver B (44 trips)
Curve 6 inner
Driver C (23 trips)
Curve 6 inner
Driver D (17 trips)
Curve 6 inner
Driver E (3 trips)
Curve 6 inner
Driver H (25 trips)
Curve 6 inner
Driver I (9 trips)
Speed [km/h]
100
95
90
85
80
75
70
65
T_in
S_in
CM_in
CM_out
S_out
T_out

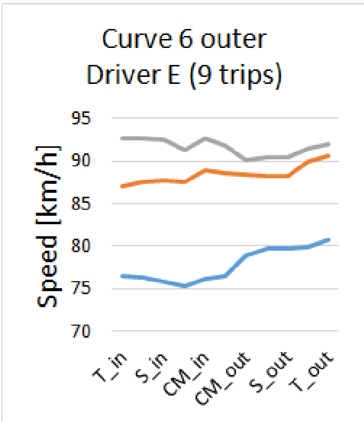

Curve 6 inner
Driver J (35 trips)
Speed [km/h]
100
95
90
85
80
75
70
65
T_in
S_in
CM_in
CM_out
S_out
T_out

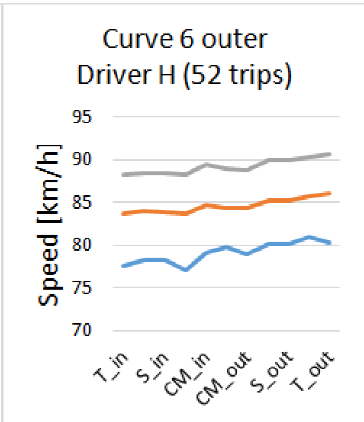

Curve 6 inner
Driver K (62 trips)
Speed [km/h]
100
95
90
85
80
75
70
65
T_in
S_in
CM_in
CM_out
S_out
T_out

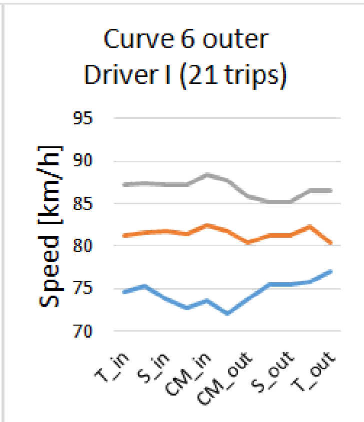

Curve 6 outer
Driver B (80 trips)
Speed [km/h]
95
90
85
80
75
70
T_in
S_in
CM_in
CM_out
S_out
T_out

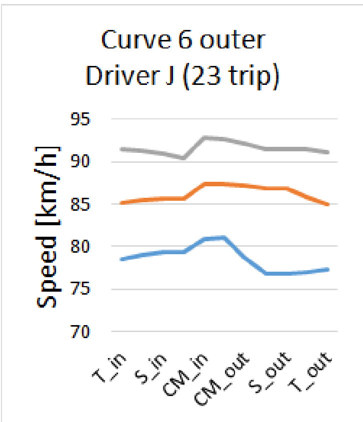

Curve 6 outer
Driver C (45 trips)
Speed [km/h]
95
90
85
80
75
70
T_in
S_in
CM_in
CM_out
S_out
T_out

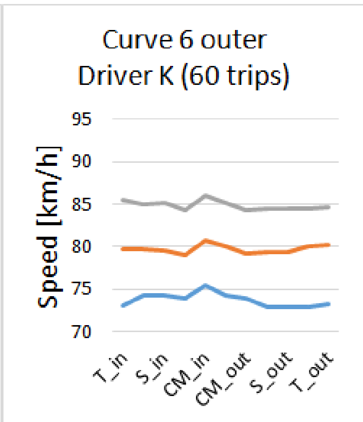

Curve 6 outer
Driver D (43 trips)
Speed [km/h]
95
90
85
80
75
70
T_in
S_in
CM_in
CM_out
S_out
T_out


Curve 6 outer
Driver E (9 trips)
Speed [km/h]
95
90
85
80
75
70
T_in
S_in
CM_in
CM_out
S_out
T_out


Curve 6 outer
Driver H (52 trips)
Speed [km/h]
95
90
85
80
75
70
T_in
S_in
CM_in
CM_out
S_out
T_out


Curve 6 outer
Driver I (21 trips)
Speed [km/h]
95
90
85
80
75
70
T_in
S_in
CM_in
CM_out
S_out
T_out


Curve 6 outer
Driver J (23 trip)
Speed [km/h]
95
90
85
80
75
70
T_in
S_in
CM_in
CM_out
S_out
T_out


Curve 6 outer
Driver K (60 trips)
Speed [km/h]
95
90
85
80
75
70
T_in
S_in
CM_in
CM_out
S_out
T_out

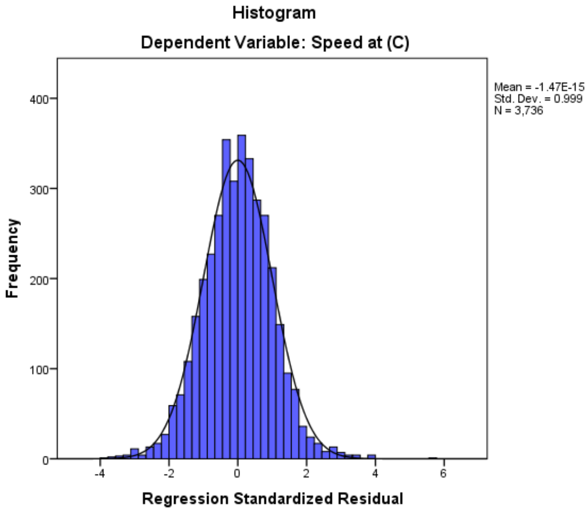
Appendix D: Regression analysis

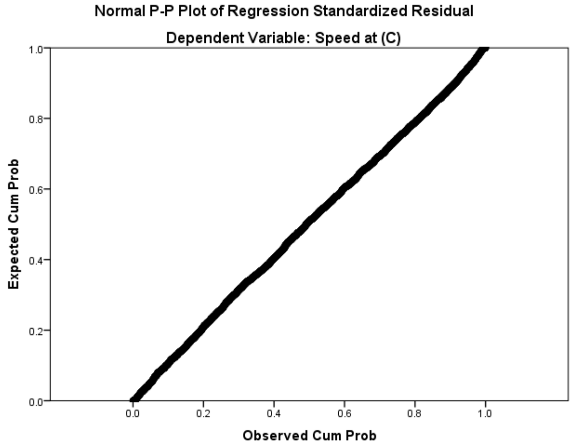
Results from linear regression analyses made in SPSS are shown in this appendix. The dependent variables are speed at C, speed at C_in, Speed differential in and out and maximum lateral acceleration within the curve. The independent variables are radius, approach tangent length[7], exit tangent length[8], approach spiral transition length[1], exit spiral transition length[2] and radius of previous curve[1].

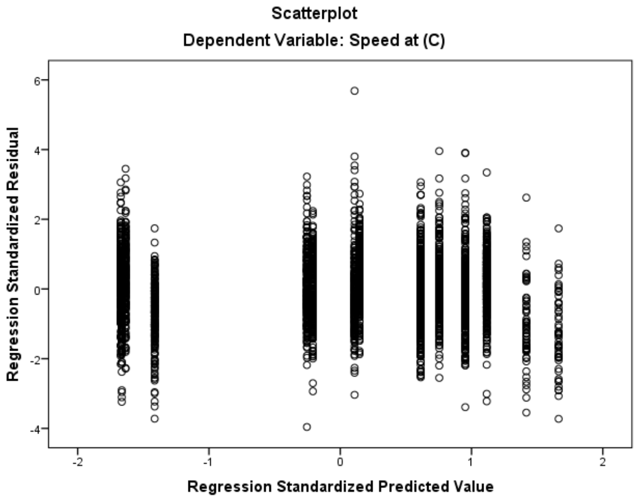
Dependent variable speed at C

		Unstandardized Coefficients		Standardized Coefficients			95% Confidence Interval for B		Correlations			Collinearity Statistics	
Model		B	Std. Error	Beta	t	Sig.	Lower Bound	Upper Bound	Zero-order	Partial	Part	Tolerance	VIF
1	(Constant)	64.459	.330		195.3	.000	63.81	65.11					
	Radius	.040	.001	.532	38.4	.000	.04	.04	.53	.53	.53	1.00	1.00
2	(Constant)	63.220	.410		154.3	.000	62.42	64.02					
	Radius	.041	.001	.547	38.7	.000	.04	.04	.53	.54	.54	.96	1.04
	Approach spiral length	.026	.005	.072	5.1	.000	.02	.04	-.04	.08	.07	.96	1.04
3	(Constant)	62.967	.416		151.4	.000	62.15	63.78					
	Radius	.044	.001	.587	31.8	.000	.04	.05	.53	.46	.44	.56	1.79
	Approach spiral length	.040	.007	.111	6.1	.000	.03	.05	-.04	.10	.08	.57	1.76
	Radius of previous curve	-.003	.001	-.068	-3.4	.001	-.01	-.00	.26	-.06	-.05	.46	2.16
4	(Constant)	62.874	.417		150.8	.000	62.06	63.69					
	Radius	.046	.002	.625	27.1	.000	.04	.05	.53	.41	.37	.36	2.80
	Approach spiral length	.050	.007	.138	6.6	.000	.04	.06	-.04	.11	.09	.44	2.29
	Radius of previous curve	-.004	.001	-.094	-4.2	.000	-.01	-.00	.26	-.07	-.06	.38	2.64
	Approach tangent length	-.003	.001	-.048	-2.7	.006	-.01	-.00	.23	-.05	-.04	.62	1.61

[7] Not in deltaVout
[8] Only in deltaVout

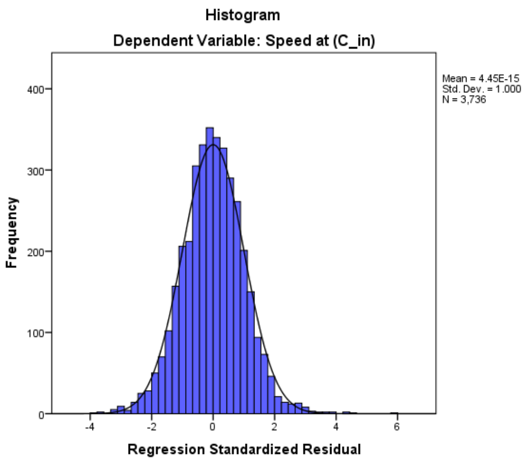

Histogram
Dependent Variable: Speed at (C)
Mean = -1.47E-15
Std. Dev. = 0.999
N = 3,736
Frequency
Regression Standardized Residual

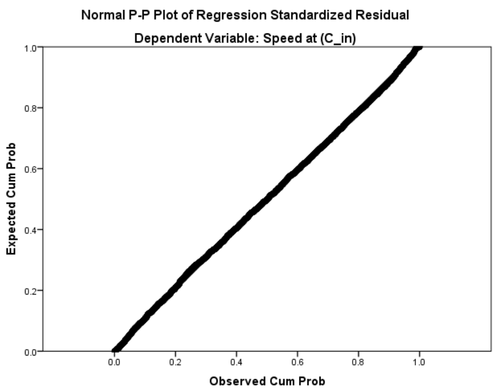

Normal P-P Plot of Regression Standardized Residual
Dependent Variable: Speed at (C)
Expected Cum Prob
Observed Cum Prob

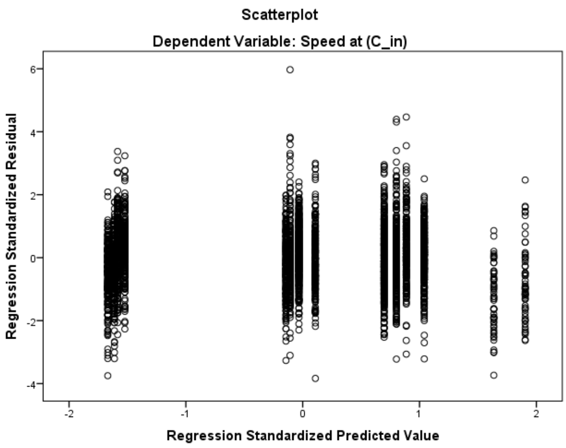

Scatterplot
Dependent Variable: Speed at (C)
Regression Standardized Residual
Regression Standardized Predicted Value

Dependent variable speed at C_in
Driver A excluded

Model	Unstandardized Coefficients		Standardized Coefficients	t	Sig.	95% Confidence Interval for B		Correlations			Collinearity Statistics	
	B	Std. Error	Beta			Lower Bound	Upper Bound	Zero-order	Partial	Part	Tolerance	VIF
1 (Constant)	63.956	.323		198.29	.000	63.33	64.59					
Radius	.040	.001	.546	39.85	.000	.04	.04	.55	.55	.55	1.00	1.00
2 (Constant)	63.787	.330		193.50	.000	63.14	64.43					
Radius	.039	.001	.531	35.21	.000	.04	.04	.55	.50	.48	.83	1.21
Approach tangent length	.002	.001	.037	2.45	.014	.00	.00	.26	.04	.03	.83	1.21

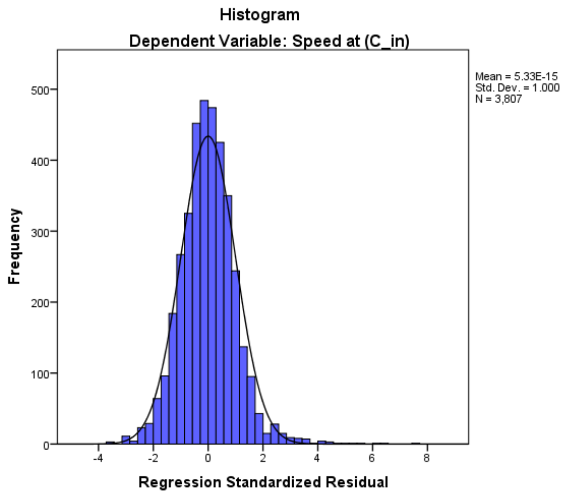


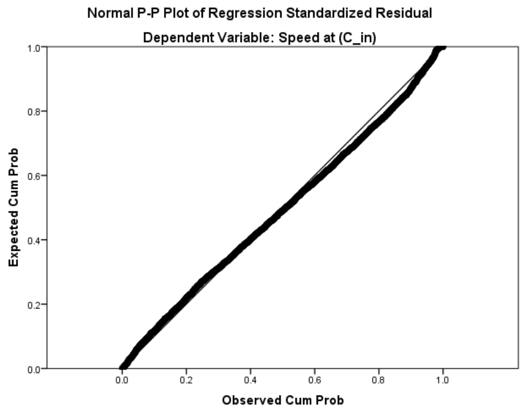


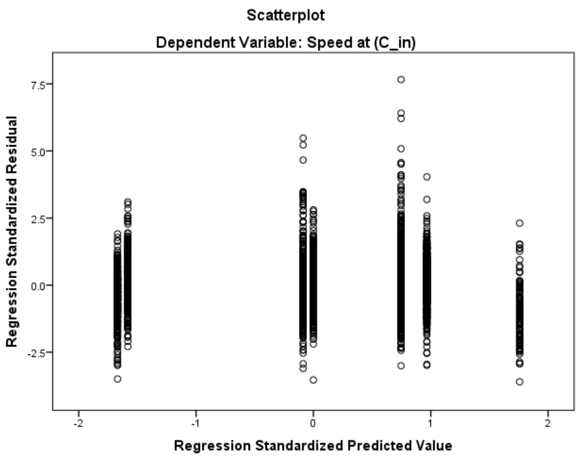


Driver A included:

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.	95% Confidence Interval for B		Correlations			Collinearity Statistics	
		B	Std. Error	Beta			Lower Bound	Upper Bound	Zero-order	Partial	Part	Tolerance	VIF
1	(Constant)	63.902	.347		184.12	.000	63.22	64.58					
	Radius	.041	.001	.526	38.19	.000	.04	.04	.53	.53	.53	1.00	1.00

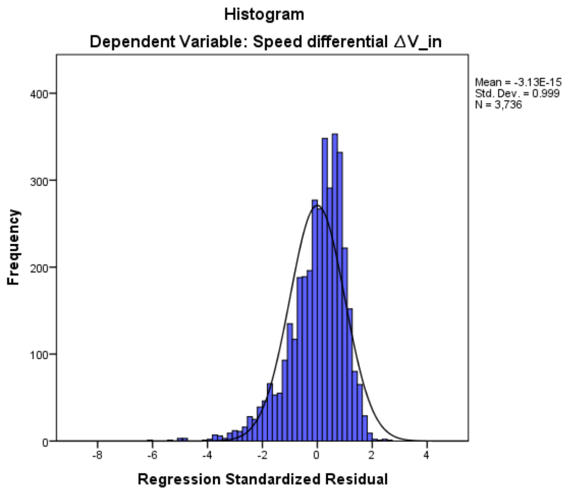


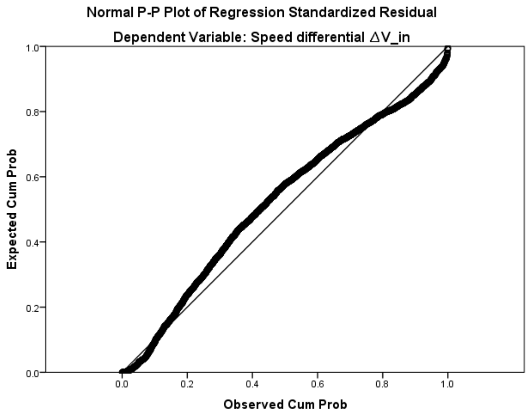


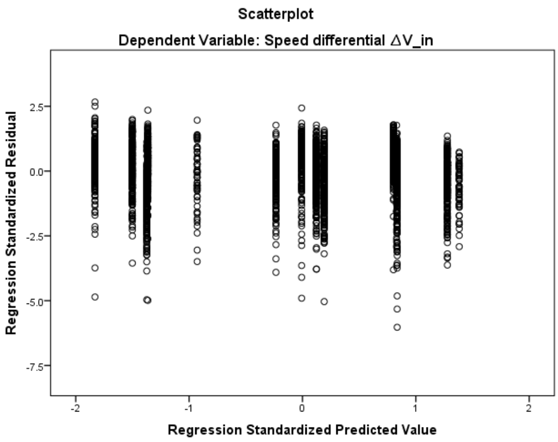


Dependent variable speed differential when approaching curve

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.	95% Confidence Interval for B		Correlations			Collinearity Statistics	
		B	Std. Error	Beta			Lower Bound	Upper Bound	Zero-order	Partial	Part	Tolerance	VIF
1	(Constant)	-5.766	.148		-38.98	.000	-6.06	-5.48					
	Radius	.007	.000	.253	15.98	.000	.01	.01	.25	.25	.25	1.00	1.00
2	(Constant)	-7.120	.181		-39.44	.000	-7.47	-6.77					
	Radius	.009	.000	.294	18.54	.000	.01	.01	.25	.29	.29	.96	1.04
	Approach spiral length	.028	.002	.199	12.57	.000	.02	.03	.14	.20	.20	.96	1.04
3	(Constant)	-7.116	.178		-39.98	.000	-7.47	-6.77					
	Radius	.011	.001	.380	21.49	.000	.01	.01	.25	.33	.33	.75	1.34
	Approach spiral length	.035	.002	.248	15.19	.000	.03	.04	.14	.24	.23	.88	1.14
	Approach tangent length	-.004	.000	-.183	-10.41	.000	-.01	-.00	.02	-.17	-.16	.76	1.32
4	(Constant)	-7.430	.180		-41.34	.000	-7.78	-7.08					
	Radius	.016	.001	.542	21.39	.000	.01	.02	.25	.33	.32	.36	2.80
	Approach spiral length	.055	.003	.392	17.08	.000	.05	.06	.14	.27	.26	.44	2.29
	Approach tangent length	-.006	.000	-.255	-13.27	.000	-.01	-.01	.02	-.21	-.20	.62	1.61
	Radius of previous curve	-.004	.000	-.217	-8.84	.000	-.00	-.00	.19	-.14	-.13	.38	2.64

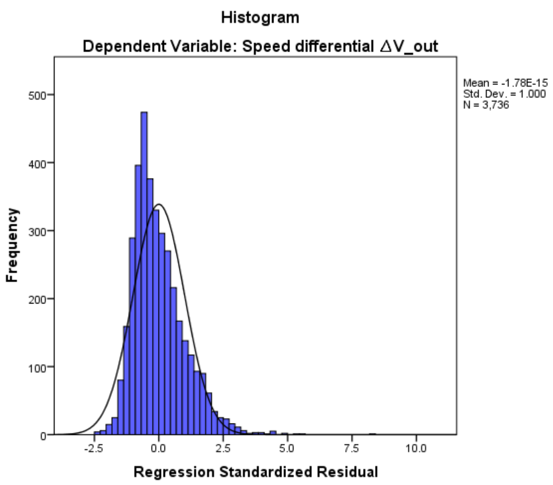

Histogram
Dependent Variable: Speed differential ΔV_in
Mean = -3.13E-15
Std. Dev. = 0.999
N = 3,736
Frequency
Regression Standardized Residual

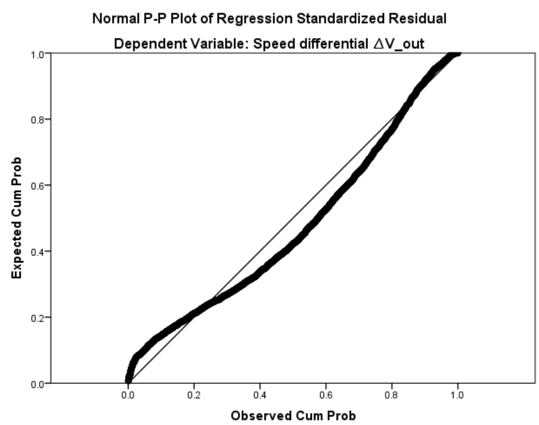

Normal P-P Plot of Regression Standardized Residual
Dependent Variable: Speed differential ΔV_in
Expected Cum Prob
Observed Cum Prob

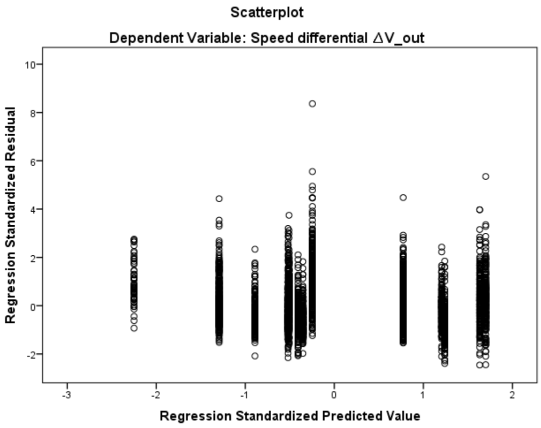

Scatterplot
Dependent Variable: Speed differential ΔV_in
Regression Standardized Residual
Regression Standardized Predicted Value

Dependent variable speed differential when leaving curve

Model		Unstandardized Coefficients B	Unstandardized Coefficients Std. Error	Standardized Coefficients Beta	t	Sig.	95% Confidence Interval for B Lower Bound	95% Confidence Interval for B Upper Bound	Correlations Zero-order	Correlations Partial	Correlations Part	Collinearity Statistics Tolerance	Collinearity Statistics VIF
1	(Constant)	6.402	.158		40.59	.000	6.09	6.71					
	Radius	-.010	.000	-.306	-19.65	.000	-.01	-.01	-.31	-.31	-.31	1.00	1.00
2	(Constant)	5.962	.162		36.80	.000	5.64	6.28					
	Radius	-.011	.001	-.362	-22.07	.000	-.01	-.01	-.31	-.34	-.34	.88	1.13
	Exit tangent length	.004	.000	.161	9.86	.000	.00	.00	.04	.16	.15	.88	1.13
3	(Constant)	6.229	.189		32.88	.000	5.86	6.60					
	Radius	-.012	.001	-.375	-21.9	.000	-.01	-.01	-.31	-.34	-.34	.81	1.24
	Exit tangent length	.004	.000	.176	10.2	.000	.00	.01	.04	.16	.16	.79	1.26
	Exit spiral length	-.006	.002	-.045	-2.7	.007	-.01	-.00	.07	-.04	-.04	.87	1.16

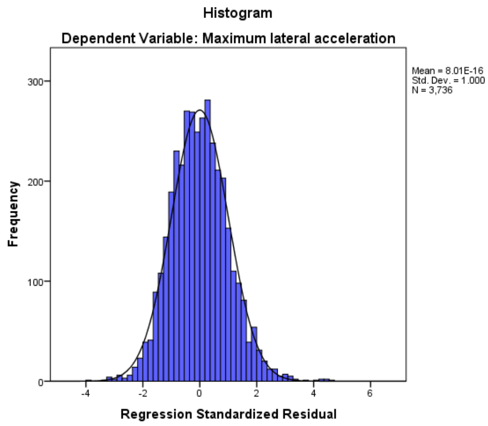


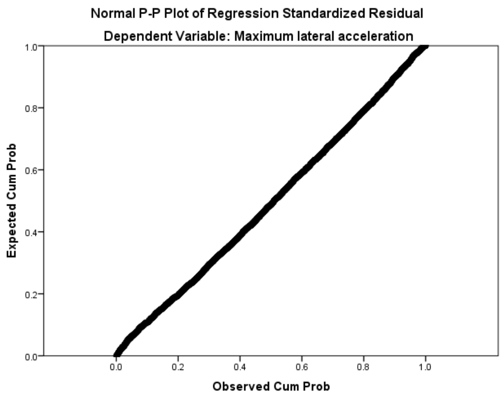


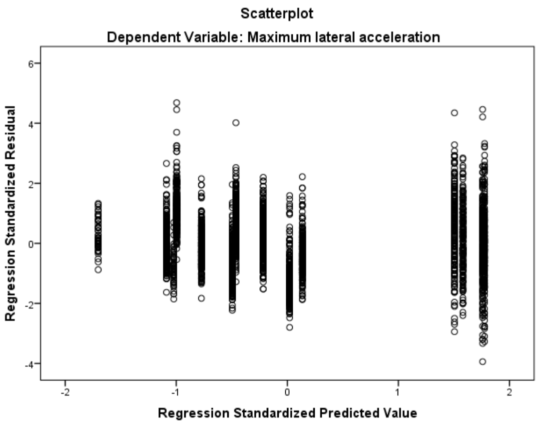


Dependent variable maximum lateral acceleration within curve

Model		Unstandardized Coefficients		Standardized Coefficients			95% Confidence Interval for B		Correlations			Collinearity Statistics	
		B	Std. Error	Beta	t	Sig.	Lower Bound	Upper Bound	Zero-order	Partial	Part	Tolerance	VIF
1	(Constant)	2.976	.025		121.1	.000	2.93	3.02					
	Radius	-.004	.000	-.614	-47.5	.000	-.00	-.00	-.61	-.61	-.61	1.00	1.00
2	(Constant)	3.095	.025		125.3	.000	3.05	3.14					
	Radius	-.003	.000	-.501	-35.5	.000	-.00	-.00	-.61	-.50	-.44	.78	1.29
	Radius of previous curve	-.001	.000	-.240	-17.0	.000	-.00	-.00	-.48	-.27	-.21	.78	1.29
3	(Constant)	3.062	.025		120.8	.000	3.01	3.11					
	Radius	-.003	.000	-.538	-34.7	.000	-.00	-.00	-.61	-.49	-.43	.64	1.57
	Radius of previous curve	-.001	.000	-.229	-16.2	.000	-.00	-.00	-.48	-.26	-.20	.77	1.31
	Approach tangent length	.000	.000	.077	5.6	.000	.00	.00	-.17	.09	.07	.81	1.23


Histogram
Dependent Variable: Maximum lateral acceleration
Mean = 8.01E-16
Std. Dev. = 1.000
N = 3,736
Frequency
Regression Standardized Residual


Normal P-P Plot of Regression Standardized Residual
Dependent Variable: Maximum lateral acceleration
Expected Cum Prob
Observed Cum Prob


Scatterplot
Dependent Variable: Maximum lateral acceleration
Regression Standardized Residual
Regression Standardized Predicted Value