THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

Safety Evaluation of Road Characteristics

Addressing a Road, Vehicle and Driver System by Exploiting Diverse Data Sources

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Cover:
A horizontal curve on highway RV40 in Sweden; the highway was included in the accident analysis and in the Field Operational Test (FOT) data used in this thesis. The photograph was taken by the author.

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To Mum, Jwan,
Lara, Rawan,
and the memory of my Dad

ABSTRACT

Accidents are rare and widely distributed on the road network, which poses a challenge for road safety improvement. Traditional methods alone, such as accident analyses and experimental studies, do not explain all accident causation factors. Traditional methods are well-established and are still important for specific contexts of road safety analyses. The objective of this doctoral thesis is to obtain an improved understanding and a safety evaluation of road features, in particular horizontal curves on non-residential roads. To explain the tendency of curves to trigger accidents is also another goal. It is essential to better understand interactions between vehicle, road, and driver components in a system which can explain possible mechanisms underlying accidents.

The overall methodology of the proposed system includes the development, implementation, and integration of complementary research approaches. The approaches are based on different kinds of data sources that together produce more detailed results. In the methodology, accident and simulation analyses provided a framework for combining road, vehicle, and human behavior data collected from Field Operational Tests (FOT).

The accident analysis in the system identified a set of Critical Road Parameters (CRP) with associated accident types. The CRPs included horizontal curves, curve direction, superelevation, and road surface characteristics; the common accident types were rear-end, single and overtaking accidents. PC-Crash was used to simulate the influence of CRPs on vehicle response, lateral acceleration and yaw rate, during overtaking maneuvers in curves. The CRPs and vehicle-road interaction results were used as a platform for developing a tool that could identify horizontal curve components and lane change maneuvers from FOT data. The tool was also able to combine the curves identified with vehicle signals and human data prior to a comprehensive curve analysis.

The accident analysis found specifically that there were more frequent overtaking crashes on right (inner) than on left (outer) curves. The simulations of road-vehicle interaction showed that the risk of a lane changing maneuver differed in curves, depending on curve direction and the lane to which the maneuver occurs. The simulations showed that requirements for drivers to remain safely within the road boundaries are greater if there is a lane changing maneuver in the curve. Despite this risk, the FOT analysis observed frequent overtaking and lane change maneuvers on the curves, of which 20% more lane changes occurred on right curves than on left curves. Interestingly, lane change maneuvers increased significantly with increasing curve radius.

The curve entrance was found to be the most dangerous segment of a curve. Current design practice assumes the safety risk is constant when driving along horizontal curves. The results also showed that drivers consider curve radius in choosing their driving speed rather than the posted speed limit of the curves.

The use of different data sources and approaches started with an open-ended analysis of accident data, as the first layer in a top-down process, and proceeded to the more specific and important findings of road curves. The system approach in the thesis made possible a safety tool whereby the empirical and simulation analyses together yielded more innovative and detailed results. Road feature analysis gave insight into how road geometry factors affect vehicle motion relevant to safety and driving strategy through curves. The findings are useful inputs for applications such as curve design reviews, selection of appropriate countermeasures, and the improvement of active safety devices.

Key Words: Road safety, Critical road parameters, Overtaking maneuvers, FOT data, Horizontal curves, Accident data, PC-Crash

List of Papers

I. Othman, S., Thomson, R., Lannér, G. (2009). Identifying Critical Road Geometry Parameters Affecting Crash Rate and Crash Type. *Proceedings of the 53rd AAAM Annual Scientific Conference*, October 4 – 7, 2009, Baltimore, MD, USA. Vol. 53, pp. 155 – 166.

II. Othman, S., Thomson, R., Lannér, G. (2010). Are Driving and Overtaking on Right Curves More Dangerous than on Left Curves? *Proceedings of the 54rd AAAM Annual Scientific Conference*, October 17 – 20, 2010, Las Vegas, NV, USA. Vol. 54, pp. 253 – 264.

III. Othman, S., Thomson, R., Lannér, G. (2011). Using Naturalistic Field Operational Tests (FOT) Data to Identify Horizontal Curves. Accepted by *Journal of Transportation Engineering*.

IV. Othman, S., Thomson, R., Lannér, G. (2011). Safety Analysis of Horizontal Curves Using Real Traffic Data. Submitted to *Journal of Transportation Engineering*.

Author's Contribution to the Papers

My contributions to Papers I – IV are as follows: study design, data analyses and main author. I have also presented results and proposed conclusions in all papers. Moreover, I supervised the data collection for Paper I.

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Acronyms and Definitions

AADT *(Vehicle/day)*	**A**nnual **A**verage **D**aily **T**raffic: the total yearly volume of traffic in both directions at a site divided by the number of days in a year. AADT provides a good comparative estimate of the traffic volume at a location (i.e. from site to site, or from year to year).
Crash rate *(Crashes/Mvkm)*	Defined as the number of crashes per Million Vehicle Kilometres per year (Mvkm)
Advisory speed *(km/h)*	A speed-limit that is recommended by a governing body, but is not enforced
ANOVA	**AN**alysis **O**f **VA**riance is a collection of statistical models, and their associated procedures, in which the observed variance of a particular variable is partitioned into components attributable to different sources of variation.
Black spot	A common term for a location (usually a short section of road) with an unusually high number of crashes that have historically been concentrated there; similarly, problematic sections of a road are sometimes called black routes.
CRP	**C**ritical **R**oad **P**arameter
Curve segment	One of the parts (entrance, middle, and end) into which the total curve length divided
Double lane-change manoeuvres	Rapidly driving a vehicle from its initial lane to a parallel lane, and returning to the initial lane. The total length of the manoeuvre according to ISO 3888 specification is 125 m.
FOT	A **F**ield **O**perational **T**est is a naturalistic method that involves collecting data continuously from a set of vehicle sensors during daily driving routines.
Grade *(%)*	A length of road sloping longitudinally, with a constant gradient. The gradient is usually measured in percentage of vertical dimension to horizontal dimension, e.g. 5% = a 5 m rise for every 100 m horizontally.
GPS	**G**lobal **P**ositioning **S**ystem is a space-based global navigation satellite system that provides location and time information in all kinds of weather, anywhere on or near the earth
Horizontal alignment	A curve in the horizontal plane of the road alignment is usually expressed in terms of radius, although it may also be described in terms of length and angular deflection.

IHSDM	**I**nteractive **H**ighway **S**afety **D**esign **M**odel, a software package developed by the US Federal Highway Administration (FHWA) to help with assessing the safety and operational effects of road design options.
International Roughness Index IRI *(m/km)*	**I**nternational **R**oughness **I**ndex is the roughness index most commonly obtained from measured longitudinal road profiles. It is calculated using a quarter-car vehicle math model, the response of which is accumulated to yield a roughness index with units of slope (m/km, in/mi).
Lateral acceleration *(rad/*s^2*)*	The acceleration generated when a vehicle corners, which tends to push a vehicle sideways
LCM	**L**ane **C**hange-**M**erge is a system which warns drivers of possible unsafe lateral manoeuvres based on adjacent or approaching vehicles in adjacent lanes; it includes full-time side object presence indicators.
LDW	**L**ane **D**eparture **W**arning is a system which warns drivers that they may be drifting inadvertently from their lane or departing the roadway
Left curve	Also known as outer curves, in the right hand driving countries, in which the road curves to the left. Left curve are inner curves in left hand drive countries
ND	**N**aturalistic **D**riving is a method that involves collecting data continuously, from a set of vehicle sensors, during daily driving routines in order to observe the natural behaviour of a driver/rider while interacting with the surrounding environment during driving/riding tasks; observational and performance data are also collected.
NVDB	*National Väg **D**ata**B**as* stands for Swedish National Road Database which includes a reference network and a large amount of data related to the road network.
Operating speed *(km/h)*	The actual speeds at which vehicles traverse a section of road; these may be observed or predicted by a model
PC-Crash	PC-Crash is an advanced Windows-based computer program for reconstruction and simulation of vehicle dynamics related to vehicle crashes.
PMS	**P**avement **M**anagement **S**ystem is a comprehensive database, which contains current and historical information on pavement condition, pavement structure, and traffic.

Right curve	Also known as inner curves, in the right hand driving countries, in which the road curves to the right, right curves are outer curves in left hand drive countries
Risk	Is the potential that a chosen action or activity (including the choice of inaction) will lead to a loss (an undesirable outcome).
SeMiFOT	Sweden-Michigan Field Operational Test project
SRA	**S**wedish **R**oad **A**dministration, now part of the Swedish Transport Administration since 2010
Superelevation	The slope between one edges of a road and the alignment of any other part of the road. This is normally found where the road is curved; raising the outer edge of the road provides a banked turn, allowing vehicles to traverse the curve at higher speeds than would otherwise be possible.
Trip (in FOT)	Each trip made by a driver for which there is origin and destination data as well as a unique identification number ID.
Vehicle heading *(deg)*	This is the angle between the intended path of the vehicle and true north. The heading is usually measured in degrees from 0° clockwise to 360° in compass convention.
Wheel rut *(mm)*	A rut is a depression or groove worn into a road or path by the travel of wheels.
Yaw *(rad/s)*	The rotation about a vertical axis that passes through the centre of gravity of a car.

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1 INTRODUCTION

1.1 Background

The transport system must provide as much mobility as possible without compromising the user's safety. Traffic safety problems outside residential areas can generally be categorized as high severity crashes, such as single and overtaking collisions, or low severity events, such as rear-end collisions. Among the crashes occurring on motorways in Sweden, the single and rear-end collision types comprise one third of the crashes each, while overtaking crashes dominate the remaining third. Moreover, single and overtaking crashes are dangerous types that usually result in severe injuries, while rear-end crashes may lead to less severe injuries (Vägverket, 2008). Severities of all types of crashes are very high on high speed-limit roads (outside residential areas), such as multiple lane highways and other main roads (Prato, et al., 2010).

Crashes are relatively rare and random in nature; thus, it is hard to assess the comparative safety of road geometry parameters by using quantitative crash analysis only (Koorey, 2010). Human behaviour is the major cause of these crashes (Lum and Reagan, 1995); however crash reports have a tendency to overlook the human factors involved (Fullar and Santos, 2002) given that crashes are multi-factor events in which the majority of traffic injuries are due to interaction between the road, vehicle and road user (Stigson, 2009). The road-related elements (the roadway variables, including the driver and the vehicle) are associated with 34% of crash causation (Lum and Reagan, 1995). Hence, the relationships and dependency of the relevant elements need to be incorporated as a multidisciplinary partnership system (Zein and Navin, 2003).

Crash analyses and controlled experiments have traditionally been employed as linear approaches to improve traffic safety. For example, crash analyses have been used to study the safety of road geometry (Fitzpatrick, et al., 2006; Fink and Krammes, 1995) and road surface (Sjölinder, et al., 1997; Leden, et al., 1998; Tholén, 1999; Velin and Öberg, 2002), as well as to evaluate the effectiveness of the measures used to improve safety (Bonneson, et al., 2007); Dupré and Bisson (2006) used crash records to evaluate the effects of increasing superelevation to improve the safety of a dangerous curve. Moreover, by a controlled experiment using an instrumented vehicle in the field, they identified the adverse superelevation in the curve as the main contributor to the high crash history. In contrast Sakshaug (2000) observed a tendency towards higher crash risk for curves with high superelevation than for those with low superelevation, due to increasing operating speed with increasing superelevation.

Controlled experiments, to investigate road characteristics, include field tests, advanced driving simulators, computer simulation programs and field observations. Bonneson et al. (2007) observed vehicle speed in curves to facilitate giving advisory speeds, criteria for identifying the appropriate advisory speed, and guidelines for selecting other curve-related traffic control devices. Reymond et al. (2001) used data collected from both field measurements and simulators to analyze the role of lateral acceleration; they developed a new driver model which predicts a quadratic decrease of vehicle lateral acceleration with driving speed. A model produced by the Swedish Road Administration (SRA) describes how the road, vehicle and road user should interact in a system to maintain safe road traffic. Crash data was studied to assess whether the model can be used to classify fatal crashes analysed in depth and to identify weaknesses in the road traffic system on Swedish roads (Stigson, 2009).

The analyses based on data from crash history and controlled experiments are valuable techniques in specific contexts, and they certainly have their place in the study of traffic safety (Neale, et al., 2005), but the benefits of using the data are limited and are not well suited to explain all possible combinations of the factors leading to an crash or incident (Neale, et al., 2005). Crash databases are not always complete; they lack essential information such as non-reported crashes (those never reported to a crash database) or missing correct information about crash location (Tholén, 1999; Jamil, 2006). Moreover, crash reports lack accurate pre-crash human behaviour data (Oppe, 1994).

Controlled studies, however, cannot avoid a certain level of artificiality and do not always capture the complexities of either the driving environment or natural behaviour (Neale, et al., 2005). These shortcomings in crash data and controlled experiments could be among the reasons that safety improvements using traditional methods are not currently maintaining the same rate of injury reductions as previously (Ward, et al., 2010; Wegman, 2010). Thus, in order to continuously reduce road fatalities and injuries, safety evaluations of road features require a systems approach based on a comprehensive and accessible dataset (Neale, et al., 2005). Field operational tests (FOT) data collection fills gaps in the traditional data collection methods. The FOT data records real-life driving with drivers using vehicles during their daily routines without special instructions about how and where to drive (Bärgman and Svanberg, 2010). Although FOT data is a breakthrough and a valuable data collection approach, the main focus of FOTs is on human behaviour (Baldanzini, et al., 2010). Furthermore, FOT data lacks explicit road geometry infrastructure information, and FOT databases are large and complicated. Thus, there is a strong motivation to develop a tool that uses a system approach to connect vehicle and driver variables with road features.

In the light of the current situation in evaluation of the safety of road features, research gaps and possible solutions, the central topic of this thesis is to design a comprehensive analytical method for evaluating the safety of road features and their tendency to trigger crashes, without having to wait for crashes to occur before the evaluation. To this end, traditional analytical techniques, crash analysis, and computer simulations can be used to identify overall road and vehicle factors affecting traffic safety. The factors identified need to be incorporated in a system that includes human behaviour in order to evaluate driving risk for specific critical road features on all road types outside residential areas. The outputs from the system could be used, in further studies, to refine and calibrate both the simulation and crash analysis work in a systematic analytical approach.

1.2 Previous studies

Research on traffic safety has a high priority worldwide due to the severe consequences of crashes for both individuals and society. The research studies reviewed generally aim to improve traffic safety by targeting specific components of within the main traffic safety pillars (environment, human, and vehicle). The approaches in general investigate current traffic safety problems and offer science-based evidence with solutions to address them. In the literature reviewed it was observed that there were two traditional approaches for collecting and analyzing data related to road safety. The traditional approaches were crash data analysis and controlled experiments. In addition, a new approach based on data collected from naturalistic driving has begun to appear in the literature. The previous studies are reviewed in the following sections according to methods of data collection; the chapter is concluded with a summary and key research gaps.

1.2.1 Crash data analysis and controlled experiments

Crash data analysis plays a major role for policy makers and professionals in the effort to improve traffic safety (Oppe, 1994). At a lower level, it is important to assess the safety of a variety of components and to identify specific problems (Othman and Thomson, 2007; Prato et al., 2010) as well as to measure the effectiveness of different kinds of countermeasures (Elvik, et al., 2009). Mechanisms underlying crash occurrence can seldom be identified by using crash analysis (Oppe, 1994). Controlled experiments, however, in specific cases can complete the crash analysis by defining deficiencies in the road system and introducing suitable countermeasures (Bonneson, et al., 2007). Both crash analysis and controlled experimental methods were until recently effective in lowering crash frequencies and decreasing injury severity (Neale, et al., 2005). Moreover, there were not any better analytical approaches due to limited advances in technology and data collection systems from traffic safety perspective (Victor, et al., 2010; Dingus, et al., 2006).

A literature search was based on crash data which included several categories: i) crash type distribution, ii) identifying deficiencies in road geometry features, iii) finding the effect of road surface characteristics, iv) black spot analysis and v) countermeasure evaluations. In addition crash databases are used to monitor process of traffic safety development and its safety consequences on national and global levels (Oppe, 1994).

Crash type distribution analyses generally showed that single, rear-end, and overtaking Crashes are the most common and that single and overtaking are the most severe ones (Othman and Thomson, 2007; Carlsson, 2002; Vägverket, 2008). Hence, further analyses have been conducted for the single and overtaking crashes. A study of fatal single crashes (Vägverket , 2002) investigated what in the road environment provoked the fatal injuries: the design of road environment, the effects of physical measures, or both. Another study presented a guide to address the run-off-road type of single crash including suitable and cost effective road environment countermeasures (Neuman, et al., 2003). Overtaking crashes were analysed from other perspectives, for example the classification of overtaking crashes (Clarke, et al., 1998), modelling passing manoeuvres for overtaking (Jenkins and Rilett, 2005; Haneen and Tomer, 2010), and driver ability to make critical passing judgments (Jones and Heimstra, 1966). Developing and examining several analytical models and field observations to formulate guidelines for safer and more comfortable roads during overtaking were also carried out (Hassan, et al., 1996). Studies that connected crash type to specific road geometry parameters were limited to relating run-off-road crashes and horizontal curves (Vägverket, 2002; Neuman, et al., 2003). Overtaking manoeuvres and crashes were widely investigated and included two-way roads only; they did not apply to separated roads or specific road features (Haneen and Tomer, 2010; Jenkins and Rilett, 2005; Hassan, et al., 1996; Clarke, et al., 1998; Jones and Heimstra, 1966). Moreover, fatal single crashes were analysed with respect to road type, speed-limit and AADT (Vägverket , 2002).

Crash data were extensively used to identify deficiencies in road geometry features (Oppe, 1994), including horizontal and vertical alignments, superelevation, road width, number of lanes, and roadside environment. Othman and Thomson (2007) assessed post-crash and pre-crash approaches to identify critical road parameters (CRP); the post-crash approach was based on crash and road data analysis. The preliminary results of the assessment showed that further use of the crash analysis approach is promising. Crash data studies, in general, indicate that curves experience a higher crash rate than tangents, with crash rates ranging from 1.5 – 4 times higher than for tangents (Bonneson, et al., 2007; Fink and Krammes, 1995; Dupré and Bisson, 2007; Granlund, 2010; Glennon, et al., 1985; Zegeer, et al., 1991; Neuman, 1992). The reasons underlying the high crash rate on horizontal curves (and sharper curves) with respect to the total percentage of crashes on the roads can be attributed to various traffic safety components. These include inadequate driving behaviour, exceeding the design speed on a curve, anticipatory behaviour of curve speed and alignment when approaching a curve, inadequate appreciation of the degree of hazard associated with a given curve (Messer, et al., 1981; Johnston, 1982). The high crash rate (CR) could be also due to poor delineation (Björketun, 2003; Srinivasan, et al., 2009) or to other design deficiencies such as inadequate superelevation (Dupré and Bisson, 2007; Granlund, 2010) and small curve radius (Neuman, et al., 2003).

Specific levels of the curve sharpness associated with increased crash rates were curves of radii less than 400 m (McLean, 1981; Choueiri and Lamm, 1987) or curves of radii less than 600 m on two-lane roads (Choueiri and Lamm, 1987; Johnston, 1982). The influence of the number of lanes and road width is a subject of controversy between scientists and road users (drivers). Thus, public opinion is generally that wider roads contribute to better safety (Harwood, et al., 2000). However, many 13m wide two-way roads in Sweden have had poor safety records due to the width inviting high speeds and improper overtaking manoeuvres. Converting the roads to 2+1 lanes was a cheap way to reach near-motorway safety levels. The 2+1 road is specific category of three-lane road, consisting of two lanes in one direction and one lane in the other, alternating every few kilometres, and usually separated by a steel cable barrier; it is well documented by Carlsson (2009). Another investigation (Hauer, 2000), highlighted that wider lanes tend to increase speed and closer following distances (less safety). In contrast, wider lanes could provide more room for correction in near-crash circumstances (more safety). The research, however, found no indications that narrower roads increase crash frequency (Hauer, 2000).

Crash data used to define the effects of road surface characteristics (friction, unevenness and roughness) on traffic safety showed that high friction on roads, such as gravelled and dry road surfaces, reduces sliding risk and results in better traffic safety (Cairney and Styles, 2006; Rudny and Sallmann, 1996). In contrast, low friction was concluded to provide better safety, since the drivers adapt their speed when it is obvious that road surfaces are slippery, such as wet or icy surfaces (Wallman and Åström, 2001). Two approaches are available to evaluate road surface characteristics based on crash data. The first approach is called a before-after study: crashes are analyzed for periods of equal length before and after resurfacing roads. The roads were less safe and a higher number of crashes were observed, after resurfacing the roads, than there had been before resurfacing. The more frequent crashes were associated with higher speed on the resurfaced roads (Sjölinder, et al., 1997; Leden, et al., 1998). The second approach, regression analysis, determined that resurfaced roads are safer than uneven and rougher roads (Tholén, 1999; Velin & Öberg, 2002). Contradicting the methods presented above, a third approach (Johansson, 2004) explained that a crash occurs when a change in the road surface arises without previous warning, which leads to loss of control of the vehicle. For example, an unevenness or wheel rut of height/depth of 50 – 70 mm that turns up unexpectedly on a small radius curve will result in markedly reducing side friction, thus increasing crash risk (Johansson, 2004).

Identifying unsafe road types (Carlsson , 2009), evaluating road surface condition (Wallman and Åström, 2001), and analyzing black spots (Dupré and Bisson, 2007) are mainly based on crash databases. However, causal factors are identified by also conducting a suitable type of controlled experiment. A black spot (a left curve) in France caused a high proportion of crashes, due to adverse or insufficient superelevation in the curves and curve sharpness, especially when the road surface friction was reduced by rain. The problem was analyzed by using an instrumented car to determine crash risk and suitable countermeasures. The curve was improved by providing adequate superelevation after removing the adverse superelevation. The effectiveness rate of the countermeasures was 96%, as crashes decreased from 25 to only one crash within one year (Dupré and Bisson, 2007). Other studies also used crash data to evaluate the effects of countermeasures used to increase road safety such as improving delineation (Björketun, 2003; Srinivasan, et al., 2009) and converting two-way express roads to 2+1 lane roads (Carlsson , 2009).The same curve deficiencies mentioned by Dupré and Bisson (2007), but in combination with high lateral acceleration during overtaking caused crashes in another left curve in Sweden (Granlund, 2010). Lateral acceleration during overtaking was analyzed theoretically to find the cause of the high crash rate on the curve. The decreasing path radius during overtaking manoeuvres and insufficient superelevation were pointed out as the main reasons for the high crash rate (Granlund, 2010). Another point of view by Sakshaug (2000) showed a tendency towards higher crash risk for curves with high superelevation than for those with lower superelevation. Thus, high superelevation leads to higher operating speed and higher risk; in contrast, low superelevation leads to lower speed and lower risk.

The number of studies using controlled experiments, such as field observations, micro simulation, driving simulator, is enormous. They are, in general, employed to collect vehicle and human factors data used to analyze and assess the relative safety of various countermeasures or scenarios, as well as to verify or model driving patterns. Odhams and Cole (2004), in a study-using a fixed-base driving simulator, found that road width and curve radius has significant influence on speed choice in curves. Bonneson, et al. (2007) fixed sensors to the pavement to measure vehicle speed at selected points along horizontal curves. Instrumented vehicles were used by Dupré and Bisson (2007) and by Alonso et al. (2007) to collect data on specific road and road sections for analysis. Several aspects of driving and overtaking manoeuvres were analyzed and modelled through controlled experiments, such as simulation and field tests (Jones and Heimstra, 1966; Hassan, et al., 1996; Jenkins and Rilett, 2005; Haneen and Tomer, 2010).

A common disadvantage in using crash history analysis is that the data is not always collected for research purposes (Oppe, 1994). Databases are not always complete and they lack essential information for the analyses, such as non-reported crashes, those never reported to the database or errors in locating where the crashes occurred (Tholén, 1999; Jamil, 2006). Moreover, the crash reports do not provide a clear picture of the scene of the crash or the sequence of events underlying it. Other information, such as road design, impaired driving, seat belt usage and operating speed, is either missing or unreliable (Vägverket , 2002). Mere identification of problematic sites using crash data is not effective (Alluri, 2010); modelling traffic safety developments in causal terms is not possible due to the rare and varied nature of crashes (Oppe, 1994).

Crash databases, however, at the highest level of aggregation can be used to describe and model traffic safety progress: for example, to evaluate the safety of different road types, to analyse crash type distributions, and to make a comprehensive classification of road geometry features in terms of traffic safety (Oppe, 1994). In this way the deficiencies of crash databases can be distributed normally for the groups analysed (Box, et al., 2005).

The weakness of data gathered by controlled experiments is that these studies are not natural, although they are assumed to be, since a certain level of artificiality cannot be avoided (Neale, et al., 2005). Experiments studies can be effective, however, to further analyse a specific problem: for example, to evaluate the safety of a black spot using an instrumented vehicle (Dupré and Bisson, 2007) or in simulating and evaluating the safety of particular road features when it may be expensive and inefficient to conduct an experiment in real life (Haneen and Tomer, 2010). The safety evaluation of particular road features based on controlled experiments or crash records alone cannot always be generalized; this can lead to conflicting conclusions, for instance in analyzing superelevation ((Dupré and Bisson, 2007; Sakshaug, 2000), road surface characteristics (Sjölinder, et al., 1997; Tholén, 1999), and delineation (Srinivasan, et al., 2009; Macaulay, et al., 2004). Consequently, controlled experiments need to be more closely connected to crash analyses in order to resolve the conflicting conclusions by understanding crash mechanisms.

1.2.2 Naturalistic driving and field operational tests

Advances in technology and data collection systems have enabled extensive naturalistic driving (ND) data collection (Dingus, et al., 2006). The ND data is an innovative method of analyzing traffic safety and human behaviour. This method is distinguished by instrumented vehicles with cameras and various sensors to continuously monitor the driving process. The wealth of information collected by ND studies provides many more useful benefits than the traditional methods mentioned earlier (Baldanzini, et al., 2010). Some completed or ongoing ND and FOT studies include:

1) 100-Car Naturalistic Driving Study (Neale, et al., 2005),

2) Field opErational teSt supporT Action (FESTA, 2008),

3) Test Site Sweden FOT (Victor, et al., 2008),

4) A comprehensive examination of naturalistic lane-changes, (Lee, et al., 2004),

5) Distractions in Everyday Driving, (Stutts, et al., 2003),

6) Sweden-Michigan naturalistic field operational test (SeMiFOT) (Bärgman and Svanberg, 2010),

7) Naturalistic Studies of Driver Assistance System Use (Baldanzini, et al., 2010) and

8) Driver distraction in commercial operations, (Olson, et al., 2009).

The last mentioned project was a “secondary analysis” that used datasets from two completed naturalistic heavy-vehicle driving studies: the Drowsy Driver Warning System Field Operational Test, DDWS FOT, (Hanowski et al., 2008) and the Naturalistic Truck Driving Study NTDS (Blanco, et al., in press).

All of the studies mentioned aimed to collect data and to investigate research questions related to driver behaviour, driver distraction, effect of system usage, and to evaluate active systems (Baldanzini, et al., 2010). However, FESTA (2008) was a project aiming to develop a harmonized methodology for the conduct of Field Operational Tests across Europe, which yielded recommendations for carrying out this type of study (FESTA, 2008). The comprehensive examination of naturalistic lane-changes analyzed the nature and severity of lane changes in a naturalistic driving environment from a human behaviour perspective. The collected data analyzed turn signal use and braking behaviour for example. The results provided recommendations for designing the lane change Collision Avoidance System –CAS (Lee, et al., 2004). The vehicle and environmental data collected by the studies include accelerations, gyroscopic signals and GPS position (Baldanzini, et al., 2010). Besides vehicle and environmental data, the studies also recorded information on the drivers, such as demographic data (i.e. sex, age, address, date of driving license), health status, habits (sleep habits), personality, and driving behaviour.

None of data collected in ND studies included road characteristics explicitly, even though FESTA (2008) stresses the importance of environmental factors such road type and road characteristics. The information recorded during driving is automatically related to road environment by GPS coordinates and video films. The SeMiFOT retrospectively connected the FOT database with the Swedish national road database (NVDB). However, the NVDB lacks specific information about road characteristics, such as curve information, road surface characteristics and superelevation.

1.2.3 Key research gaps

The studies reviewed show a broad range of research efforts that have examined the relationship, between specific geometric design features and crash rates, by which deficiencies in road geometry parameters were identified. The studies provided and discussed the effects of many geometric features on driving performance measures. The topics discussed were horizontal and tangent alignments, sight distance issues, and other physical features (e.g., number and width of lanes and shoulders). Moreover, the studies included investigations of rate, distribution, nature and type of the collected crashes. However, for the most part, data analyses in the studies have not included and related road geometry parameters and crash type. Thus, only a very few of these studies have established links between critical road geometry parameters and crash types. These studies focused on the frequency of run-off-road crashes on horizontal curves. The studies, however, lack detailed investigations of curve radius and distribution according to curve direction.

Lane changing crashes are another type that is represented by many studies. These utilized crash databases, driving simulators, field observations, and analytical investigations. However, almost all the studies reviewed were associated with two-lane roads with oncoming traffic; they focused on passing distance and head on collisions. These studies lack analysis of overtaking on separated roads such as motorways. More surprisingly, there were no studies that analysed curves, the most dangerous road section, in connection with lane change crashes (manoeuvres), the frequent and most dangerous crash type. Hence, it is very plausible and logical to believe that significant overtaking or lane changing crashes occur on curves and that they are strongly related. Moreover, due to definition, a lane change crash on a curve could be classified as a run-off-road crash in the databases when only one vehicle is involved. Reporting lane change crashes as run-off-road crashes is more likely to occur for fatal crashes, when sufficient information about the crash mechanism is not available or for severe crashes when the drivers do not remember what that caused the crash. Further, run-off-road crash studies are usually limited to fatal crashes, which may lead to missing lane change types in the analysis. In-depth studies in some countries, such as in Sweden, minimize errors in reporting crash types, however the possibility still exists when the in-depth studies are limited to fatal crashes and only a few countries. Further analyzing vehicle motion during overtaking on curves is certainly essential to better understand vehicle-road interaction during overtaking.

Because of the shortcomings of traditional methods of data collection and research gaps mentioned in Sections 1.2.1 and 1.2.2, FOT is considered a breakthrough and an enormously valuable data collection method. However, the focus of FOT is generally on human behaviour issues. Consequently, FOT data lack sufficient road information to be helpful when combining road parameters with vehicle responses and human behaviour data collected by FOT. The road information is necessary for the assessment of interactions between contributing factors that lead to crashes, which helps to understand and prevent the crashes.

The studies reviewed reveal the following key gaps in a comprehensive evaluation of the road geometry parameters of non-residential roads, which is intended to exclude effects such as vulnerable road users, traffic lights, roundabouts, and junctions. These gaps include:

a) a holistic evaluation of road geometry parameters associated with different types of crashes;
b) an analysis of curve-overtaking interactions; and
c) an adaptation of a system in which a) and b) are incorporated with human information, to understand crash mechanisms that can contribute to selecting suitable countermeasures for increasing safety.

1.3 Objectives and scope

The overall objective of this doctoral thesis is to obtain an improved understanding and a comprehensive safety evaluation of road geometry parameters by using crash history, computer simulations and field operational test (FOT) data. To this end, this thesis aims to develop and implement a sequence of interdependent research approaches based on different types of data sources to design a system effective for analysing road parameters. In the sequence of approaches, the crash and simulation data analyses are expected to provide a framework for a platform in which road, vehicle and human information are combined based on a comprehensive data source such as FOT. The system identifies and evaluates risk along CRPs, such as curves, based on human behaviour. The findings can be used as a basis for selecting suitable countermeasures to increase safety.

To keep the scope within reasonable limits, the thesis focuses mainly on the analysis of horizontal curves and vehicle responses, including interactions between them. Hence, the human behaviour variables are touched upon implicitly in terms of outcomes embedded in driving strategy such as driving path, speed, lateral acceleration, yaw rate and lane changing manoeuvres. Moreover, the scope of the analyses was limited to non-residential roads of which only separated roads were analysed, as a starting point in the crash analysis; however, the FOT investigation included non-separated roads also. The focus on non-residential roads was chosen to exclude both the effects of vulnerable road users and of roads with low speed driving such as traffic lights and roundabouts.

Taking into account the literature review and research gaps, the following specific goals of the present thesis are defined:

- To develop an analytical approach, using crash and available road maintenance databases, able to identify critical road geometry parameters including crash type distribution (Paper I);
- To investigate road-vehicle interaction in order to analyze vehicle motion during overtaking manoeuvres on curves (Paper II);

- To construct an approach that can extract horizontal curves and lane changing manoeuvres from naturalistic driving data, in order to connect road and driver behaviour databases (Paper III); and
- To analyse the influence of horizontal curve components on vehicle motion and on drivers’ strategy, by using naturalistic driving data (Paper IV).

2 METHODOLOGY AND MATERIAL

The first stage in the research program was to conduct a feasibility study with the aim to recommend a suitable research method for a holistic investigation of critical road parameters (i.e. CRPs). The results of the studies based on crash history were the most promising; hence they were used as a starting platform in the present thesis as described more closely in Section 2.1.

A more specific version of the methodology and the thesis strategy is shown in Table 1; the details are presented in the following sections which summarize the papers included. Paper I is a broad investigation of the effects of road geometry parameters on crash rate and type. Paper II follows up on the results from Paper I by focusing on simulating the interaction of curve components and vehicle responses, for both curve directions using identical driver inputs. Paper III develops a method, to identify driving path and lane change manoeuvres on curves by using real traffic data, FOT, which served as a tool to identify the data analysed in Paper IV. The final paper provides a systematic approach to traffic safety analysis by which the vehicle and driver interactions with infrastructure can be evaluated under real traffic conditions.

Table 1. Research questions, strategy and analytical methods used in line with the aims given in Section 1.3.

Research Questions	**Papers**	**Research Strategy / Analytical method**
RQ1: How do road geometry parameters affect crash rate and crash type?	**I:** Identifying Critical Road Parameters Affecting Crash Rate and Crash Type	Quantitative analysis of crash data, integrating and then analysing existing crash and maintenance data
RQ2: What road geometry parameters affect responses of a vehicle while negotiating curves? **RQ3:** Are vehicle dynamics responses (lateral acceleration and yaw angular velocity) different when manoeuvring (overtaking) through right and left curves?	**II:** Are Driving and Overtaking on Right Curves More Dangerous than on Left Curves?	Empirical simulation of road-vehicle interaction while driving on curves; statistical analysis of the vehicle response outputs
RQ4: How can drive path and lane changing manoeuvres in horizontal curves be extracted from FOT data?	**III:** Using Naturalistic Field Operational Test (FOT) Data to Identify Horizontal Curves	Empirical approach to identify curves from FOT data, combining curves with vehicle response data, identifying lane changes from vehicle offset records.
RQ5: How are safety relevant vehicle motions and human behaviours affected by curve components such as radius, direction, speed-limit, road width and vertical grade?	**IV:** Safety Analysis of Horizontal Curves using Real Traffic Data	Analysis of quantitative and qualitative data derived from FOT data

2.1 Identifying holistic CRP of the road network including corresponding crash type

Research to identify the influence of road section characteristics on crashes lacks a clear understanding of the mechanism that underlies crashes, despite many efforts to promote safer roads and eradicate dangerous road sections. For parameters such as, superelevation, wheel rut and road roughness, for example, there are sometimes conflicting opinions. Furthermore, the studies usually focus on numbers of crashes and crash rates; they do not include crash type. Therefore a more detailed investigation of the problem was initiated to determine infrastructure features that are associated with the crashes. The study also investigates the relation between crash type and road geometry parameters, which is important in understanding the traffic safety of the road networks. As a result of evaluating a variety of investigation approaches, an analytical method was developed to integrate existing crash and maintenance data. The method adopted aims to identify dangerous road parameters and to find crash type distributions for these parameters. Moreover, the results were used as a framework to integrate specific road features with vehicle dynamics and human behaviour in the subsequent work for this thesis.

The crash data collected comprises personal injury crashes, while the road type investigation was limited to median-separated public roads in the western region of Sweden. The period of investigation was 6 years (2000 – 2005). The total length of the roads selected was 810 km, for which a total of 3599 traffic crashes involving personal injury (including fatal, severe and slight injuries) were reported to the databases. After combining road and crash data, crash rate (CR) was used in the analysis to normalize the results by taking into account the length of a roadway section and the traffic volume. This allows a direct comparison of specific roadway sections with respect to traffic safety. Crash rate is defined as the number of crashes per million vehicle kilometres (Mvkm):

$$CR = \frac{crash \times 10^{6}}{AADT \times 365 \times T \times L} \quad crashes\ per\ Mvkm \qquad (1)$$

where:

CR = Crash rate, crashes per Mvkm,
AADT = Average annual daily traffic, $\frac{Vehicle}{day}$,
L = Length of section investigated, *km*, and
T = Length of time period investigated, *year (*365 days).

To evaluate the effects of road parameters on crashes, regression analysis techniques were used for modelling the relationship between variables, with a simple linear equation, in which crash data, represented as crash rate, was the dependant variable, while the road parameters were independent factors.

2.2 Simulating road-vehicle interaction to analyze vehicle responses

Studies that analysed vehicle -road interaction are usually case studies to improve the safety of specific black spots. A study to find the reason for a high crash rate in multiple lane curves and how can the safety be improved, recommend changes in curve design codes as well as measures to improve safety in existing unsafe curves (Granlund, 2010). Moreover, the removal of adverse cross fall in left curves improves vehicle safety while negotiating curves, according to crash data and a field test (Dupré and Bisson, 2007). Consequently, an investigation to analyse vehicle-road interaction in curves, and to link it to human behaviour was of interest. A follow-up study developed a simulation analysis based on the results of the crash history investigation in Section 2.1. The analysis simulated interaction between road curves and lane changing manoeuvres of the vehicle, with the aim to find road features that affect vehicle dynamic responses during overtaking on curves, as well as to explain the more frequent overtaking crashes on right curves than on left curves. The road factors simulated were speed, superelevation, radius and friction, including their interactions, while the vehicle dynamic variables were lateral acceleration and yaw angular velocity. A simulation program, PC-Crash, was used to simulate the influence of road parameters on vehicle response in curves. The different combinations of road and vehicle variables led to 108 overtaking manoeuvre runs in which the vehicle followed a predefined double lane changing path as well as possible. An analysis of variances (ANOVA) was performed, using a two-sided randomized block design, to find the differences in vehicle responses for the curve parameters.

2.3 Identifying driving path and lane change manoeuvres on curves using real traffic data

An effective approach to understand the mechanism of crashes is to assemble all factors that may contribute to causing a crash. Analysing the factors separately have limited success, since it does not take into account all effects or interaction of the other factors. In this context, it is of great interest to devise a method which combines the parameters of specific road segments with vehicle dynamic responses and human behaviour, based on real-life driving data. More specifically, the method should facilitate observation of vehicle responses for a road segment and combine them with associated driver behaviour data for further assessment. One of the most reliable sources is data that is recorded and stored during a natural driving situation, such as data from a Field Operational Test (FOT) which is Naturalistic Driving (ND). In a FOT, driver behaviours and vehicle responses are recorded and stored during normal operations. The problem with FOT is that the data set is large and complex, which causes many practical difficulties in simultaneously analysing data sets. Hence, it is essential to design an approach able to separate and extract road segments from FOT data and to combine them with other elements. It is preferable to focus on critical road segments, for example to extract horizontal curves including their components. Horizontal curves are one of the most important geometric features that can affect the level of service and safety of a road, as indentified in previous studies. To obtain the curve characteristics (radius, start-end points) from natural driving data is fundamental for analysing vehicle responses in relation to curves.

The study focused on extracting horizontal curves from real traffic data, which also provides access to vehicle responses and human behaviour data on curves, while the vehicle was being driven. As mentioned, associated curve components of interest during the process were radius and start-end of the driving path on curves. The previous work had identified horizontal curves as a main contributor to crashes, and it was necessary to limit the area of interest in the road network covered in FOT data. The approach also includes identifying lane changing manoeuvres on curves, which can be used to model lane change rate with respect to curve radius. In addition, lane changes can be used to define a potential crash trigger in a subsequent analysis.

Field operational testing is a more natural data set than the other data sources, such as simulations, crash history and field tests, all of which are studies with a higher degree of experimental control. The approach first identifies horizontal curves from FOT data and then combines them with other safety factors on a common axis that consists of several steps. The steps consist of plotting GPS data in the FOT database to define the FOT road network and then selecting road sections of interest as the first step. In the second step the curves are identified and their radii are estimated from the selected road section for further analysis. Matlab scripts have mainly been used in implementing the steps.

An equation has been implemented to estimate path radii using the heading of the vehicle and distance travelled. The Δ Heading is the change in heading of the vehicle between two points on the curve, as shown below in Figure 1. The distance travelled is given by the velocity of the vehicle and time between the two points.

$$R = \frac{180^\circ \times L}{\pi \times \Delta\, Heading} \qquad (2)$$

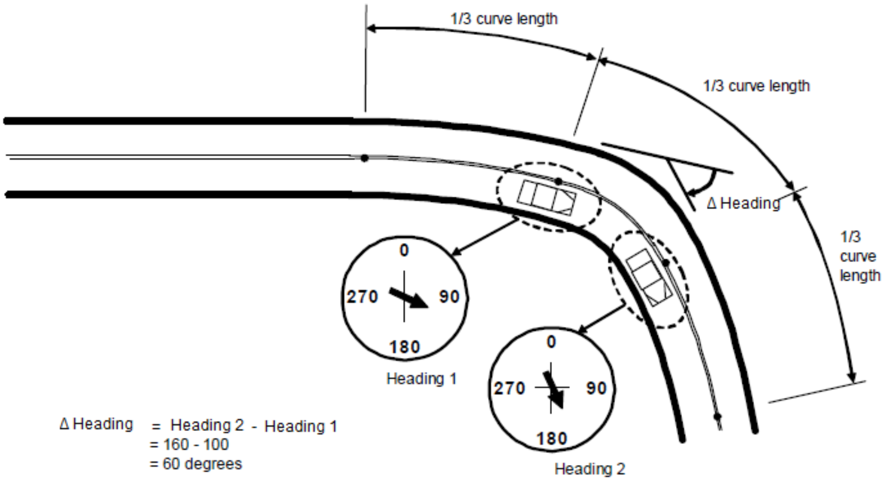


Figure 1. Change of heading during driving on a curve (Modified from Bonneson, et al. ,2007)

The challenge is to make sure that the points lie on the curve section and that the estimation is correct. Thus accumulated ΔHeading is used, as a threshold, to define the two points in the curve. The first point is set where ΔHeading, from the beginning of the section to the first point, reaches the threshold. Similarly the second point is set when ΔHeading, from the end of the section to the second point, reaches the threshold.

2.4 Analyzing safety of driving on horizontal curves using real traffic data

When reviewing the methodology chain described in Sections 2.1, 2.2 and 2.3, critical road segments were identified and vehicle responses related to safety were examined. Furthermore, a method is available to combine these factors with the human behaviour based on the comprehensive FOT data set. The resources are now available for a comprehensive analysis using the tool which is the aim of this thesis.

The last stage in the study is to identify and evaluate the safety performance of horizontal curves together with vehicle responses and human behaviour by using recorded naturalistic driving data from FOT. To access the FOT data and overcome the data set difficulties, the tool developed in Section 2.3 was used to identify curves and to mine associated data. The safety analyses of the curve data collected was carried out by different kind of statistical hypotheses, such as analyzing effects of specific curve features on vehicle dynamic responses and modelling lane changing manoeuvres with respect to curve radius. The curve features collected and used in the analysis were curve radius, length, vertical grade and road width. The vehicle response variables used as indicators to evaluate curve safety were lateral and longitudinal acceleration, yaw rate and speed. The radius of a curve, estimated from the ΔHeading using the method in Section 2.3, is the path chosen by a driven for negotiating the curve and it is not the same as the physical radius of the curve. The driver's path was transformed to the curve radius in relation to the curve deflection angle in order to facilitate future comparison with other studies. However, in this study both driver's path and curve radius were taken into account in the analysis.

Trips containing lane changing manoeuvres on the curves were identified and separated from trips without lane changing. Moreover, lane changing trips on different curves were normalized by taking into account the total number of trips. Lane changing trips were used to find correlations between lane changing and various fixed factors, such as curve radius, direction and speed-limit. Furthermore, the separate trips can be used in when analyzing human behaviour by using the video films, for example to explain where, how, and why manoeuvres occur.

The human behaviour variables are only analyzed implicitly in this study, in terms of outcomes such as speed, lateral acceleration, yaw rate and lane changing manoeuvres. Thus, the video films were not analyzed, although the data was collected and identified for further analysis. Analyzing video films to study in-vehicle distractions, for example, is outside the scope of this investigation and requires other research specialties.

3 RESULTS

The important findings of the thesis are summarized here. A more detailed presentation of the results can be found in Papers I – IV at the end of the thesis.

3.1 Critical Road Parameters (CRPs)

The crash and road information reported in the present thesis has produced a wealth of data which was analysed to find the road parameters that cause the most crashes. Analysing crashes according to type showed that rear-end and run-off-road crashes were the dominating ones representing 49% and 32%, respectively, followed by overtaking crashes at 8%, as shown in Figure 2.

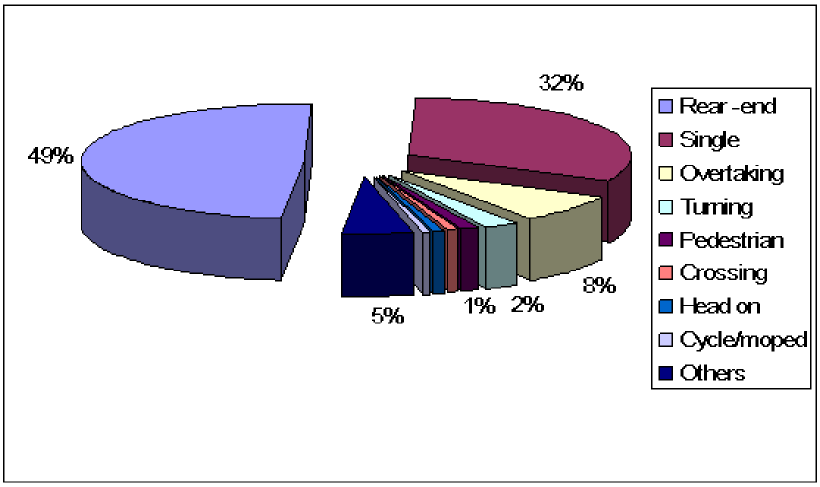


Figure 2. Crash distributions according to type

The results showed that the CR rose with increasing width for all road types, however, the effect of the width for motorways showed that it is the edge treatment, rather than overall width that affects the CR. Moreover, crashes cluster at curves, which make them one of the most dangerous parts of the road network. Of more interest, the results revealed that right curves are more dangerous than left curves during lane changing or overtaking manoeuvres. Poor visibility (view obstructed by the vehicle being overtaken) and shorter sight distances for right curves than for left curves are other possible reasons for this finding. The fact that this tendency was most easily identified in wider curves (greater than 700 m radius) is interesting to investigate, as this is the lower radius limit for motorway curves that do not require superelevation.

Another finding of this study related to curves was the effect of superelevation on CR: the highest CR was found for the greatest superelevations. In addition there were unfavourable results for left curves combined with negative superelevation. This can be associated with a lack of adequate dynamic safety characteristics, especially when design speed is not harmonized with operating speed.

The result of the study showed a significant rise of CR with both increasing wheel rut depth and road roughness, International Roughness Index (IRI), which is consistent with some previous studies in Sweden. The precise effects of road surface on safety have often been difficult to interpret in previous studies. However there is a boundary wheel rut depth at which safety becomes a concern and work should be carried out to determine threshold values. In Sweden, repaving or remediation is required when ruts are 17 mm deep on paved roads. In light of the studies mentioned earlier, horizontal curves including corresponding components were chosen for further study because they are one of the most important geometric features that can affect a the service and safety of a road.

3.2 Road-vehicle interaction

The critical road parameters (CRP) identified, in Section 3.1, were horizontal curve components, superelevation, and road surface. The CRPs were investigated using vehicle dynamics simulation to analyse their influence on vehicle responses in curves during overtaking or lane changing manoeuvres. Simulating lane changing manoeuvres was done to investigate why there was an increased rate of crashes attributed to lane changing on right curves. Furthermore, lane change manoeuvres generate critical vehicle responses; this could explain the safety risk of curves from a vehicle dynamics perspective.

The simulation results showed that the road parameters which affect lateral acceleration on right and left curves were speed, road condition, and their interaction. However to understand the difference between left and right curves, it is of greater concern to analyze the road factors that affect overtaking manoeuvres differently in left and right curves. For lateral acceleration, overtaking on right curves was sensitive to radius and the interaction of radius with road condition; overtaking on left curves was more sensitive to superelevation. The sensitivity of a left curve to radius was observed when starting overtaking (leaving initial lane) and returning to the initial lane, while for right curves it was seen when starting to return to the initial lane, as shown in Figure 3. Moreover, the results showed significant differences between overtaking on curves and straight sections.

The results of the simulation do not explain more frequent overtaking crashes on right curves; however, they clearly demonstrate that vehicle performance differs for right and left curves during overtaking.

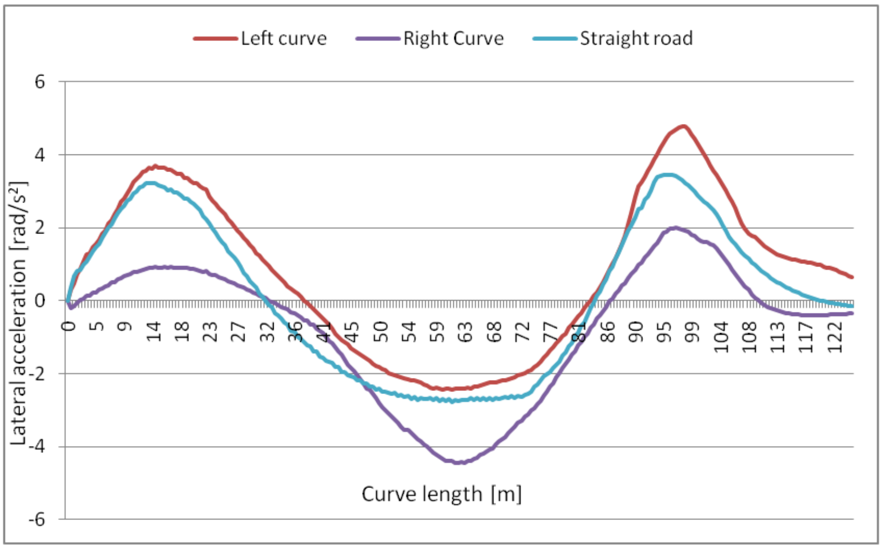


Figure 3. Lateral acceleration during a double lane-change manoeuvre on left and right curves in comparison with straight sections [Radius = 500 m, Speed = 70 km/h]

3.3 The Safety of horizontal curves

A tool was developed (Section2.3) that functioned successfully in identifying the driving path on curves and lane changing manoeuvres from naturalistic driving. Using the tool, 96 curves, equally distributed on left and right travel directions, were collected and grouped according to their radii. The curve information could be combined with other safety relevant data on a common axis. More specifically, the tool synchronized vehicle responses and human behaviour, collected by FOT, on the horizontal curve segments identified for analytical purposes.

To determine an optimal threshold in estimating curve radius, five threshold limits, between 5 and 22 degrees, were tested. ΔHeading values within the range of 8.5 – 11.5 degrees can be used as the threshold to estimate curve radius. The points selected can be checked on the heading plot to determine whether they are on the road curve and are suitable points. This is shown in Figure 4 (b and d) where the inclined lines represent the curve section and the red points on the curve are used to estimate curve radius.

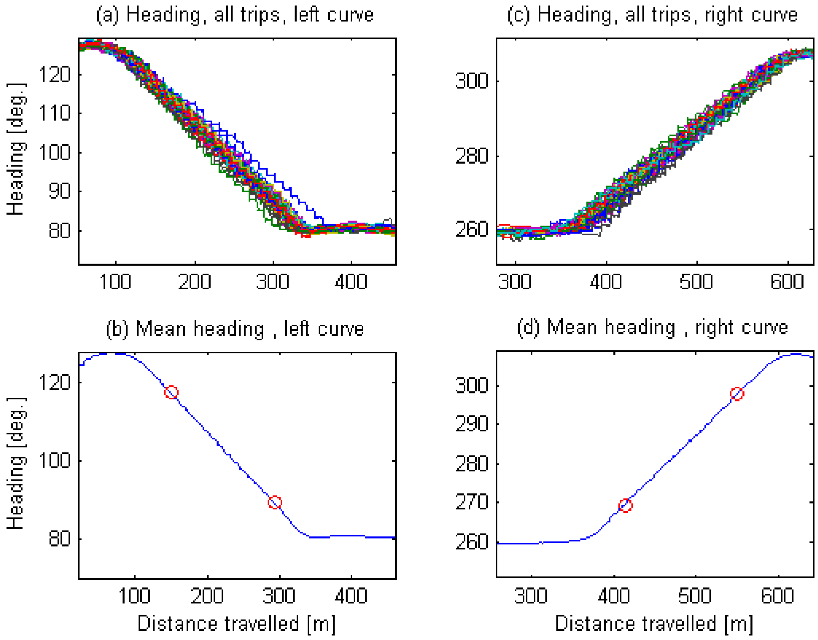
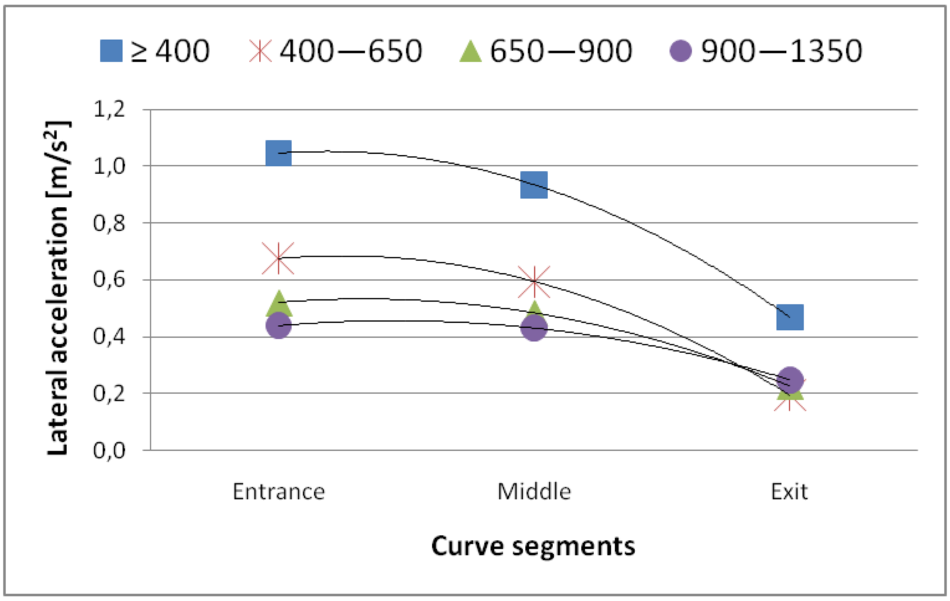


Figure 4. Heading signal for a vehicle during negotiating a horizontal curve section

3.3.1 Lateral acceleration and yaw rate

Lateral acceleration and yaw rate are used, as indicator signals to measure the safety of vehicle operation on horizontal curves, by examining the factors that influence these indicator signals. The results showed that the risk of driving on curves increases with decreasing radius; this is in line with crash analysis results in Section 3.1. More interesting was how the risk was distributed along the curves. The entrance clearly was the most critical part along the curve for all curve radius groups followed by the middle section of the curves. This is illustrated in Figure 5 where vehicles experience higher lateral acceleration and yaw rate at the entrance than in the middle and exit for all radius groups. The figure shows also that, at the curve exits, lateral accelerations and yaw rates for the three larger radius groups converge to the same value, which could be a transition point for the curve toward zero lateral acceleration on straight sections.



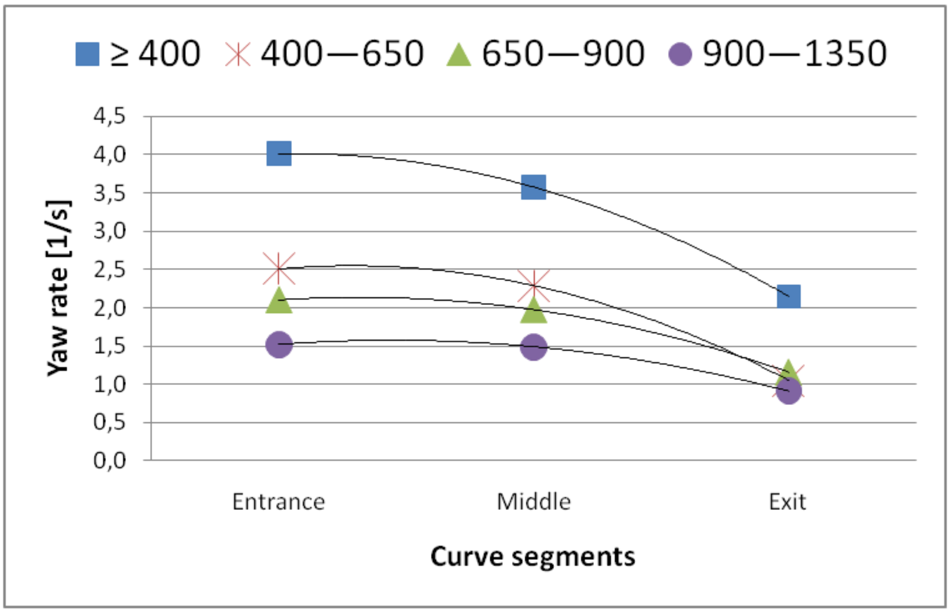


Figure 5. Lateral acceleration and yaw rate along horizontal curves for four radius groups

The differences in lateral acceleration, as a risk index, between left and right directions of travel shows right curves to be more dangerous. However, there was no significant difference between left and right when yaw rate was used as a risk index. The results of separate radius groups usually followed the same trend as the groups combined for both lateral and yaw rate signals. No difference between left and right in terms of yaw rate was observed; there was higher lateral acceleration for the right curves than for the left curves.

3.3.2 Lane changing manoeuvres

The rate of lane change manoeuvres observed on the curves was 11% of the total trips, of which 40 % occurred on left and 60% on right curves. The results showed that drivers change lanes more frequently as the curve radius increases, as shown in Figure 6. Furthermore, the lane change frequency was affected significantly by interaction between curve radius and speed-limit.

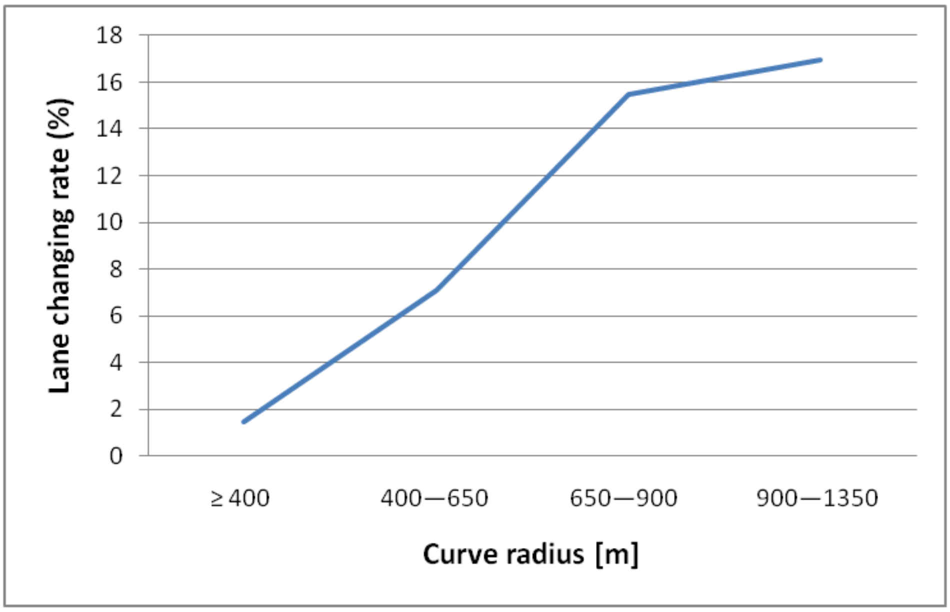


Figure 6. Rate of lane changing manoeuvres on horizontal curves for four curve radius groups where the rate is the proportion of lane changing trips to all trips

The linear model of correlation between lane changes and curve radius for both curve directions together exhibited very strong correlation, with a coefficient of 0.89.

Speeds of trips with and without lane changing manoeuvres were compared to determine whether lane changes are a method to "cut the curve" and maintain speed through the curve, speeding takes place during the lane changing, or both. The result showed that the average speed of trips with lane changing manoeuvres was higher than trips without lane changing, although the difference was not statistically significant. However, when a lane change occurred before or after an analysed curve, the trip was regarded as a non-lane changing trip since the manoeuvre did not occur in the curve. These manoeuvres outside the curves were clear in the plots of the vehicle lane offset, especially when there was nearby curve that preceded or followed the curve analyzed.

3.3.3 Speed

Operational speed increased as curve radius increased, as shown in Figure 7 where speed is demonstrated along curve segments of the radius groups.

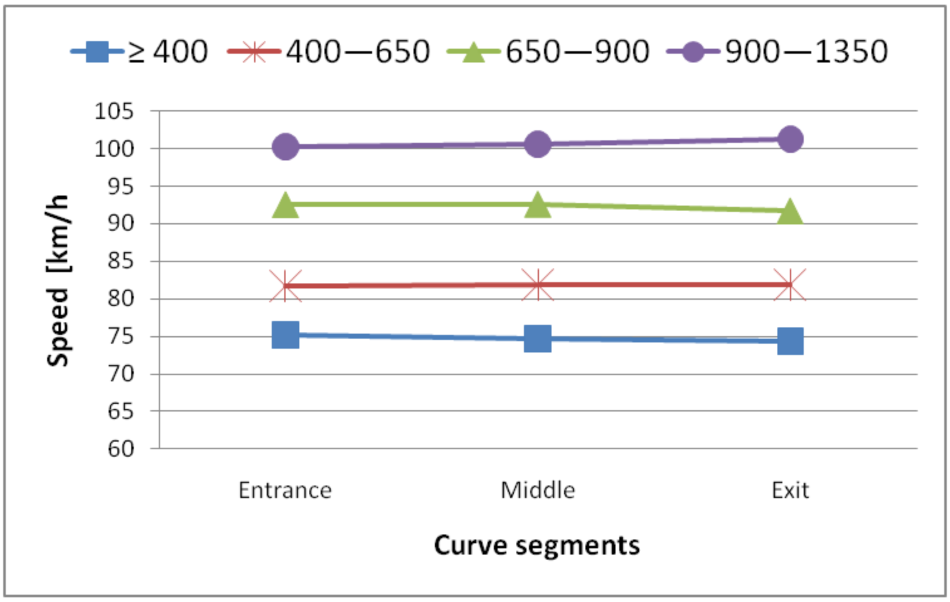


Figure 7. Operating speed along curves for four radius levels

To identify confounding factors in the analysis, a study of specific speed-limits in curves revealed that operational speed generally increases with increasing curve radius, regardless of speed-limit, as shown in Table 2. However the difference between operational speed and speed-limits was inconsistent: some drivers keep their speed below the speed-limit on smaller radius curves in high speed-limit roads (90 and 110 km/h) while they drive at higher speed on a road with a speed-limit of 70 km/h. This shows clearly that drivers take into account curve radius more than speed-limits. This was more obvious when the operational speed was 20 km/h below the 110 speed-limit for curve radii 400 – 650, while the speed was 15 km/h above the 70 speed-limit level for the radii of 900 – 1350.

Table 2. Operational speed for four radius levels and speed-limits

	Radius	>400	400-650	650-900	900-1350
Speed-limit					
70		73.73	77.07	76.69	85.75
90		88.56	89.67	96.38	95.46
110		0	90.7	98.36	111.99

4 GENERAL DISCUSSION

Traffic crash victims represent a significant public health issue. Historically, traditional approaches such as crash analyses and controlled experiments have had notable success in reducing crash fatality. Indeed, there have been large steps forward in traffic safety in recent years. However, the rate of safety improvement has slowed in many of the developed countries. The slowing rate of improvement could be partly due to limitations in crash databases and deficiencies in using controlled experiments. Moreover, there are factors not currently addressed by traditional traffic safety interventions, since the use of information is limited to a subset of, but not all, factors that affect crash rate. In this context, evaluating the safety of road parameters requires a higher level system in which vehicle and human behaviour data are integrated with road data, based on a comprehensive and more objective data source.

Shortcomings in the traditional methods and advances in technology led to FOT and its recognition as a breakthrough and enormously valuable data collection method. However, the focus of FOT is generally on human behaviour; it lacks sufficient road information which must be combined with vehicle response and the human behaviour data collected by FOT. This is needed to assess the interactions of contributing factors that affect road safety. Thus the rich, but complicated, data source collected by naturalistic driving requires a novel approach to identify and extract critical road parameters. Moreover, complementing FOT with road data can facilitate better ways to measure, interpret and statistically model the safety risks of the parameters. This will reverse the typical question connected with the FOTs: "What was the road section where the driver behaved in a certain way?" to "How do drivers behave in critical road sections?"

In light of the traffic safety situations highlighted earlier, their respective research gaps and associated solutions, the main objective of this thesis is a comprehensive safety evaluation of critical road parameters (CRP) by establishing a relationship between road geometry, vehicle, and driver performance in a system-based approach.

The proposed system is used to examine the safety of road parameters as a whole, rather than waiting for crashes to occur before making an evaluation. Designing an analytical system that is not based on crashes alone requires a sequence of interdependent analytical methods by which CRPs, using crash history, are identified (Paper I), and further analysed using computer simulations (Paper II). In the last step both crash history and simulation were linked to FOT data (Papers III and IV). The approaches are based on three kinds of data sources aimed to:

a) Identify CRP associated with specific types of crashes (Paper I);
b) Simulate and analyse road-vehicle interactions (Paper II); and
c) Develop a tool based on a) and b) that integrates CRPs with vehicle and human data prior to analysis (Papers III and IV).

The thesis work has succeeded in making a comprehensive analysis of CRP. Furthermore, both right and left curves associated with overtaking crashes were identified, as a part of a framework for vehicle-road interaction simulations (Paper I). The simulation study identified and analysed the risk of overtaking and lane changing manoeuvres on curves, after which later acceleration and yaw rate were taken into account as risk indicators (Paper II). Finally, a tool was devised to identify and integrate curve components with FOT data (Paper III) using the variables identified in Papers I and II. The tool was used to extract data related to horizontal curves from FOT data in order to facilitate evaluating road, vehicle and human factors (Paper IV). The main quantitative and empirical findings are discussed in the following sections according to the sequence of the approaches. At the end, the overall contributions, findings and limitations of the thesis work are summarized.

4.1 CRP and crash types

The crash and road information linking approach produced a wealth of data that has been analysed to find road parameters which are associated with most of the crashes collected. The approach developed is relatively cost effective, because the crash data was already available and the road information used was initially collected for planning and road maintenance purposes. Moreover, there were no alternative information sources that could provide data supporting a holistic analysis of critical road parameters and crash type. An analytical method based on human behaviour did not succeed in finding the critical road parameters of Swedish roads (Othman and Thomson, 2007); the method was also time consuming and inefficient. It is not possible, either, to identify CRP of highways using traffic conflict research, particularly given the greater incidence of single-vehicle crashes (Koorey, 2010; Güttinger, 1977).

The specific and relevant findings showed that crashes cluster at curves; thus they are dangerous parts of the road network. This finding was also related to the high crash rate (CR) found on the largest superelevations, because superelevation is associated with curves. However, there were unfavourable results for left curves combined with negative superelevation; this does not provide adequate superelevation needed to counter some of the lateral force induced when a vehicle traverses a curve, especially when design speed is not harmonized with operating speed (Bonneson, et al., 2007) or performing a severe lane change on the curve (Granlund, 2010). The negotiation of curves can be facilitated by providing superelevation through the curve; that is, the side friction required by the vehicle to safely negotiate the curve is significantly reduced (Voigt and Krammes, 1995; Zegeer, et al., 1991). The finding of different crash frequencies between right and left curves and in particular, overtaking crashes were more frequent on right than on left curves. The interesting combination of curves and overtaking has been further discussed in this section and was the base for the road-vehicle interaction analysis (Paper II).

In the studies reviewed, Section 1.2, a broad scope of comprehensive research examines the relationship between specific geometric design features and crash rates; various deficiencies in road geometry parameters were identified. Some studies discussed the effects of geometric road features on driving performance. Topics discussed were horizontal and tangent alignments, sight distance, and other physical features (e.g., number and width of lanes and shoulders). The high crash rate on curves in this thesis was in agreement with all crash analysis studies reviewed (Oxley, et al., 2003; Fink and Krammes, 1995; Granlund, 2010) (Halcrow, 1981; Lamm, et al., 2000; Bonneson, et al., 2007).

The previous studies included investigations of type, rate, distribution and nature of crash history. However, for the most part, data analyses in the studies did not include or connect road geometry parameters with crash type. Few studies focused on the frequent run-off-road crashes on horizontal curves. Thus, the studies lack detailed investigation of radius and, usually, lack crash distribution according to curve direction. Two studies, Halcrow (1981) in UK and Vägverket (2002) in Sweden, identified more frequent single crashes on outer curves than on inner curves; note that outer curves are left curves in Sweden and right curves in the

U.K. The results of these two disagreed with those of this thesis that more run-off-road crashes were found on highway exits that are combined with a right curve. One possible interpretation, however, of run-off-road crashes at small curve radii, highway exits, is the sharp decrease of speed required when driving from motorways onto the exits. Thus, misjudging the speed and a more difficult lane keeping tendency can cause run-off-road crashes in these locations.

Overtaking in curves has not been dealt with previously despite large-scale investigations on curves (Bonneson, et al., 2007; Fink and Krammes, 1995; Dupré and Bisson, 2007; Glennon, et al., 1985; Zegeer, et al., 1991; Neuman, 1992), and on overtaking manoeuvres (Clarke, et al., 1998; Jenkins and Rilett, 2005; Haneen and Tomer, 2010; Hassan, et al., 1996).The closest study was a black spot investigation, of decreasing driving radius that occurs during lane changing in curves, which was theoretical (Granlund, 2010). The lane changing studies included crash databases, driving simulators, field observation, and analyses. However, almost all the studies reviewed were associated with two-lane roads with oncoming traffic, focusing on passing distance and head on collisions.

The previous studies lack analyses of overtaking on separated roads, such as motorways. More surprisingly, there were no studies analyzing lane change crashes (manoeuvres), the frequent and most dangerous crash type, on curves, which are the most dangerous road section. Hence, it is logical to believe that a significant number of overtaking and lane changing crashes occur on curves and that these variables are strongly related. Moreover, due to definition, a lane change crash on a curve could be classified as a run-off-road crash in the databases, when only one vehicle is involved. This can happen, especially, when there is insufficient information about the crashes mechanism. Thus, the findings that relate overtaking crashes to both curves and curve directions in this thesis (Paper I) are unique ones that can contribute to improved safety.

The overall findings report how road safety analyses benefit from linked databases. When all of the information related to curves is combined, the increases in CR on curves suggest that a combination of driver behaviour (overtaking, interpretation of road environment) and road characteristics needs to be taken into account for road design. It is important to consider more than the number of crashes occurring at curves and to include the crash type in an investigation of road safety.

Crash analysis is a reactive method which does not necessarily take into account specific road design flaws that may exist (Lee and Mannering, 1999). This often makes it hard to assess the comparative safety of a particular road feature from historical crash data alone (Koorey, 2010). However the crash data findings (Paper I) were complemented with road information, which allowed the identification of the overall road feature problems including crash type. This facilitates and contributes to selecting suitable countermeasures, when the results are combined with more specific data sources (Paper II and Paper IV).

The crash analysis, however, at the highest level of aggregation, fulfilled the aim of this part of the present thesis by presenting the CRPs and overtaking crashes in a framework to facilitate analysis the complex relationships between the drivers, road and vehicle motions during overtaking. The CRPs identified were curve direction, radius, superelevation and friction (Paper I). These road features were given priority in vehicle-road simulations (Paper II) where the interaction of the road features with vehicle manoeuvres was discussed;

Section 4.2 also discusses this to better understand the effect of CRP on vehicle motion signals related to safety.

4.2 Road-vehicle interaction

The design of the empirical simulation conducted in order to model the vehicle-road interaction (Paper II) was based on the framework given in 4.1 (Paper I). The crash data analysis showed that both crash rate and overtaking crashes are affected by curve direction, radius, superelevation and friction. Overtaking, modelled as a double lane-change, was chosen for further investigation on curves, rather than single crashes, despite the severity and higher frequency of single crashes in 4.1 (Paper I). Double lane-change manoeuvres produce more peaks in critical vehicle dynamic responses (Heydinger et al., 2002); the double lane-change manoeuvre modelled in the simulations includes single lane-change scenarios on the left and right curves. Moreover, lane changing in curves can cause single crashes, which is a common type on curves (Vägverket, 2002).

Full size vehicle dynamic tests are very expensive and time consuming to organize, especially when multiple curve configurations are required. Using a numerical simulation, the PC-Crash program, for predicting the interaction of curve components with the vehicle and the effects of the components to the driving safety, was an effective approach: it identified the design changes that will affect vehicle motions and responses during driving on curves. A major advantage of utilizing the PC-crash program to simulate the vehicle-road interaction instead of other simulation methods, such as driving simulators, is that PC-Crash is commercially accessible software, has a friendly user interface, and that running manoeuvres on different curve configurations is independent of driver variability; the drivers' behaviour is beyond the scope of this thesis. Using driving simulators to predict vehicle handling responses during overtaking can also predict the timing of important vehicle responses during the manoeuvres required (Heydinger et al., 2002). However, using driving simulators for the manoeuvres, as with field tests, is usually driver dependent and requires repeatable data to minimize the effects of driver variability (McAvoy, et al., 2007), given that driving simulators are usually adapted to collect data of human behaviour interactions with the vehicle, road environment, or both.

Simulating and evaluating the interaction of a critical road section (curve) and a complicated manoeuvre (overtaking) has not been reported previously. Accordingly, there was not available track dimension of the double lane-change on a curve. The predefined double lane-change manoeuvre, used in the simulation, was modified to a curve using the ISO 3888 specification that defines a double lane-change along a straight road [ISO, 1999]. The manoeuvre path of all the runs on right and left curves were identical in order to minimize effects of human behaviour. Thus, the simulation did not account for the human behaviour in terms of speed or driving path. The speed and driving path were predefined; the vehicle followed as well as the desired path the vehicle and driver model allowed.

Specific outcomes of the simulation showed that the factors which affected lateral acceleration on both right and left curves were speed, road condition (friction) and their interaction. These results are significant safety factors: they indicate that vehicle motions are sensitive to these features of the curve geometry, regardless of curve direction, and they could be explained by the basic performance of the vehicle dynamics (Paper II).

The road factors that affected only right curves were radius and the interaction of radius with road condition, while left curves were sensitive to superelevation. These shows there are different vehicle response configurations depending on curve direction and manoeuvre path. Moreover, left curves were sensitive to radius when initiating overtaking (leaving initial lane), while right curves were sensitive to radius when returning to the initial lane as shown Figure 3 (Paper II). This rapid change of lateral forces through the curve is a result of the vehicle experiencing a transient “curve radius” much smaller than that indicated by the curve design radius. This can generate higher lateral force than the road design code has applies to (Granlund, 2010), which may reach or exceed the limit condition for the vehicle.

The outcome of the simulations explained how curve components (radius and direction, superelevation, friction) affect vehicle responses during overtaking and lane changing manoeuvres in both curve directions. The effect of road parameters on vehicle motion, in terms of lateral acceleration and yaw angular velocity, during manoeuvring on right and left curves was significantly different. Thus, operating risk during lane change was dependant on curve direction and on where in the curve the lane changing occurs. Furthermore, the simulation showed how variations in radius reduced safety of overtaking. This occurs not only when returning to the initial lane on right curves, but also when leaving or completing return to the initial lane in left curves. The increase of lateral acceleration due to decreasing radius during overtaking (Granlund, 2010) may contribute to the frequency and severity of overtaking crashes (Clarke, et al., 1998)

The traditional methods used in 4.1and 4.2 (Papers I and II) analysed overtaking-curve interaction together with crash type and CRP connection, which yielded some new outcomes and useful necessary research findings. However the findings need to be incorporated and linked to a more extensive system approach in order to include human behaviour data that was predefined in the PC-Crash simulation. Thus, the risk factors identified in the controlled experiment were included in naturalistic driving, which is discussed in the following section. The interesting variables and factors that were identified and incorporated in FOT were: operational speed, lateral acceleration, yaw rate, lane changing manoeuvres, curve radius and direction, and speed-limit. Road surface condition is an essential factor that is not explicitly addressed in FOT. However, an initial attempt using FOT data succeeded in estimating and including road surface friction taken from precipitation sensors, which is discussed in Section 4.3.3. Estimating superelevation, however, was not possible from the available data; hence it was not included in the FOT analyses. Up and downgrade factors were included, although they were excluded in the simulations, since they probably affect the drivers’ behaviour and strategy during driving on curves.

The safety management process described above led to a system in which traditional analysis approaches and naturalistic driving are combined. Thus, although traditional approaches are useful and have been important in lowering vehicle-related crashes, it is reasonable to believe that the next significant crash reduction will require system approaches. Focusing only on linear cause and effect approaches, as in the traditional methods, does not give a whole picture of road deficiencies combined with other relevant traffic safety factors.

4.3 The safety of horizontal curves

The comprehensive safety evaluation of curves conducted was based on the results introduced by the crash analysis (Paper I) and computer simulations (Paper II) described in Sections 4.1and 4.2. The results employed the more extensive FOT data when evaluating road curves. This was done by, first, providing FOT with a tool to identify curves and lane changing manoeuvres (Paper III) and, second, by extracting and analyzing the various types of data associated with the curves (Paper IV).

The empirical approach developed (Section 3.3 and Paper III) yielded a procedure to obtain the data flow from vehicle to analysis. The analytical tool identifies horizontal curves from FOT data, then extracts the data and presents it on a common axis. The process includes plotting roads and collecting trips, locating the curves, estimating the curve radii, and identifying the start-end points of the curve path. The tool was used successfully to extract 96 curves from FOT data for safety evaluation (Paper IV), including their components. The evaluations are based on vehicle responses, which are driver inputs controlling the vehicle's lateral acceleration, yaw rate, and speed. They also identify lane changes in the curves. The specific findings are discussed in the following sections.

4.3.1 Lateral acceleration and yaw rate

Lateral acceleration and yaw rate were considered vehicle responses relevant to driving safety as a risk index during driving, where safety is assumed to be inversely related to the vehicle responses (Reymond, et al., 2001; Leonard, et al., 1994). The results showed that lateral acceleration and yaw rate increased with decreasing curve radius, which means increasing driving risk with decreasing curve radius (Paper IV). This result was in line with the results of both the crash history analysis (Section 4.1 and Paper I) and the simulation results (Section 4.2 and Paper II); as well with all previous studies reviewed. A more interesting result, however, was when the risk was found to be unequal along the curve length, i.e. between curve segments. The highest record of lateral acceleration and yaw rate was observed at the curve entrances, in comparison with to middle and exit segments of the curves. This result was valid for all radius groups in both travel directions (Paper IV). The novel result that curve entrance is more dangerous than the rest of the curve cannot be determined by crash analysis or controlled experiment approaches. Crash locations from police information (recorded at the time of the crash) are not always precise (Sjölinder, et al., 1997; Jamil, 2006; Oppe, 1994; Alluri, 2010). Moreover, the road factors contributing to the crash could be few hundred meters before the crash location, or there is simply not enough crash data to analyze a specific road section. In controlled experiments such as simulations, driver inputs are usually predefined or subjected to high experimental control, as in volunteer and simulator driving.

Lateral acceleration, by definition, is directly dependant on speed squared and inversely dependant on curve radius. The results showed that the mean speeds along curve segments were not significantly different for the same radius group. This suggests that the only factor that most likely affected change of lateral acceleration along the curve segments is the path radius, i.e. flattening the radius along the curve to maintain the same speed. However this is inconsistent with many studies which attempted to reduce the lateral acceleration required by introducing countermeasures to lower velocity along the curve, assuming that the radius of the curve is constant (Carlson, et al., 2004; Srinivasan, et al., 2009). The effect of reducing driving radius, by steering, rather than speed, was validated when path radius was calculated using the recorded speed of operation and lateral acceleration (Paper IV). The results of the calculation are revealed in Figure 8 where the variations of path radius are plotted along the curve segments for all four radius groups that were estimated from change in heading. This confirms that despite the same speed along the curve, entrances are still the most dangerous part, followed by the middle segment with a slight increase of radius, and then a sharply increasing radius in the exit segment. There is an exception for small radius curves, R < 400, for which the change of path radius was not extreme along the curves, but still followed the same pattern as for the large curves. Lane change manoeuvres influence the calculated driving radius when they influence the mean lateral acceleration of a curve segment. Lane changes were observed at different positions along the curve, which minimizes the effect of lane changing on the global average in lateral acceleration for each curve. In addition lane change manoeuvres were present in 10% of the total trips. Thus, it was assumed that lane change manoeuvres did not significantly affect the radius estimations.

The curves were treated as simple (constant radius) when using the change in heading, Section 2.3, to estimate their radius; in the calculation using lateral acceleration and speed, Figure 8, the driving radius along the curves was not constant. The curves were assumed to be simple in the initial data mining procedure, because most horizontal curves on the road network are simple (Donnell, et al., 2009). This was needed to facilitate the initial identification of curves in the database. The heading was used to find the radius, which is not sensitive to small changes in the driving radius, when the physical curve is simple. However lateral acceleration and yaw rate are sensitive to radius; they were used to calculate the radius and to find the driving path based on measured lateral acceleration.

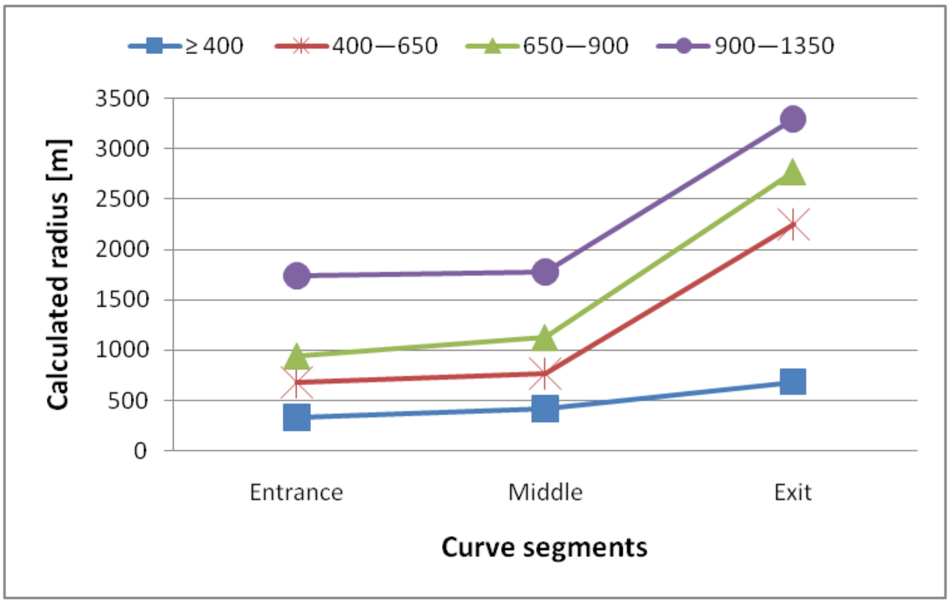


Figure 8. Calculating radii along curves using recorded lateral acceleration and speed

The earlier results of travel direction from the crash analysis suggest that right curves are more dangerous for all radius groups (Paper I). A possible reason is that right curves are inner curves; they have smaller radii than associated (reverse direction) left curves, which increases lateral acceleration. The speed on left and right curves was the same, within 0.5 km/h, which makes it less likely that speed caused an increased risk of right curves. However, higher lateral acceleration on right curves (Paper IV) could partially be explained by the more frequent overtaking crashes (Paper I). Moreover, the 20 % greater lane change manoeuvres observed on right curves (Paper IV) should also be considered in relating this study to the crash history analysis (Paper I). This indicates that drivers tend to change lanes (i.e. overtake) more often on right curves, which could be a reason for higher representation of the overtaking crashes on right curves. The result of higher lateral acceleration on right curves, however, was inconsistent with two other crash analyses (Vägverket, 2002; Halcrow, 1981); these found more frequent single crashes on outer curves which may be due to incomplete crash causation data in the previous studies.

It should be noted that the radius groups, generally, follow the same pattern in terms of lateral acceleration, yaw rate and radius recalculation (Figure 5 and Figure 8 and Paper IV). This makes it theoretically possible to form new radius groups with corresponding vehicle responses by interpolating available results.

A limitation in discussing lateral acceleration and yaw rate is that superelevation was not included however it is an important safety in the design of curves (Papers III and IV). Superelevation is not included in the national road database (NVDB) which is connected to the FOT database. The Pavement Management System (PMS), as an external source, could have been used but this would have been too time consuming especially in light of FOT's data confidentiality. However, the effects of superelevation are implicitly included in terms of lateral acceleration and yaw rate outputs. Moreover, it is assumed that superelevation of left and right curves is constructed according to the design norms.

Horizontal curves as a whole are viewed as problem road sections, hence, countermeasures such as enhancing delineation are usually implemented along the whole curve (Srinivasan, et al., 2009). The records of highest lateral accelerations were noted at the entrance of curves in this thesis work. The finding of variations in lateral acceleration along curves (Paper IV) is a step forward in evaluating the risk when designing curves. The safety risk (lateral acceleration) during designing curves is currently considered constant (study state turn) along a curve constant radius (Wong, 2001). The findings are more important in selecting countermeasures to improve the safety of curves, such as providing chevrons or enhancing delineation as well as improving road design by increasing friction and improving banking of the critical sections of the curves.

4.3.2 Lane changing manoeuvres

The tool developed to identify lane change manoeuvres automatically from lane offset records is an important finding of this thesis (Paper III). Lane offset is an output of a specific camera signal which is used to warn the driver when the vehicle approaches the lane edges, LDW (i.e. Lane Departure Warning/Assist). Moreover, identifying lane changing was essential in order to connect the results with overtaking crashes (Paper I) and overtaking simulations (Paper II) in curves (Sections 3.1 and 3.2). The results showed that drivers changed lanes 20% more often on right curves than on left curves (Paper III). This driving phenomenon was not further investigated; however, a possible reason for it could be that the driver experiences much lower lateral acceleration during lane changing at the entrance and end of curves for left curves, as shown in Figure 3. Another interesting finding was more frequent lane changes as the curve radius increased (Paper IV), which could be cutting the curves to increase the radius or simply changing lanes due to overtaking. This is the opposite of what was known previously. For example Felipe and Navin (1998) found that, for curves with large radius, the drivers followed the centre of the lane in both directions. However, for smaller radius curves, the drivers "cut" the curves in both directions. To minimize the speed change, the drivers "flattened out the bends" by driving on the shoulder or in the other travel lane (Felipe and Navin, 1998). The reason for a higher lane changing rate on larger radius curves (Paper IV) due to the fact that larger radius curves are associated with motorways that are wider roads with multiple lanes which simplify lane changing. Moreover, no oncoming traffic on such roads increases the possibility for lane changing. Previous investigations of overtaking manoeuvres focused mostly on two-way roads (Haneen and Tomer, 2010; Clarke, et al., 1998; Jenkins and Rilett, 2005; Jones and Heimstra, 1966; Hassan, et al., 1996) despite the higher severity of all types of crashes on high speed-limit roads, such as multiple lane highways (Prato, et al., 2010). Crash investigations on high speed-limit roads identified fatal single crashes, especially on outer curves (Vägverket, 2002) without addressing the possible contribution of lane changing, which could be the reason underlying some of the fatal run-off-road crashes on curves. That more overtaking crashes are related to right curves was identified in the crash investigation (Section 4.1 and Paper I); this was attributed either to human factors, i.e. poor visibility and shorter sight distances when overtaking in right curves, or to a higher lateral force, during lane changing, than the curve design code allowed for, i.e. a vehicle-road factor. However, neither human behaviour nor vehicle-road factors data are given in available crash databases to explain the reasons underlying higher overtaking crashes on right curves.

The simulation results in Section 4.2 showed how the risk of overtaking is added to the already existing risk of driving along curves for which a high risk was found during lane changing in the middle of right curves. The simulation (Paper II), for its part, lacks human behaviour and accurate lane changing scenarios. This shows the importance of a system approach in which all relevant results are combined (Papers I-IV). The FOT analysis (Papers III and IV) showed how frequently lane changing occurs with respect to curve radius and direction. The overall results suggest that human behaviour factors, 20% more lane change in right curves (Paper IV), poor visibility and shorter sight distance together with higher lateral force during a lane change could explain the more frequent crashes on right curves. Why drivers change lanes, as mentioned, has not been included in the analysis, since it is beyond the scope of this study. However, the higher speed of trips with lane changing than without, though not especially significant, is an indicator that one of the reasons is to maintain a higher speed. The video films of the lane changes were identified and separated in the data collection process. The films need to be further analysed in order to better understand the mechanism and driver behaviour for the lane changes. For example, the data includes relative speed, distance to the vehicle ahead, and the possible approach of a vehicle from behind. This additional data can be used to study the interaction of the vehicle with other road users. However, automatically noticing a vehicle ahead in curves is more difficult when the viewing angle view of the sensors is limited. Based on the results of a variety approaches, it is reasonable to investigate countermeasures that could be used to improve curve safety and decrease the rate of overtaking and lane changing crashes in curves with high speed-limits.

4.3.3 Speed

The speeds along curve segments of the same radius groups did not differ, which confirms that the variations in driving path radius along curves are the main contributor to significant differences in the risk level along the curves in terms of vehicle responses. This is consistent with a study which found energy and side friction measures are better indicators of curve risk than the speed measure (Bonneson, et al., 2007). Constant speed along the curve (Paper IV) was in line with reports indicating that drivers slow their speed in the tangent to an acceptable speed before entering a curve (Bonneson, et al., 2007; Glennon, et al., 1985).

The speed choice behaviour of drivers in curves was related to the curve radius rather than the speed-limit (Paper IV). The speed choice could be an adjustment of their perceived lateral acceleration according to a dynamic safety margin (Reymond, et al., 2001), and/or the drivers simply predict radius and severity of the curves from foresight and select a suitable speed accordingly (Odhams and Cole, 2004). The results are consistent with a study that observed speeds on horizontal curves routinely exceed designated design speeds (Donnell, et al., 2009). It also in agreement with a study (Torbic, et al., 2004) suggesting that enhanced delineation improves the safety of curves by improving visual cues allowing the driver to recognize the presence and geometry of the curves. The conclusion to use the drivers' curve radius to identify driving speed, rather than speed-limit (Paper IV), is important in reconsidering other countermeasures, such as reducing speed-limits, to improve safety. However, the overall results of driving speed could have been affected by the seasons of the data collection (Nov. 2008 to April 2009). This period is regarded as winter for road maintenance in Sweden (Vägverket, 2004); the average driving speed in winter is more than 11 km/ hr lower than in summer (Wallman, 1997) which means it is also lower than the yearly average. Thus, it is suggested that the speed for the whole year be investigated to improve understating of the speed on curves under different weather conditions.

The expected result of longitudinal acceleration being influenced by vertical grade (Paper IV) is an indicator of data collection quality and accuracy. Furthermore, the grades of the curve pairs matched very well, 94%, in that every downhill right curve was associated with an uphill left curve and vice versa. Only three pairs did not match of which two were close to the threshold limit of the classification, while the other one differed because the start and end points of left and right directions varied significantly causing large differences in curve length between directions. This resulted in variation of inclination degree, as well as radius estimation. However, there was a bias in analysing the grade for the two curve directions: most of the downhill grades were right curves, which means their associated uphill grades were left curves.

The overview of curve speed in this thesis showed that drivers generally maintained the speed chosen when entering the curves. However, the curve speed they chose was higher than the speed-limit for the curves, in relation to the radius (Paper IV). The speed along the curves is the same as that maintained before entering the curve (Bonneson, et al., 2007) which means that reducing curve speed requires measures that enforce drivers to choose lower speeds. Delineation or passive speed control measures, such as markings on the road surface, affect drivers' perceptions, persuading them to slow down (Hancock, 2004). The countermeasures mentioned succeeded to some extent in increasing the safety of curves, in that their principle is in line with the results of this thesis, i.e. suggesting that drivers' choice of speed is based on curve radius and not speed-limit. However, a more optimal solution is to design roads that are "self-explanatory" by providing an image that is in accordance with the actual speed-limit drivers should choose automatically (Martens, et al., 1997).

A limited investigation on a sample of trips was conducting to study the possibility of analysing road condition from FOT data. A sample of travel speed with respect to road condition was investigated; the road condition was estimated from precipitation and temperature information in the database. Windshield wiper activity was recorded in the database and was used to indicate precipitations. Temperature and wiper combinations were used to refine road condition estimates. If the wipers were active, the road condition was considered wet for ambient temperatures above 3° C, while for icy, snowy or slushy roads for temperatures less than 3° C. The roads were considered dry when there was no precipitation indicated by wiper activity. The sample included 410 trips on 10 curves of which 27 (6.5 %) and 15 (3.6%) trips on wet and icy roads, respectively, were identified. The driving speeds on wet and icy roads were, in general, less than on dry roads. However, the statistical significance of the results was not tested due to limited data. The qualitative results also showed that driving under wet and icy road conditions rarely exceeds the corresponding posted speed-limits. Moreover, the maximum driving speed on all of the curves examined was on the dry road surfaces. These results, however, could be biased, in particular because roads were assessed and classified as dry when there was no precipitation. Roads could be wet even without any precipitation during driving time. Moreover, on a sunny day, the roads can be wet due to flowing water from melting snow on the shoulders. The extra cross fall (i.e. superelevation) in the curves could increase the water flow which may also freeze during falling temperature at night. The roads could be slippery and icy, without rain or snow, due to frost when the road surface temperature is lower than the dew point temperature or due to snowdrifts when it is windy (Vägverket, 2004). Validating the actual road condition from video films may not be accurate especially in darkness and in case of frost. Thus, a more direct measurement of road conditions needs to be integrated into the FOT databases to find more accurate correlations of road condition on speed. Road condition data can be improved by combining the time of driving with the reports of road weather stations which are used for winter maintenance (Vägverket, 2004). Drivers usually adapt their speed to the appearance of the road surface rather than to the friction condition during winter time (Wallman and Åström, 2001). Similar roadway appearances may have different friction values and vice versa, which introduces classification problems. Further work is needed to develop a continuous road surface monitoring of conditions for future improvement of safety.

The overall finding in this thesis showed that a variety of data sources and approaches can be used to assess the safety of horizontal curves (Papers I-IV). However, a considerable limitation, which was encountered in analysing speed, lane changing manoeuvres, and lateral acceleration, was that the effects of curves before or after the curve of interest were not taken into account in the curve safety analysis using FOT data.

4.4 Summary

The several data sources and analytical approaches included in this thesis work were linked and integrated to evaluate the safety of CRP by taking into consideration vehicle responses and human behaviour (Figure 9). The overall approach progressed from an open-ended analysis of crash data (Paper I) to the more specific analysis of road curves (Papers II – IV). The crash data analysis was conducted at a strategic level, with a limited amount of detail as the first layer in a top-down process (Paper I) followed by a simulation to test vehicle-road interaction (Paper II). While results of the crash data and simulation were important findings, further studies were needed to completely define the issues. Thus, the results were incorporated in the more comprehensive and accessible FOT data (Paper III and Paper IV). The function of dependency and linking the approaches (Papers I – III) are described in a model shown in Figure 9. The figure shows how crash data provides a general foundation of critical road parameters (Paper I) for the simulation analysis. This further refines the crash investigation results and adds vehicle signals (Paper II) which were missing from the crash data. In the next step the simulation results are translated to real-life data by using natural driving data using FOT (Paper III). The FOT analysis, which was based on the findings of the crash and simulation analyses, facilitated evaluation of driving risk and of modelling driving manoeuvres on horizontal curves (Paper IV). The outcomes of the FOT analysis inside the triangle (Figure 9) are innovative results which can be used in the applications suggested in Chapter 5. However, further refinement and connection of the results are possible, for example, connecting the horizontal curves analyzed to crash data and identifying the type and frequency of the crashes. Furthermore, overtaking/ and lane change information, including location on a curve and vehicle signals identified from FOT, can be used as input data to further simulate lane changing manoeuvres on horizontal curves.

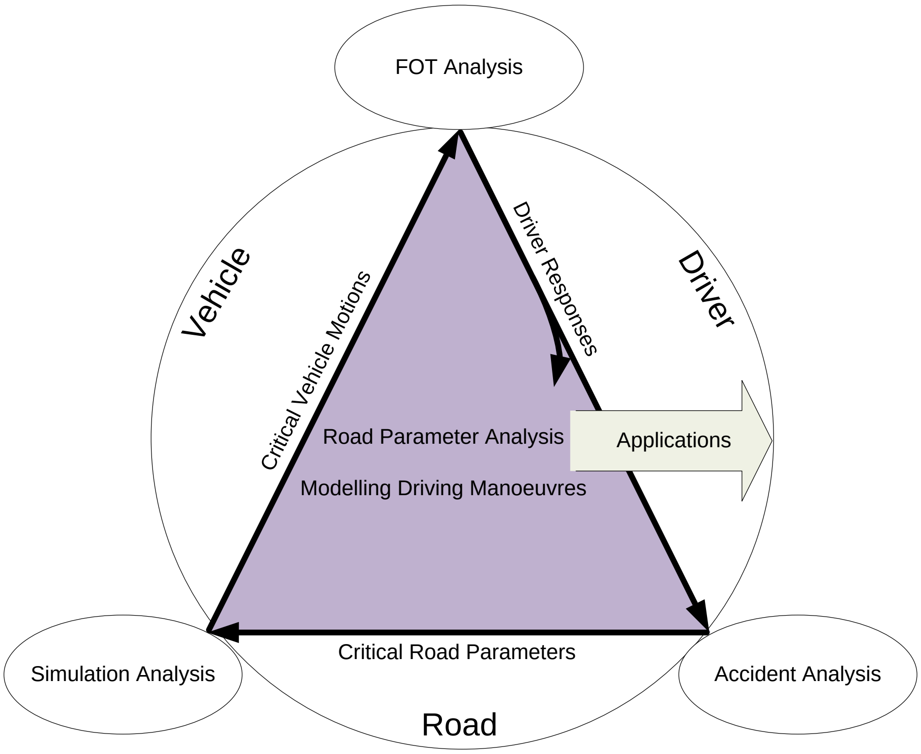


Figure 9. Model of integrating several data sources and using three types of approaches to analyse the safety of CRP, taking into consideration vehicle responses and human behaviour

The crash data analysis (Section 4.1) was an effective method to indentify extensive CRP and corresponding crash types (Paper I). When all of the information related to curves, for example, is combined, the increased crash rate at curves suggested that a combination of driver behaviour (overtaking, interpretation of road environment) and road characteristics needs to be taken into consideration for road design. It is important to take into account more than the number of crashes occurring at curves and to include the crash type in an analysis of road safety. In the crash analysis, overtaking crashes were found to be more frequent on right than on left curves, and the analysis of road width reveals lower crash rates for narrower sections where lane changing may be restricted. The crash analysis alone could not be used to scan the road network to identify and give priority to problem sites. However, the main interesting results of CRP related to crash type are used as a platform to design vehicle-road interaction in the simulation analysis described in Section 2.2 (Paper II).

The simulation analysis identified and examined vehicle responses related to driving safety together with the inputs from crash analysis (Section 3.1). Designing and simulating road-vehicle interactions yielded valuable information on safety risks for lane change manoeuvres on curves. The risk of lane changing was related to the curve direction, segment, and the lane to which the manoeuvre was made. Moreover, it showed that lane changes on left curves are more dangerous in the entrance and exit of the curve, while in the middle of right curves lateral acceleration and yaw rate are highest. The simulations, however, were conducted with a significant degree of control; because driver behaviour was not included, the manoeuvre path was predefined.

Field operational tests (FOT) and naturalistic driving (ND) studies provide extensive datasets for safety analyses. Thus, driver behaviour and vehicle response data are recorded and stored during regular operations, without subjecting the driver to any experimental controls. This approach promoted FOT as a potential dataset for further analyzing safety factors identified in the crash and simulation analyses. However, the FOT lacks road information and is a complex and very large database. To provide road information, access the data, and overcome the data set difficulties, an effective tool was developed that identified curves and extracted the associated data (Paper III). The safety analysis results of the curves collected contributed important findings about the safety of operating on curves, by taking into account road information, vehicle and driver performance. The findings showed the effects of specific curve features on vehicle dynamic responses relevant to safety such as lateral acceleration and yaw rate. Moreover, the analysis facilitated modelling of lane changing manoeuvres with respect to curve radius (Paper IV). The relevance of FOT as data sources and a tool for traffic safety research was demonstrated when developing and implementing a method for the extraction of horizontal curves. Further, interesting results were obtained by combining and analyzing road features and human behaviour, in terms of vehicle responses.

There are other studies that used vehicle, road and driver system approaches to evaluate the safety of road systems and to identify deficiencies. Stigson (2009) evaluated a model, introduced by the Swedish Road Authority (SRA), for a safe transport system. The model represented how road, vehicle and road user should interact to achieve a safe road system. This study found that the model is useful to classify in-depth fatal crashes, but that a more advanced system is needed to identify weaknesses in the road traffic system (Stigson, 2009). The SRA model does not take into account driver behaviour, for example, and it presumes that the drivers comply with the speed-limit as a criterion. However, this was not the case neither in data in this thesis nor in other studies (Wallman, 1997); the speed-limits were not obeyed, in all times, although the data collection occurred during driving in winter time.

A widely used method to evaluate road safety and safety effects in systems is the Empirical Bayesian (Peltola, 2009; Hauer, et al., 2002). This method is used in the Interactive Highway Safety Design Model (IHSDM) to assess the safety and operational effects of road design options. The Empirical Bayesian method improves the precision of road safety evaluation when crash data is limited; it also corrects the regression-to-mean bias. The regression-to-mean bias is useful when a dangerous road section has a low crash history or an assumed safe road section has a high crash record (Hauer et al., 2002). Although the Empirical Bayesian method is based on crash history, it addresses the limited data availability in the crash history. Thus, it can evaluate the current and predicted safety of a road section as a unit; however, the method lacks in-depth analysis of the unit. For example, the safety of a specific curve section could be evaluated using the method, but this would lack detailed information about the other components which may have caused the crashes, such as driving behaviour or vehicle dynamic responses during driving on the curve.

Bonneson, et al. (2007) conducted a comprehensive traffic system approach to investigate driver behaviour, curve geometry components and vehicle dynamics. The study facilitated the formulation of guidelines for a specific curve countermeasure, to bring about effective curve advisory speeds. This system approach overcame the challenge of a uniform advisory speed for curves and was consistent with driver assumptions. The Bonneson et al. study is in line with the conclusion of this thesis that relevant vehicle, road and human components need to be combined in safety evaluations.

Another similar, four stages, long-term study by Macaulay et al. (2004) tried to determine the effectiveness of perceptual countermeasure designs in curves. The study was based on controlled experiments alone (simulation and driving simulator) to identify suitable countermeasures; however field observations were used to test the countermeasure implemented. The four stages included a literature review, simulation validation study using an instrumented vehicle, driving simulator, and the application of the most promising countermeasures with an evaluating of them. The results of the study were not promising after implementing the countermeasures, suggested by the study, to reduce speed along the curves. The treatment used guide posts of ascending heights, towards the outside of the curve (Macaulay, et al., 2004) as shown in Figure 10. Field observations to determine its effectiveness were first conducted after implementing the countermeasure. The observations should have been made before choosing the countermeasure in order to assess the simulation results. Vehicle dynamic responses, an important factor in negotiating curves (Wong, 2001), have not been included in the study even though drivers take lateral acceleration into account when choosing driving speed along curves (Glennon, et al., 1985). A general visual assessment of the photograph shows almost no superelevation in the outer curve to keep the vehicle on the road. Superelevation, however, has not been considered explicitly for the road geometry or implicitly by measuring lateral acceleration. Moreover, the selection of the curves for their study was based mainly on suitability for design of the study and on practical aspects of the observation, although there was not enough crash history to validate the countermeasure. The crashes reported are probably due to speed as a contributing factor, but the reason could be insufficient superelevation. The results of the current thesis showed that the radius of the curve is crucial to speed choice rather than speed-limit.

The reason the guide post countermeasure described had no effect could have been that the speed choice of drivers was already suitable before the countermeasure was implemented. Insufficient crash records to evaluate countermeasures, and the success of similar countermeasures for problem curves in other studies (Srinivasan, et al., 2009), support this theory, especially when the drivers are familiar with the road and are aware of suitable driving speeds. In this type of study, a system approach including the main safety components is required: superelevation, curve and driving radius, familiarity of drivers with the road, vehicle dynamic responses, operating speed, and crash history.

Figure 10 Curve countermeasure adding guide posts to reduce speed (Macaulay, et al., 2004)

The overall safety approach as a system in this thesis progressed in a natural progression of analysis complexity. The development started with a few general results of an crash analysis (Paper I), followed by a simulation of road-vehicle interaction (Paper II), and progressed to more specific findings in the FOT data analysis (Paper III – IV). The three approaches and data sources complemented one another and were effective to fill information gaps. The controlled experiments led to the more specific findings in the FOT analysis; the FOT results could be used as inputs to refine the simulation and crash analyses as a closed-loop in a dynamic system. For example, the lane-change manoeuvres identified in FOTs can be used as input scenarios in the road-vehicle interaction simulation approach. In this manner it is possible to further investigate the variables and results of interest.

5 CONCLUSIONS

The overall objective of the thesis is to improve the understanding of the interaction of the three main traffic safety pillars: environment, vehicle, and human factors, in relation to how safety can be evaluated. Based on the reviews of relevant empirical and theoretical work, a number of specific research questions were posed.

The systematic approach proposed in the thesis made it possible to devise a useful safety tool that enabled the empirical and simulation analyses to generate more informative results when analysing road features. The analytical results provided insight into how road geometry factors affect vehicle motions relevant to safety and driving strategy through curves. The main conclusions of this thesis are listed below.

- Accidents cluster on curves, where overtaking accidents occur more frequently on large radius right curves and more frequent run-off road accidents occur on small radius right curves.
- Overtaking and lane changing manoeuvres are more dangerous on curves than on straight sections; right curves are more sensitive to radius and left curves to superelevation.
- Overtaking and lane changing differ for right and left curves. It is dangerous on left curves when the vehicle is leaving the initial lane and more dangerous on right curves when leaving the overtaking lane.
- Vehicle responses, in terms of lateral acceleration and yaw rate, increase during lane changing manoeuvres in curves; the safety risks were shown to be significantly affected by curve direction and the lane of the of the curve from which the change is made.
- Identifying lane changing manoeuvres automatically in curves can be used to add functions and to improve the Lane Departure Warning (LDW) system.
- Lane changing manoeuvres increase with increasing curve radius.
- Drivers pay more attention to the radius of curves than to speed limits when choosing operating speed in curves.
- The entrances are the most dangerous part of curves.
- A first effort to estimate road conditions indirectly may be possible by using precipitation data available in the field operational test cars.

The road safety investigation in this thesis showed how approaches based on three data collection methods can be combined to design an analytical system for assessing critical road geometry parameters. Accident data, simulation, and field operational test data were linked and used to analyze the safety of road characteristics. The approach integrated the vehicle response and human behaviour data. Matlab tools were used to identify the links between vehicle manoeuvres on curves and accidents, to better understand accident mechanisms. The system, in general, fulfilled all of the thesis research objectives and provided answers to the research questions.

Applications of the new approach include the improvement of curve design guidelines, safer posted speed limits, appropriate selection of countermeasures, and the improvement of active safety devices. More specifically, possible applications include:

- Specifying risk categories in curves and developing guidelines to select reasonable cost curve signing countermeasures, such as curve warning signs, delineation strategies, and curve advisory speeds;

- Checking and improving curve design guidelines, in particular calculating superelevation and curve radius by:
    - Considering overtaking and lane change scenarios on curves instead of just driving along the curves, and
    - Increasing safety at curve entrances and accepting that safety levels are not constant along the whole curve;
- Applying methods to reduce overtaking on existing curves by using road marking to prevent overtaking and lane change, for example;
- Improving guidelines for setting speed limits and monitoring operational speed, in particular, applying the results showing that drivers take curve radius into account rather than speed limit;
- Improving functions such as lane departure warning (LDW) and lane change-merge warning (LCM) to include overtaking in curves by taking into account navigation data in addition to the radar and video camera signals;
- Enhancing data collection by installing the proposed tool, for identifying curve radius and curve ends, in the next generation of FOT vehicles.

6 REFERENCES

Alluri, P. (2010). *Development of Guidance for States Transitioning to New Safety Analysis Tools.* Ph.D. Thesis, Clemson University, No. 3439336. Clemson, SC, USA.

Alonso, M., Vega, H., & Plaza, J. (2007). Human Factors in Road Infrastructure Design: Analysis of Road Layout Influence in Driver Behaviour. *Proceeding: International Conference RSS, 7-8-9th November, 2007.* ARACNE. Rome, Italy.

Baldanzini, N., Huth, V., Regan, M., Spyropoulou, I., Eliou, N., Lemonakis, P., Galanis, A. (2010). *Literature review of Naturalistic Driving Studies.* Deliverable 4, European Commission 7th Framework Project 2-Wheeler Behaviour and Safety, Contract No. 218703

Bärgman, J., & Svanberg, E. (2010). *Sweden-Michigan Naturalistic Field Operational Test (SeMiFOT).* Report No. 2010:05, Data Management. SAFER/ Chalmers University of Technology Gothenburg, Sweden.

Björketun, U. (2003). *Olycksdata och linjeföringsmått.* Report No. 11-2003. Swedish National Road and Transport Research Institute (VTI). Linköping, Sweden.

Blanco, M., Hickman, J., Olson, R., Bocanegra, J., Hanowski, R., Nakata, A., Greening, M., Madison, P., Holbrook, G.T., Bowman, D. (in press). *Investigating critical incidents, driver restart period, sleep quantity, and crash countermeasures in commercial vehicle operations using naturalistic data collection.* Report DTFH61-01-C-00049, Interim Project. Federal Motor Carrier Safety Administration.Washington, D.C., USA.

Bonneson, J., Pratt, M., Miles, J., & Carlson, P. (2007). *Development of Guidelines for Establishing Effective Curve Advisory Speeds.* Technical Report No. FHWA/TX-07/0-5439-1.Texas Transportation Institute.Texas, USA.

Box, G. E., Hunter, J. S. & Hunter, W. G. (2005). *Statistics for Experimenters* (2nd Edn.). John Wiley & Sons. New York, USA.

Cairney, P., & Styles, E. (2006). Macrotexture and Crash Risk – Some Recent Findings from Australia and their Implications. *Preceding: 22nd ARRB Conference Oct. 29 – Nov. 2 ,2006, Research into Practice, Canberra.* Canberra, Australia.

Carlson, P. J., Rose, E. R., Chrysler, S. T., & Bischoff, A. L. (2004). *Simplifying Delineator and Chevron Applications for Horizontal Curves.* Report No. 0-4052-1, The Texas A&M University System. Texas Transportation Institute. Texas, USA.

Carlsson, A. (2009). *Evaluation of 2+1 roads with cable barriers.* Report No. 636. Swedish National Road and Transport Research Institute (VTI). Linköping, Sweden.

Carlsson, G. (2002). *Fatalities in Swedish road traffic*. (Report: The National Society for Road Safety (NTF)) Retrieved 21 Sept., 2011, from The National Society for Road Safety (NTF): http://www.ntf.se/english/pdf/0209Killed%20in%20Sweden.pdf

Choueiri, E. M., & Lamm, R. (1987). *Rural Road Speed Inconsistencie Design Methods: Part I, Operating Speeds and Accident Rates on Two-Lane Rural Highway Curved Sections.* Accession No. 00464581. Department of Civil and Environmental Engineering, Clarkson University, New York, USA.

Clarke, D., Ward, P., & Jones, J. (1998). Overtaking road accidents: Differences in maneuver as a function of driver age. *Accident Analysis and Prevention , 30* (4), 455-467.

Dingus, T. A., Klauer, S., Neale, V. L., Petersen, A., Lee, S. E., Sudweeks, J. P., Perez, M. A.; Hankey, J.; Ramsey, D.; Gupta, S.; Bucher, C.; Doerzaph, Z. R.; Jermeland, J.; Knipling, R.R. (2006). *The 100-Car Naturalistic Driving Study, Phase II – Results of the 100-Car Field Experiment.* Report, DOT HS 810 593. Virginia Tech Transportation Institute, Virginia, USA.

Donnell, E., Hines, S., Mahoney, K., Porter, R., & McGee, H. (2009). *Speed Concepts: Informational Guide.* Report No. FHWA-SA-10-001. U.S. Fedral Highway Administration. Department of Transportation. PA, USA.

Dupré, G., & Bisson, O. (2007). *Safety in curves on urban express roads.* Internal Report for Deliverable 2.1, European Commission 6th Framework Project Ranking for European Road Safety (RANKERS), Contract No. S07.36996/001678.

Elvik, R., Hoye, A., Vaa, T., & Sorensen, M. (2009). *The Handbook of Road Safety Measures* (Vol. II). Emerald Group Publishing, Bingley, U.K.

Felipe, E., & Navin, F. (1998). Automobiles on Horizontal Curves: Experiments and Observations. *Journal of Transportation Research Record* , (1628), 50-56.

FESTA, C. (2008). *FESTA Handbook: Field opErational teSt supporT Action.* Handbook, Deliverable 6.4, European Commission 7th Framework Project FESTA, Contract No.214853.

Fink, K. L., & Krammes, R. A. (1995). Tangent Length and Sight Distance Effects on Accident Rates at Horizontal Curves on Rural Two-Lane Highways. *Journal of Transportation Research Record* , (1500), 162-168.

Fitzpatrick, K., Schneider, W., & Carvell, J. (2006). Using the rural two-lane highway. *Journal of Transportation Research Record ,* (1950), 44-45.

Fullar, R., & Santos, J. (2002). *Human Factors for Highway Engineering.* Emerald Group Publishing. Oxford, U.K.

Glennon, J., Neuman, T., & Leisch, J. E. (1985). *Safety and Operational Considerations for Design of Rural Highway Curves.* Report No. FHWA/RD-86/035. Department of Transportation, Federal Highway Administration. Washington, USA.

Granlund, J. (2010). Safer Curves on Multiple Lane Roads. *Proceeding: Transport Research Arena Europe*. Brussels, Belgium 2010.

Güttinger, V. (1977). *Conflict Observation Technique in Traffic Situations.* Proceedings of the First Workshop on Traffic Conflicts, Transportokonomisk Institutt, Oslo, Norway 1977, pp. 16-21.

Halcrow, F. (1981). *Effects on Safety of Marginal Design Elements.* Report ID 54046000268977, Department of Transport, 1981, Halcrow Fox and Associates, U.K.

Hancock, K. L. (2004). *Passive Speed Control Devices: Speed and Traffic Operations Evaluation.* Report: No. 04-G020-001, Project MassSAFE. University of Massachusetts. Amherst, MA, USA.

Haneen, F., & Tomer, T. (2010). Passing behavior on two-lane highways. *Journal of Transportation Research Part F: Traffic Psychology and Behaviour* , 13 (6), 355-364.

Hanowski, R., Blanco, M., Nakata, A., Hickman, J., Schaudt, W., & Fumero, M. O. (2008). *The drowsy driver warning system field operational test, data collection.* Report: Final, No. DOT HS 810 035. National Highway Traffic Safety Administration. Department of Transportation. Washington D.C., USA.

Harwood, D. W., Council, F. M., Hauer, E., Hughes, W. E., & Vogt, A. (2000). *Prediction of the Expected Safety Performance of Rural Two-Lane Highways.* Report: No. FHWA-RD-99-207. Federal Highway Administration. Department of Transportation. Washington D.C., USA.

Hassan, Y., Easa, S. M., & Abd El Halim, A. O. (1996). Passing sight distance on two-lane highways: Review and revision. *Journal of Transportation Research Part A* , 30 (6), 453–467.

Hauer, E. (2000). *Lane width and safety.* Review of Literature for the Interactive Highway Safety Design Model, Toronto, Canada.

Hauer., E., Harwood, D. W., Council, F. M., & Griffith, M. S. (2002). Estimating Safety by the Empirical Bayes Method. *Journal of Transportation Research Record* , (1784), pp. 126 – 131.

Heydinger, G. J., Salaani, M. K., Garrott, W. R., & Grygier, P. A. (2002). Vehicle dynamics modelling for the National Advanced Driving Simulator. *Journal of Automobile Engineerig* , (216), pp. 307 – 318.

Jamil, S. (2006). *Samband Mellan Trafikolyckor Och Väggeometri.* Master Thesis: 2006:76, Väg och Trafik, GEO, Chalmers Tekniska Högskola. Göteborg, Sweden.

Jenkins, J. M., & Rilett, L. R. (2005). Classifying passing maneuvers: A behavioral approach. *Journal of Transportation Research Record* , (1937), 14–21.

Johansson, Ö. (2004). *Hur uppkommer olyckor på olika vägytetillstånd? En metodrapport som ger en tentativ teori.* Report: VV publikation 2004:75, Swedish Road Administration, Borlänge, Sweden.

Johnston, I. (1982). Modifying Driver Behavior on Rural Road Curves- A Review of Recent Research. *Proceeding: Eleventh Australian Road Research Board Conference,* (4), pp. 5-24. Melbourne, Australia.

Jones, H. V., & Heimstra, N. W. (1966). Ability of drivers to make critical passing judgments. *Journal of Highway Research Record* (122), 89-92.

Koorey, G. F. (2010). *Incorporating Safety into Rural Highway Design.* Ph.D. Thesis. University of Canterbury, Christchurch, NewZealand.

Lamm, R., Beck, A., & Zumkeller, K. (2000). Analysis and Evaluation of Interrelationships between Traffic Safety and Highway Geometric Design on Two-Lane Rural Roads.

Proceeding: 2nd International Symposium on Highway Geometric Design, June 2000, (pp. 557-570). Mainz, Germany.

Leden, L., Hämäläinen, O., & Manninen, E. (1998). The effect of resurfacing on friction, speeds and safety on main roads in Finland. *Journal of Accident Analysis & Prevention* , 30 (1), 75–85.

Lee, J., & Mannering, F. L. (1999). *Analysis of Roadside Accident Frequency and Severity and Roadside Safety Management.* Report: Final, No. WA-RD 475.1. Washington State Transportation Center (TRAC). Washington D.C., USA.

Lee, S. E., Olsen, E. C., & Wierwille, W. W. (2004). *A Comprehensive Examination of Naturalistic Lane-Changes.* Report: DOT HS, No. 809 702. Department of Transportation, National Highway Traffic Safety Administration., Washington D.C., USA.

Leonard, J., Bilse, D., & Recker, W. (1994). *Super-elevation rates at rural highway intersections.* Report: No. RTA-53P434. University of Carolina, Institute of Transportation Studies, DE, USA.

Lum, H., & Reagan, J. (1995). *Interactive Highway Safety Design Model: Accident Predictive Module.* (Vol. 58). Federal Highway Administration. Washington D.C., USA.

Macaulay, J., Gunatillake, T., Tziotis, M., Fildes, B., Corben, B., & Newstead, S. (2004). *On-Road Evaluation of Perceptual Countermeasures.* Report No. CR 219, Accident Research Centre, Monash University. Victoria, Australia.

Martens, M., Comte, S., & Kaptein, N. (1997). *The Effects of Road Design on Speed Behaviour: A Literature Review.* Deliverable D1 Report 2.3.1, European Commission 4th Framework, Contract No. RO-96-SC.202.

McAvoy, D. S., Schattler, K. L., & Datta, T. K. (2007). Driving Simulator Validation for Night time Construction Work Zone Devices. *Proceeding: 86th Annual Meeting of the Transportation Research Board, January 2007, Washington, D.C.* (pp.55 – 63), Washington D.C., USA.

McLean, J. (1981). Driver Speed Behavior and Rural Road Alignment Design. *Journal of Traffic Engineering and Control* , 22 (4), 208-211.

Messer, C., Mounce, J., & Brackett, R. (1981). *Highway Geometric Design Consistency Related To Driver Expectancy.* Report No. FHWA-RD-81-035. Federal Highway Administration. Washington, D.C., USA.

Neale, N., Dingus, T., Klauer, S., Sudweeks, J., & Goodman, M. (2005). An Overview of the 100-Car Naturalistic Study and Findings. *Proceeding: 19th International Technical Conference on the Enhanced Safety of Vehicles (ESV), No. 05-0400.* Washington D.C., USA.

Neuman, R. T., Pfefer, R., Slack, L. K., Council, F., & Mcgee, H. (2003). *A Guide for Addressing Run-off-Road Collisions.* Report: NCHRP, No. 500: Volume 6. Transportation Research Board. Washington D.C., USA.

Neuman, T. (1992). *"Chapter 6: Roadway Geometric Design."* , *Traffic Engineering Handbook,* (4th Edn.). Institute of Traffic Engineers. Englewood Cliffs, NJ, USA.

Odhams, A., & Cole, D. (2004). Models of Driver Speed Choice in Curves. *Proceeding:7th International Symposium on Advanced Vehicle Control, (AVEC 04), 23-27 August 2004,* Arnhem, Netherlands.

Olson, R. L., Hanowski, R. J., Hickman, J. S., & Bocanegra, J. (2009). *Driver Distraction in Commercial Operations.* Report: No. FMCSA-RRR-09-042. Department of Transportation Federal Motor Carrier Safety Administration, Washington D.C., USA.

Oppe, S. (1994). Possibilities and Limitations of Accident Analysis. *Proceeding: 6th ICTCT workshop Salzburg,* (pp. 32 – 47). Institute for Road Safety Research, Salzburg, Austria.

Othman, S., & Thomson, R. (2007). Influence of Road Characteristics on Traffic Safety. *Proceeding: No. 07- 0064, 20th International Technical Conference on the Enhanced Safety of Vehicles (ESV).* Lyon, France.

Oxley, J., Corben, B., Koppel, S., Fildes, B., Jacques, N., Symmons, M., Johnston, I. (2003). *Cost-Effective Infrastructure Measures on Rural Roads.* Report: No. 217. Accident Research Centre, Monash University, Victoria, Australia.

Peltola, H. (2009). Evaluating road safety and safety effects using the Empirical Bayesian method. *Proceeding: 4th IRTAD Conference,* (pp. 307-314). Seoul, Korea.

Prato, C. G., Bekhor, S., Galtzur, A., Mahalel, D., & Prashker, J. N. (2010). Exploring the Potential of Data Mining Techniques for the Analysis of Accident Patterns. *Proceeding: 12th WCTR, July 11-15, 2010.* Lisbon, Portugal.

Reymond, G., Kemeny, A., Droulez, J., & Berthoz, A. (2001). Role of Lateral Acceleration in Curve Driving: Driver Model and Experiments on a Real Vehicle and a Driving Simulator. *The Journal of the Human factors and Ergonomics Society* , 43 (3), 483-495.

Rudny, D., & Sallmann, D. (1996). Analysis of Crashes Involving Alleged Road Surface Defects. *Document Number 960654, SAE International Congress & Exposition.* Detroit, USA.

Sakshaug, K. (2000). *Overhøydens innvirkning på ulykkesfrekvens i kurver.* Report: No. STF22 A00562, SINTEF.Trondheim. Norway.

Sjölinder, K., Velin, H., & Öberg, G. (1997). *Vägytans inverkan på trafiksäkerheten.* Report: No. 67, Statens väg-och transportforskningsinstitut, VTI. Linköping, Sweden.

Srinivasan, R., Baek, J., Carter, D., Persaud, B., Lyon, C., Eccles, K., Gross, F., Lefler, N. (2009). *Safety Evaluation of Improved Curve Delineation.* Report: No. FHWA-HRT-09-045. Department of Transportation. Washington D.C. USA.

Stigson, H. (2009). *A Safer Road Transport System – Factors Influencing Injury Outcome for Car Occupants.* Ph.D Thesis. Karolinska Institute. Stockholm, Sweden.

Stutts, J., Feaganes, J., Rodgman, E., Hamlett, C., Meadows, T., Reinfurt, D., Gish, K., Mercadante, M., Staplin, L. (2003). *Distractions in Everyday Driving.* Retrieved September 21, 2011, from AAA Foundation for Traffic Safety: http://www.aaafoundation.org/pdf/distractionsineverydaydriving.pdf

Tholén, E. (1999). *Trafikolyckor före och efter beläggning. Beläggningsår 1995 och 1996.* Report: TR80 99/237,VVÄ.Vägverket Region Väst. Göteborg, Sweden.

Torbic, D. J., Harwood, D. W., Gilmore, D. K., Pfefer, R., Neuman, T. R., Slack, K. L., Hardy, K. (2004). *Guidance for Implementation of the AASHTO Strategic Highway Safety Plan: A Guide for Reducing Collisions on Horizontal Curves.* Report: NCHRP 500.Transportation Research Board. Washington D.C., USA.

Vägverket. (2008). (Retrieved June 5, 2008, from Vägverket Web Site, Trafiksäkerhet. Skade- och olycksstatistik: www.vv.se

Vägverket. (2004). *Vägverkets ersättningsmodell för vinterväghållning.* Retrieved September 21, 2011, from http://www.trafikverket.se/PageFiles/30411/vagverkets_ersattningmodell_for_vintervaghallning.pdf

Vägverket. (2002). *Analys av singelolyckor med dödlig utgång på det statliga vägnätet, exklusive motorvägar 1997-2000.* Publication: 2002:109. Vägverket. Borlänge, Sweden.

Velin, H., & Öberg, G. (2002). *Analys av trafikolyckor före och efter beläggningsåtgärd.* Report: No. 929, Statens väg-och transportforskningsinstitut (VTI), Linköping, Sweden.

Victor, T., Moeschlin, F., Bärgman, J., Grönvall, J.-F., & Gellerman, H. (2008). *Test Site Sweden Field Operational Test (TSS)* . Report: SAFER 2008:1, Göteborg, Sweden.

Victor, T., Moeschlin, F., Hjälmdahl, M., & Ahlström, C. (2010). *Sweden-Michigan Naturalistic Field Operational Test (SeMiFOT). Evaluation of Methodology.* Report: Safer2010:06, Göteborg, Sweden.

Voigt, A., & Krammes, R. (1995). An operational and safety evaluation of alternative horizontal curve design approaches on rural two-lane highways. *International Symposium on Highway Geometric Design Practices, Aug. 30 - Sept.1, 1995, Boston, Massachusetts*, (11:pp.1-8).

Wallman, C. G. (1997). *Driver Bheaviour on Winter Roads, a Driving Simulator Study.* Report: No. 419A. Statens väg- och transportforskningsinstitut (VTI), Linköping, Sweden.

Wallman, C., & Åström, H. (2001). *Friction measurement methods and the correlation between road friction and traffic safety. A literature review.* Report: No. 911A, Swedish Road and Traffic Research Unit, Linköping, Sweden.

Ward, N., Linkenbach, J., Keller, S., & Otto, J. (2010). *Traffic Safety Culture - White Paper.* Western Transportation Institute. College of Engineering Montana State University. Helena, Montana, USA.

Wegman, F. (2010). *IRTAD: International Traffic Safety Data & Analysis Group.* Report: IRTAD Annuall 2010, OECD/ITF 2011. Retrieved 20 Sept., 2011, from The International Transport Forum: http://www.internationaltransportforum.org/irtad/pdf/10irtadreport.pdf

Wong, J. Y. (2001). *Theory of ground vehicles.* (2nd Edn.). Department of mechanical aerospace engineering. Ottawa, Canada.

Zegeer, C., Stewart, J., & Reinfurt, D. (1991). *Cost effective geometric improvements for safety upgrading of horizontal curves.* Report: No. RD-90-021, Federal Highway Administration. Washington D.C., USA.

Zein, S. R., & Navin, F. (2003). Improving Traffic Safety: A New Systems Approach. *Journal of Transportation Research Record* , (1830), 1-9.

Paper I

Identifying Critical Road Geometry Parameters Affecting Crash Rate and Crash Type

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ABSTRACT – The objective of this traffic safety investigation was to find critical road parameters affecting crash rate (CR). The study was based on crash and road maintenance data from Western Sweden. More than 3000 crashes, reported from 2000 to 2005 on median-separated roads, were collected and combined with road geometric and surface data. The statistical analysis showed variations in CR when road elements changed confirming that road characteristics affect CR. The findings indicated that large radii right-turn curves were more dangerous than left curves, in particular, during lane changing manoeuvres. However sharper curves are more dangerous in both left and right curves. Moreover, motorway carriageways with no or limited shoulders have the highest CR when compared to other carriageway widths, while one lane carriageway sections on 2+1 roads were the safest. Road surface results showed that both wheel rut depth and road roughness have negative impacts on traffic safety.

Keywords**:** Traffic Safety, Crash Analysis, Road geometry, Road Surface, Curve safety, Crash Data.

INTRODUCTION

Road safety engineers are faced with the challenge of addressing safety issues within the three major traffic safety pillars: human, vehicle, and infrastructure performance. All three aspects must be part of a traffic safety plan and dealt with subject to budget limitations. Consequently, the cost efficiency of systems and countermeasures are decisive factors for policy making.

The European Commission (EC) funded the RANKERS project (Ranking for European Road Safety) in the 6th Framework Research Program. The ambitious objective of this project was to develop scientifically-researched guidelines enabling optimal decision-making by road authorities in their efforts to promote safer roads and eradicate dangerous road sections. It was also designed to gain new knowledge by performing research and empirical studies of the road's interaction with the driver and their vehicle in order to identify road design recommendations and predict their impact on safety. The main output of the project included an index used for assessing and monitoring road safety and a comprehensive catalogue of road infrastructure safety recommendations ranked according to their cost-effectiveness [RANKERS project, 2008].

The crash analysis discussed herein was a part of the RANKERS project and its main purpose was to find dangerous road parameters and variations of crash types on them. This was achieved by defining a methodology to better understand road characteristics that leads to traffic crashes. The crash analysis conducted was a further investigation of the data collected to find out the influence of road geometry characteristics on crash rate [Othman, 2007]. Thus, studying and analyzing crashes data on selected roads was the starting point to determine black spots. A post-crash approach was the method used in this paper to find correlations between road geometry parameters and crash rate. Furthermore the analysis examines the types of crashes that were most influenced on the critical road parameters.

PREVIOUS STUDIES

The primary objective in the reviewed literature was to find road parameters describing road sections that can be linked to traffic crashes. Analyzing available crash data has been the starting point in the most of the investigations reviewed [Ihs et al, 2002], [Sjölinder et al, 1997], [Johansson, 1997], [Hemdorff et al, 1989]. However, the crash databases are not always complete and they lacked essential information such as non-reported crashes (crashes that are never reported to crash databases) or missing crash location information **[**Tholén, 1999], [Jamil, 2006]. In the USA, Fink el at. (1995) showed that the degree of curvature is a good predictor of crash rate on horizontal curves. Although the effects of approach tangent length and sight distance were not as clear, the results suggest that the adverse safety effects of long approach tangent lengths and short approach sight distances become more pronounced on sharp curves [Fink el at, 1995]. A study by CETE (1995) revealed that super-elevation, in combination with sharp curves, is the main factor of crashes on motorway access ramps. However, Sakhaug (2000) disagreed and claimed the opposite, stating that there was a tendency towards higher crash risk for curves with high super-elevation than with low super-elevation. Furthermore, Sakhaug found that the crashes are related to the operating speed of the vehicle in the curves: high super-elevation – higher speed and higher risk; low super-elevation - lower speed and lower risk.

According to a Swedish study [Nilsson, 2000] reviewing the influence of speed, there is an obvious improvement in traffic safety when speed limit is reduced. In another study in the northern part of Sweden by Brüde el at, (1998), reducing the speed limit from 110 to 90km/h resulted in a positive effect in terms of fatality rate, injury severity, and number of police reported crashes. Conclusions of effects of the road surface on traffic safety were different among researchers, rougher roads with high friction result in better traffic safety from a vehicle dynamic perspective [Cairney el at, 2005], [Rudny el at, 1996). While Wallman el at, (2001) believe that low friction lead to better safety since the drivers adapt their speed when it is obvious to the driver that the road surfaces are slippery, such as wet or icy surfaces.

Although previous research has identified the influence of road section characteristics on crash rate, a clear understanding of the issues was not found. In some cases, super-elevation for example, there are conflicting opinions. Therefore a more detailed investigation of the problem was initiated to determine if infrastructure or vehicle related factors for the crashes could be identified. Furthermore, the results of previous studies were generally on number of crashes and crash rates and they do not include crash type. Thus, a study that also investigates the relation between crash type and road geometry parameters would be a contribution to our understanding of traffic safety on motorways.

OBJECTIVE

The primary objective of this study was to find dangerous road parameters affecting the crash rate and crash type. This was to be investigated by using existing crash and road maintenance data stored by the road administration, police and hospitals. To further investigate the possible mechanisms for the crashes, the crash type distribution for the identified dangerous road parameters were also studied to assist in identifying appropriate strategies for countermeasures.

METHODOLOGY

An analytical method was developed for integrating existing crash and maintenance data to enable identification of unsafe road geometry parameters and corresponding crash type. The crash data was reported by police and hospitals while maintenance data was from the maintenance routines for the Swedish Road Administration (SRA). The crash data analyzed was limited to personal injury crashes, while the road type of investigation was limited to median-separated public roads in the western region of Sweden. The period of investigation was 6 years (2000-2005). The analysis was carried out in four phases: 1- Collecting crash data, 2- Collecting road characteristics data, 3- Locating crashes and combining them with the road data, 4- Analyzing collected-combined data.

Roads in the Western Region district of Sweden have been chosen for the investigation as analysts from the regional office were involved in the analysis. The weather variations within the district are comparable with other regions in Sweden and the amount of traffic on the selected public roads represents 36% of the total Swedish traffic flow. Specific road types were targeted to fulfil the RANKERS project guidelines, which focused on public divided roads. The total length of the selected roads in 2005 was 810 km including 480 km motorway (Figure 1), 170 km 2+1 roads (Figure 2 and Figure 3), 97 km dual carriageway (4-lane road) as shown in Figure 4, 47 km 2+1 semi-motorway and 15 km semi-motorway[*].

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[*] Semi-motorway in Sweden is roads with only 2 or 3(2+1) lanes but the same traffic conditions apply as motorways (i.e. grade-separated crossings, no slow traffic) [Motorways, 2006].

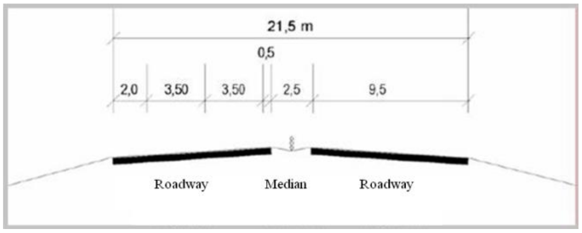

Figure 1 Cross section of a standard motorway in Sweden

The 2+1 road is a Swedish concept of converting unsafe rural motorways to '2+1' roadways. In this configuration, a passing lane is created in the centre of the road between the opposing travel lanes, and is used a passing lane that alternates about every 1 to 1.25 km between the row directions of travel (Figure 2 and Figure 3).

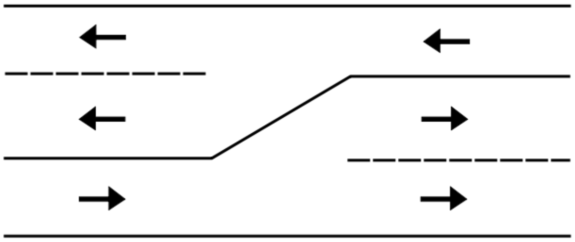

Figure 2-Top view of a "2+1" road in Sweden

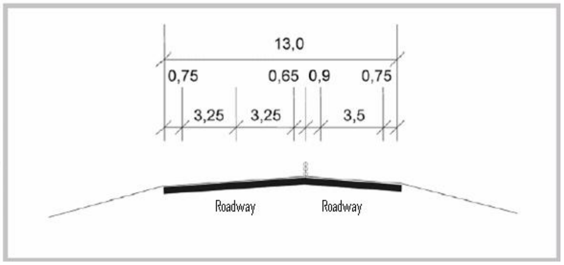

Figure 3-Cross section of a '2+1' road

The 4-lane roads (Figure 4) are dual carriageways with separated 2-lanes in each direction, but they are not motorways due to the presence of on-grade intersections.

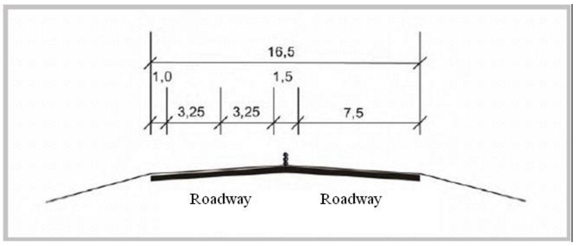

Figure 4- Cross section of a "4- lane road" road

Crash data have been collected from two national crash databases, OLY (Crash Database) and STRADA (Swedish Traffic Accident Data Acquisition). Both databases contain only personal injury crashes. OLY contains crashes based on police reports until the end of year 2002 when OLY was replaced by STRADA which is based on reports from police and hospitals to minimize loss of crash data. The hospital data provides a better picture of the injuries severity degree [STRADA, 2006]. The crashes known by both the police and hospitals are matched in the database.

In 2000-2005, a total of 3599 road traffic crashes involving personal injury (including fatal, severe and slight injuries) were reported to the databases for the roads of interest. The crashes involved all vehicle types. Of these, 690 crashes have been excluded due to missing road geometry information at the crash location or non-criteria crashes such as wildlife crashes, property damage only crashes and crashes that were registered twice. After removing crashes that had not occurred on relevant roads and those that occurred before the road's opening day, a total of 1057 crash have been collected from OLY, while 1855 crash were collected from STRADA.

Sources used to collect parameters describing the road data were the Pavement Management System (PMS) and the national road database (NVDB) databases. Both systems are owned and maintained by the SRA. The PMS contains data for the road and its surface condition to identify optimum maintenance repairs and rehabilitation activities. However it must be emphasized that the purpose of the PMS system is not explicitly for safety analyses. To take advantage of the database for traffic safety purposes, measurements at crash locations have been extracted and recorded together with the crashes for further analysis. The chosen parameters are speed limit, carriageway width, curvature, super-elevation, wheel rut depth, road surface roughness and grade. The use of NVDB in this study was limited to the speed limit for OLY crashes and road opening day to make sure that the crashes have occurred on the desired type of roads. Another use of NVDB was to make sure that collected crashes in STRADA belong to targeted roads.

The last step before analyzing data was to link the road geometry information from PMS and NVDB to the crash locations. This part was the most time consuming in the method since it had to be done manually. The procedure began by determining the associated roads and driving direction for the crashes and then collecting road information for those crash locations. Crash locations were reported differently in the crash databases, OLY uses start and end nodes in the motorway infrastructure database and the crash locations are given as a distance from the start node to the crash location. STRADA uses a Geographical Information System (GIS) which permits mapping tools to locate crashes during both the registering and analysis of the data. In determining the crash location from the police information (recorded at the time of the crash) was not always precise. Errors of up to two hundred meters can occur in crash localization. But crash localization can be considered as normal distributed around the real crash location [Björketun, 2003]. Because of this, average values of the road characteristics over a minimum 200 m section (100 m before and 100 m) have been taken for the analyzed parameters. In the sections where no crashes occurred, a mean value of the road parameters has been taken, where length of sections varies according to the length of the NVDB sections (0.2 – 1.5 km).

To ensure appropriate data was being used, the road information had to be measured the same year the crash occurred so that the effect of relevant road parameters on crashes could be studied. CR has been used in the analysis instead of absolute number of crashes. In this way, the results are normalized and consider the length of a roadway section and the traffic volume. This allows a direct comparison of different roadway sections with respect to traffic safety [Lamm el at, 1999]. Crash rate (Equation 1) is defined as the number of crashes per **M**illion **V**ehicle **K**ilometer (MVKm).

$$CR = \frac{crash \times 10^6}{AADT\ 365\ T\ L} \quad crash\ per\ 10^6\ \ vehicle\ kilometers \qquad (1)$$

Where:

CR = Crash rate.
AADT = Average annual daily traffic.
L = Length of investigated section, km.
T = Length of investigated time period, year.
365 = Number of days/year.

After determining CR, the data was processed by grouping CR into histogram plots. Data sorting bins were defined for each infrastructure characteristic and, when possible, with simple and multiple linear regression analyses were assessed with CR as the dependent variable. The road parameters used in the analyses were road type, carriageway width, curvature, grade, super-elevation and road surface parameters such as wheel rut depth and road roughness. All parameters were referenced to the vehicle's original travel direction.

RESULTS

Analyzing crashes according to crash type showed that rear-end and run-off crashes were the dominating crash types representing 49% and 32% respectively followed by overtaking crash types 8% (Figure 5). Moreover, pedestrian crashes were 1,4% and only 0,5% of the crashes involved bicycles or mopeds. The explanation for low percentage of pedestrian and cycle/moped crashes is that the investigated roads were divided types with no slow moving traffic.

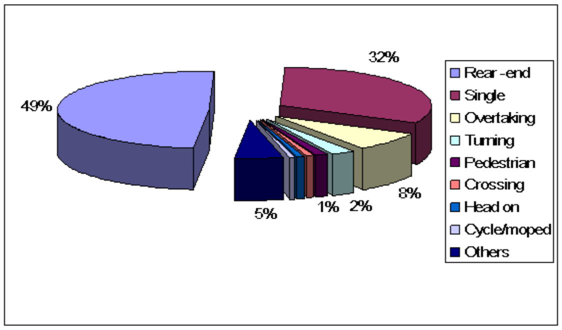

Figure 5-Crash distribution according to crash type

The crash rate level for all type of roads was between 0.04 and 0.056 (Figure 6). Moreover, the crash rate over the six years of analysis showed increasing number of crashes annually. This can be explained by the increasing length of the investigated roads for the period of investigation and also the better data capture in the STRADA database in the later part of the investigation. As the changing number of crashes could be a problem for the analysis, a system to normalize the crash rate for the length of road sections and AADT was used as opposed to comparing absolute number of crashes. Without this process, a short road section with little traffic flow could be more dangerous than a longer one with more traffic although the first road has less registered crashes.

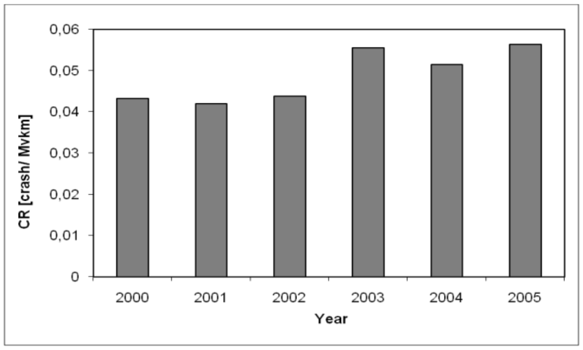

Figure 6-Crash rate of the six years of analysis

Using CR**,** as it has been explained in the previous section, was the way to normalize the results and overcome this problem. Results of the analysis will be presented in the following sections to show the relationships between road design/traffic variables and crash history.

Regression models were calculated for the individual parameters presented below. Each had high correlation coefficients but since the data sorting was affected by confounding factors, it not possible to statistically confirm that these relationships were solely related to the selected variable or if other relationships were also present. Therefore the sorted data is presented and the influence of the road characteristics on crash rate is discussed.

Influence of Carriageway Width

Carriageway width, W, [m] was classified to four groups which were, (W≤5.8), (5.8 < W ≤ 7.5), (8<W ≤ 11.7) and (W ≥ 12). The investigated types of roads contain all four carriageway width categories except W ≤ 5.8 which exists only for 2+1 road types. The influence of carriageway width on crash rate (Figure 7) showed a distinct tendency for crash rate to increase with increasing lane width. This result could be connected with the relationship between overtaking behavior and road width in different road alignments. Thus wide carriageway may encourage lane changing maneuvers, higher speeds and/or shoulder driving.

The data was grouped around the mean value of the lower and upper limit of the carriageway width categories which are 4.90, 6.65, 9.85, and 14.00m. The carriageways up to 5.8 m width had the lowest crash rate. These are one-lane road sections in 2+1 road type where CR was up to 3 times lower than other carriageway widths. However they constitute only 7% of the total number of investigated road sections. In analyzing carriageway width on motorway road type only, road category 5.8< W ≤7.5 (mostly two-lane roads with no or limited shoulders) have the highest CR. More interesting was that this road category was associated with highest percentage of run-off crashes (40%) and lowest percentage of rear-end crashes (38%). Thus, only this carriageway width category had higher run-off crash rates than for rear-end. The safest road width found in the study was 8< W ≤11.7. When comparing CR for various road types, results showed that motorways and 2+1 road are twice as safe as 4-lane roads (Figure 8).

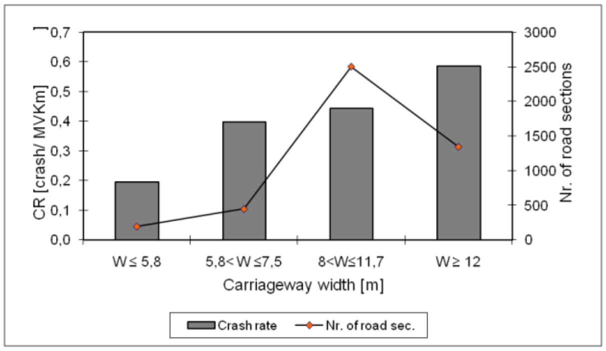

Figure 7-Variation of CR for all type of roads with respect to carriageway width

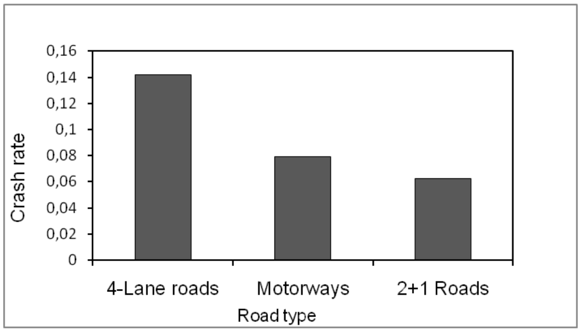

Figure 8 Variation of CR with respect to road type

Influence of Curvature

Curvature is measured by the survey vehicle as it scans the roads. It is classified as left and right curves and is the inverse of the curve radii [Equation 2].

$$Curvature\ [1/m] = \frac{10000}{r} \qquad (2)$$

Where: r is the curve radius in [m]

Right and left curves were studied separately and divided according to the length of the radius: greater than 1250, 1000, 700, 400 and less than 250m. Radii, greater than 700m, reflect motorway designs in Sweden and lower curvature indicate exit and entrance ramps on to motorways and non-motorways such as 2+1 road and four-lane roads in this study [SRA, 2004a]. Moreover, curve radii greater than 1250 include all straight road sections. Thus, it can be considered as straight road section group. Analyzing left and right curves separately showed large curve radii, greater than 1000m, are at least two times safer than sharp curves with radii less than 500 m. As shown in Figure 9-Variation **of CR with respect to curve radius**, crash rate decreases with increasing curve radii for both right and left curves. The results al so showed that right-turn curves have a higher crash rate than left-turn for large radii greater than 700 m. The results show clearly that crash rates are higher at curves and the average of speed limit on curves varies between approximately 60 km/h at curve radii ≤250 m to more than 90 km/h on curve radii >1250m. The low average speed on sharp curves is an indication that the curves generally lie on the roads inside urban areas, for example motorway exits. The result that right curves became more dangerous than left curves starting from radii 700 m and upwards makes it worthwhile to further investigate crashes at curves by studying distribution of crash type on curves. Moreover investigating effect of curves combined with other road parameters, such as super-elevation, road condition and speed, on CR is needed to identify possible reasons behind this finding.

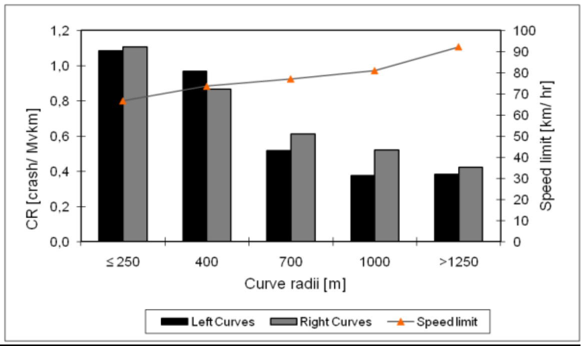

Figure 9-Variation of CR with respect to curve radius

Crash type on curves. Details about crash type on curves did not show any significant difference of rear-end type crashes on different curve radii neither on left or right curves. But the analysis showed that run-off crash percentage on right curves with radii less than 250 m were significantly higher than on left curves. The run-off crashes, according to the databases; occurred on motorway or on 4-lane roads. Furthermore, these types of roads have no small curve radii except at exits or slipway [SRA, 2004a]. One possible interpretation of run-off crashes at small curve radii is the sharp decrease of speed required when driving from motorways onto the exits. Thus, misjudging the speed and a more difficult lane keeping tendency can cause run-off crashes in these locations.

Overtaking crashes were two and three times higher on right curves of radii 700 and 1000 m respectively than on left curves (Figure 10). Furthermore, the high-representation of overtaking crashes on right curves was the reason behind higher CR generally found for right curves as compared to left curves seen in Figure 9-Variation **of CR with respect to curve radius**. Insufficient descriptions of the crash details were provided in the databases for the overtaking crashes on curves. It was not possible to investigate the crashes on a case-by-case basis. However, lower visibility when overtaking another vehicle (vehicle obstructing view) on right curves comparing with left curves could be one, among other reasons for the difference. Drivers who overtake at left curves have longer sight distance which may increase the safety of these manoeuvres compared to right curves. It is worth mentioning that the percentage of overtaking crash was higher on day light than on night for both left and right curves for all curve radii.

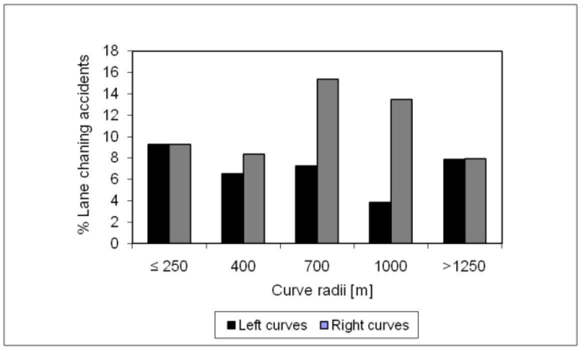

Figure 10-Overtaking crash distribution on left and right curves

Influence of super-elevation. Super-elevation was classified into negative and positive groups and each divided to subgroups of (0 – 1.5), (1.5 – 2.5), (2.5 – 3), (3 – 4) and ≥ 5%. Design speed and curve radii combined will define the amount of lateral acceleration experienced in the vehicle and super-elevation is built into the road to support cornering. Positive super-elevation is needed to support driving in left curves and negative super-elevation supports right turns. Figure 11 shows how super-elevation is built into the road. The basic cross fall of the road (about 2.5%) is built into straight road segments to provide drainage [SRA, 2004b].

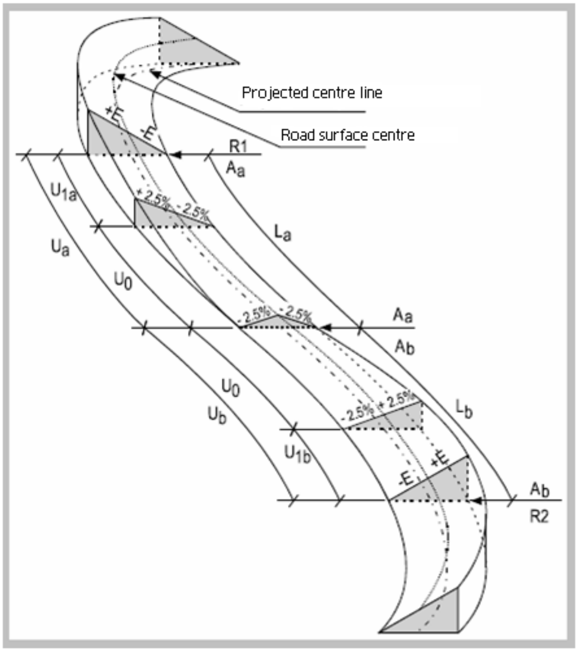

Figure 11-Super-elevation on straight road section, transition into curves and both left and right curves.

Results of the analysis, Figure 12, show that CR is generally similar on negative and positive super-elevations apart from super-elevations of between +3 and +4 % which have the lowest CR. CR increases significantly for super-elevations greater and lower than the interval 2.5 – 4 % with greatest CR on super-elevations ≥ 5% which are always on curves with high expected values of lateral acceleration.

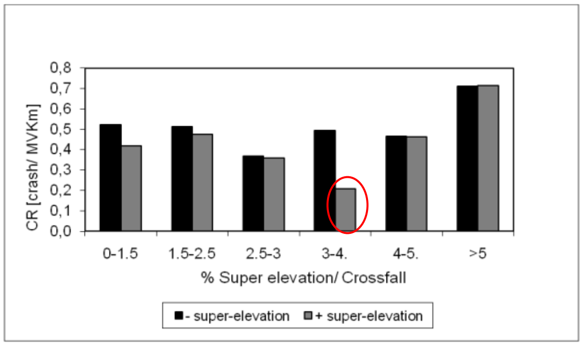

Figure 12-Variation of CR with respect to super-elevation

The positive super-elevations of between (3-4)% that had substantially lower CR values than the corresponding negative super-elevations. These values should only occur at curves (Figure 11) and/or transition into curves since straight sections have super-elevation no more than 2.5 % [SRA, 2004b]. Thus, it is important to study the distribution of CR on curves that have super-elevation (3-4) %.

Figure 13 reveals that left curves are twice as sensitive to negative super-elevation as to positive. Vehicle dynamics behaviour could be one possible reason of this unsafe negative super-elevation at left curves. Hence, negative super-elevation should be used very carefully in left curves and only when radii of curves are very large. For example, in Sweden using negative super-elevations of -2.5% is acceptable for radii 1800 m and upward when the speed limit is 110 km/h [SRA, 2004b]. In contrast to what was expected, CR is higher at right curves with negative super-elevation than left curves (Figure 13). Explanation needed for higher risk for negative super-elevation in right curves. However, this higher CR on right curves is consistent with the results in Figure 9-Variation **of CR with respect to curve radius** that right curves are generally more dangerous than left curves.

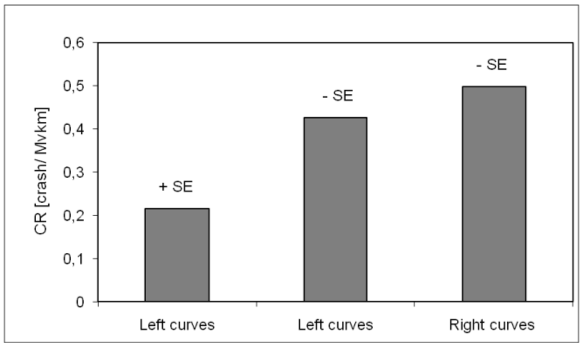

Figure 13-Variation of CR on left and right curves those have super-elevations 3-4%

Influence of wheel rut and road roughness

In analyzing the effects of road surface parameters (wheel rut and road roughness) the measured data has been divided into four groups as shown in Table 1. The road roughness is expressed in terms of International Roughness Index (IRI). IRI [mm/m] is used to define a characteristic of the longitudinal profile of a traveled wheel track and constitutes a standardized roughness measurement [UMTRI, 1998].

Table 1-Intervals of IRI and wheel rut groups

Group	Roughness (IRI) [mm/m]	Wheel rut [mm]
1	≤ 1.5	≤ 3.1
2	1.5 – 2.5	3.1 – 10
3	2.5 – 3.5	10 – 15
4	> 3.5	> 15

The first wheel rut group, WR<3.1 mm, has been taken form SRA requirements that new paved roads should not have wheel ruts exceeding 3,1 mm [SRA, 2007a]. Additionally, the maximum values for wheel ruts are 17 mm and roads with these values require resurfacing [Huvstig, 2008]. Regression analysis results were confirmed by the tendencies in Figure 14 and Figure 15 which indicate a strong correlation between CR and both wheel rut and road roughness. The results highlight how CR increases with both increasing rutting depth and road roughness. This can be interpreted that a degradation of road surface properties increases the crash rate for the road types investigated. Furthermore, the last two groups of wheel rut (deeper than 10 mm) had the greatest CR which was about twice as maximum limit of wheel rut on new paved roads (first group).

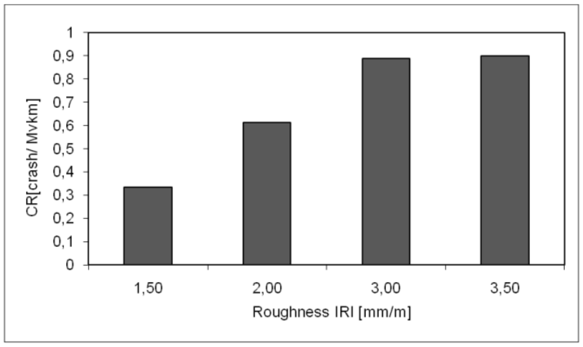

Figure 14-Variation of CR with respect to road roughness (IRI)

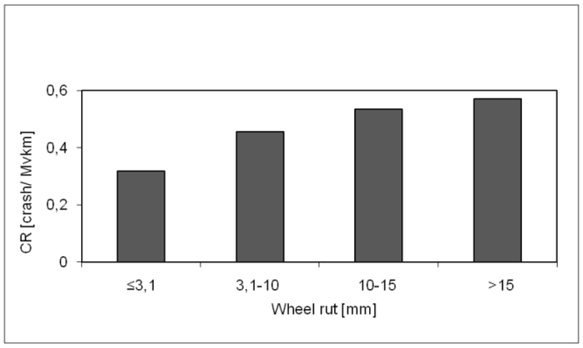

Figure 15-Variation of CR with respect to wheel rut depth

In a parallel study in Finland [Thomson et al, 2007], different results were noticed. Road surface conditions were less correlated to crash rate than the geometrical parameters however all the Finnish data corresponded to the first bin in the Swedish data (Figure 14). The number of crashes for low (less than 1 mm/m) IRI were higher than one would expect for the amount of exposure. These low IRI values may infer reduced friction conditions when wet.

DISCUSSION

The crash and road information reported on in this paper has produced a wealth of data and that has been analyzed to find road parameters that cause most of the crashes. The roads chosen for investigation are among the safest types in Sweden [EuroRAP, 2005]. However, the crashes occurring on them usually have severe consequences [Thulin, 2004]. With regard to carriageway width, CR increased with increasing carriageway width for all type of roads, however, the effect of carriageway width only on motorways showed that it is the edge treatment, rather than carriageway width that affected CR. Specifically, the crash frequency increased on the motorways sections with carriageways of width less than 7,5 m. These sections most probably are roads with no or limited shoulders. Intuitively, a wide shoulder will provide more space and levels of friction in which to maintain or regain control of a vehicle above all in case of overtaking and run off type of crashes. Unfortunately the databases do not mention existence of shoulders.

In agreement with most of the crash analysis studies [Oxley el at, 2003], results of this study showed that crashes cluster at curves and they were one of the most dangerous parts of the road network. More interesting, the results showed that right curves were more dangerous than left curves during lane changing or overtaking manoeuvres. Poor visibility (obstructed view by the vehicle being overtaken) and shorter sight distances for right curves compared to left curves can be among other reasons for this finding. The fact that this tendency was most easily identified in larger curves (greater than 700 m radius) is interesting to investigate as this is the lower radius limit for curves on motorways that may not need speed advisory warnings.

Another finding of this study related to curves was the effect of super-elevation on CR, in which the highest CR was found on the greatest super-elevations. In addition there were unfavourable results for left curves combined with negative super-elevation. That can be associated with not providing adequate dynamic safety criteria of driving, especially when design speed is not harmonized with operating speed. The negotiation of curves can be facilitated by provision of super-elevation through the curve. That is, the side friction required by the vehicle to safely negotiate the curve is markedly reduced [Voigt el at, 1998], [Zegeer el at, 1991]. The right curves with negative super-elevations had a higher CR than left curves with negative super-elevations (Figure 13). In practice these conditions are identical but the higher CR for right curves could be attributed to the higher CR in large radius curves during overtaking (Figure 10). When all of the information related to curves is combined, the increases in CR at curves suggest that a combination of driver behaviour (overtaking, interpretation of road environment, etc) and road characteristics need to be considered for road design. It is important to consider more than the number of crashes occurring at curves and to include the crash type in an analysis of road safety. Overtaking crashes were shown to increase in corners and the analysis of carriageway width show better crash rates for narrower sections where lane changing / overtaking may be restricted. These results suggest that curves with higher crash rates can be improved if drivers have restrictions on lane changing or support for the cornering manoeuvres (sight conditions, improved side friction, etc.)

Addressing the precise effect of road surface on crash has been difficult to interpret in previous studies, however the boundary rutting depth at which safety becomes a concern and work should be carried out to determine threshold values. In Sweden, the repaving/remediation are required when ruts are 17 mm on paved roads [Huvstig, 2008]. The result of the present study showed significant increase of CR with increasing both wheel rut depth and road roughness (IRI), which is consistent with some of previous studies in Sweden. [Tholén, 1999; Velin, 2002]. The previous studies were based on all road types not only on separated median roads as in this analysis. Contradictory results were found in before-after studies for new pavement [Sjölinder et al, 1997], [Johansson, 1997] which state that traffic safety is better on poor road surfaces since motorists drive more carefully on bad roads than on good standard road surfaces.

It is interesting to find interaction between all road characteristics but this can be considered as a further study for this study, however interaction between curve radii and super elevation has been done to further investigate higher overtaking crashes at right curves.

Whether the drivers were impaired by alcohol or not is another important factor effecting CR. Thus, an in-depth study analysis in western region of Sweden showed that 30% of male fatalities between 1997 and 2006 were impaired by alcohol (SRA, 2007b). But the study was limited to relation between road infrastructure and crash/crash type. The data available for the analysis did not include driver impairment data (due to legal issues). Thus alcohol/ drag influence included in the human behaviors which has not been considered in this study.

The paper reports how road safety analyses benefit from linked databases. The grouping of data and presentation of results should provide useful information for researchers and designers. However the material could not be grouped into statistically independent bins for complete analysis. Further developments of the method in this direction is of interest but will require more data but with more limitations on the different road characteristics.

CONCLUSION

Road features, especially road geometry parameters, have been identified in a study of linked databases. Crash and maintenance data could identify road characteristics which contribute to increased crash and injury risk. The results in this safety analysis study suggested that curves, shoulders and super-elevation were more strongly related to crash rate. In particular, the high proportion of run-off crash on small right curves and lane changing crashes on larger right curves were of special interest. In addition, negative super-elevations at left curves had negative impacts on traffic safety.

The study results indicate that additional information available in the linked databases gave additional depth to the analysis. This is particularly important for determining the type of countermeasure that provides the best results. By identifying the types of crashes on curves, strategies for countermeasures can be developed.

Undoubtedly, crashes on curves result from the complex relationships between the driver, the vehicle, and the road. Nevertheless, given that high rate of crashes continue to occur at these locations, it is reasonable to further study crashes at curves. For example vehicle behaviour in curves could be more closely examined to identify the relationship between crash risk and operational measures such as lateral acceleration, speed, etc and non-operational measures (curve radii, super-elevation, road condition, etc). This closer examination could identify the over-representation of overtaking crashes on right curves found in this paper and identify the role of vehicle dynamics.

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REFERENCES

Björketun U. Olycksdata och linjeföringsmått. Väg- och transport forskningsinstitutet. VTI notat 11-2003. Linköping. Sweden; 2003.

Brüde U, Wretling P. 13-m vägar-samband utformning, hastigheter och olyckor PM. Statens väg-och transportforskningsinstitut. Linköping. Sweden; 1998.

Cairney P, Styles E. A pilot study of the relationship between macrotexture and crash occurrence. Australian Transport Safety Bureau. Australian; 2005.

CETE Normandie-Centre. Road Safety Study on A13 Motorway, Junction 22, Rouen to Oissel. CETE Normandie-Centre. France;1995.

Elvik R, Christensen P, Amundsen A. Speed and road crashes. The Institute of Transport Economics (TOI). Rapport 740/2004. Norwegian; 2004.

EuroRAP. EuroRAP-First Pan-European Progress Report. Published by EuroRAP AISBL; 2005.

Fink K L, Krammes R A. Tangent Length and Sight Distance Effects on Crash Rates at Horizontal Curves on Rural Two-Lane Highways. Transportation Research Record. No. 1500, p. 162-168. (1995).

Hemdorff S, Leden L, Sakshaug K et al. Trafiksäkerhet och vägytans egenskaper (TOVE). Slutrapport. Tiedotteita 1075. VTT. 1989.

Huvstig A. Road safety specialist at Western region of Swedish Road Administration (SRA), unpublished work. Private communication). Gothenburg. Sweden; 2008

Ihs A, Velin H, Wiklund M. The influence of road surface conition on traffic safety. Swedish Road and Traffic Research Unit.VTI Rapport 909. Linköping, Sweden; 2002.

Jamil S. Samband mellan trafikolyckor och väggeometri. examensarbete 2006:76. GEO-avdelningen. Grupp Väg och Trafik. Chalmers Tekniska Högskola. Göteborg. Sweden; 2006.

Johansson F. Traffic crashes before and after new pavement Ex-job 1997. Department of Civil Engineering, Chalmers University of Technology. Gothenburg, Sweden; 1997.

Lamm R, Psarianos B, Mailender T. Highway design and traffic safety engineering handbook. McGraw-Hill; 1999.

Motorways. List of motorways in Sweden, http://en.wikipedia.org/wiki/List_of_motorways_in_Sweden; 2006.

Nilsson G. Hastighetsförändringar och trafiksäkerhetseffekter. VTI Rapport 76. Swedish Road and Traffic Research Unit. Linköping, Sweden; 2000.

Othman S, Thomson R. Influence of Road Characteristics on Traffic Safety. ESV 20th Conference. Paper Number 07- 0064. Lyon. Paris; 2007.

Oxley J, Corben B, Koppel S, el at. Cost-Effective Infrastructure Measures on Rural Roads. Monash University Crash Research Centre. Australia; 2003.

RANKERS Project. Ranking for European Road Safety. homepage http://rankers.cidaut.es. Spain; 2008.

Rudny D, Sallmann D. Analysis of Crashes Involving Alleged Road Surface Defects. SAE International Congress & Exposition, February 1996. Document Number 960654.Detroit, MI, USA; 1996.

Sakshaug, K. Overhøydens innvirkning på ulykkesfrekvens i kurver. SINTEF rapport STF22 A00562. Trondheim. Norway; 2000.

Sjölinder K, Velin H, Öberg G. Vägytans inverkan på trafiksäkerheten. VTI notat 67. Statens väg-och transportforskningsinstitut. Linköping. Sweden; 1997.

SRA. Swedish Road Administration. VV publikation 2004:80. 2004-05. Road Design Manual. Regulation. Home page www.vv.se. Sweden; 2004a.

SRA. Swedish Road Administration. VV publikation 2004:80. 2004-05. Linjeföring 8 Tvärfall. Home page www.vv.se. Sweden; 2004b.

SRA. Swedish Road Administration. VV publikation 2007:119. 2007-08. VVTBT Bitumenbundna lager. Home page www.vv.se. Sweden; 2007a.

SRA. Swedish Road Administration. VV publikation 2007:38. Regionväst2006. Trafiksäkerhetsrapport. Home page www.vv.se. Sweden; 2007b.

STRADA. Swedish Traffic Accident Data Acquisition. Användarhandledning för Polisens programvara för rapportering av trafikolyckor Version 1.0. www.vv.se. Sweden; 2006.

Tholén E. Trafikolyckor före och efter beläggning. VVÄ. TR80 99/237. Vägverket Region Väst. Göteborg. Sweden; 1999.

Thomson R, Othman S, Lannér L el at. The Role of Road Infrastructure on Crash Rate. International Conference, Road Safety and Simulation. RSS 2007 - 7,8,9th November 2007. Rome. Italy; 2007.

Thulin H. Traffic, traffic environment and traffic safety in different types of Swedish municipalities. VTI Rapport 950. Swedish Road and Traffic Research Unit. Linköping, Sweden; 2004.

UMTRI. University of Michigan Transportation Research Institute, 1998. http://www.umtri.umich.edu/erd/roughness.

Velin H, Öberg G. Analys av trafikolyckor före och efter beläggningsåtgärd. VTI notat 929. Statens väg-och transportforskningsinstitut. Linköping. Sweden; 2002.

Voigt A, Krammes R. An operational and safety evaluation of alternative horizontal curve design approaches on rural two-lane highways. Transportation Research Board USA; 1998.

Wallman C, Åström H. Friction measurement methods and the correlation between road friction and traffic safety. A literature review. VTI Rapport 911A-2001. Swedish Road and Traffic Research Unit. Linköping, Sweden; 2001.

Zegeer C, Stewart J, Reinfurt D el at. Cost effective geometric improvements for safety upgrading of horizontal curves. (Report No RD-90-021). Federal Highway Administration. USA; 1991.

Paper II

Are Driving and Overtaking on Right Curves More Dangerous than on Left Curves?

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ABSTRACT – It is well known that crashes on horizontal curves are a cause for concern in all countries due to the frequency and severity of crashes at curves compared to road tangents. A recent study of crashes in western Sweden reported a higher rate of crashes in right curves than left curves. To further understand this result, this paper reports the results of novel analyses of the responses of vehicles and drivers during negotiating and overtaking maneuvers on curves for right hand traffic. The overall objectives of the study were to find road parameters for curves that affect vehicle dynamic responses, to analyze these responses during overtaking maneuvers on curves, and to link the results with driver behavior for different curve directions. The studied road features were speed, super-elevation, radius and friction including their interactions, while the analyzed vehicle dynamic factors were lateral acceleration and yaw angular velocity. A simulation program, PC-Crash, has been used to simulate road parameters and vehicle response interaction in curves. Overtaking maneuvers have been simulated for all road feature combinations in a total of 108 runs. Analysis of variances (ANOVA) was performed, using two sided randomized block design, to find differences in vehicle responses for the curve parameters. To study driver response, a field test using an instrumented vehicle and 32 participants was reviewed as it contained longitudinal speed and acceleration data for analysis. The simulation results showed that road features affect overtaking performance in right and left curves differently. Overtaking on right curves was sensitive to radius and the interaction of radius with road condition; while overtaking on left curves was more sensitive to super-elevation. Comparisons of lateral acceleration and yaw angular velocity during these maneuvers showed different vehicle response configurations depending on curve direction and maneuver path. The field test experiments also showed that drivers behave differently depending on the curve direction where both speed and acceleration were higher on right than left curves. The implication of this study is that curve direction should be taken into consideration to a greater extent when designing and redesigning curves. It appears that the driver and the vehicle are influenced by different infrastructure factors depending on the curve direction. In addition, the results suggest that the vehicle dynamics response alone cannot explain the higher crash risk in right curves. Further studies of the links between driver, vehicle, and highway characteristics are needed, such as naturalistic driving studies, to identify the key safety indicators for highway safety.

Keywords: Overtaking maneuver, Curves, Crash Analysis, Vehicle Dynamics, Simulation

INTRODUCTION

An analysis of highway safety was conducted in the western region of Sweden [Othman, 2009] by integrating crash and maintenance data for 3000 crashes. The combination of data sources allowed for more insightful analyses than would be possible with only crash data normally reported to the police. In particular, the analysis of crash type and infrastructure characteristics is an important added value. Further analysis of the crash types highlighted the differences between run-off-road crashes and lane changing (overtaking) crashes. In particular, distributions of crashes with respect to curve direction were of interest and an area for further collaborative research with human factors and vehicle dynamics researchers.

The analysis [Othman, 2009] showed that overtaking crashes are more frequent in right curves compared with left curves. A further investigation to analyze vehicle/road interaction as well as human behavior in curves was therefore of interest. Safe tracking of a vehicle along a curve at relatively high speed requires greater attention by drivers than when driving along a straight section of a roadway. Subsequently, the demands on the driver to stay safely within the road boundaries are amplified if there is a lane changing maneuver in the curve. Driving challenges presented to the driver are greater when there is inconsistency and lack of predictability in the road alignment ahead. Moreover, the effects of inconsistency are of greater concern when curves are severe [Oxley, 2003]. Curves induce lateral acceleration and higher crash rates are expected when vehicles experience higher lateral accelerations [Leonard, 1994].

The handling characteristics of a road vehicle determine its response to steering commands and to environmental inputs, such as road parameters, that affect its direction of motion. There are two basic issues in vehicle handling: one is the control of direction of motion of the vehicle; the other is the vehicle's ability to stabilize its direction of motion against external disturbances [Wong, 2001]. During turning maneuvers, the steer angle from the driver can be considered as an input to the vehicle system and the motion variables of the vehicle such as lateral acceleration and yaw velocity may be regarded as outputs. Thus, lateral acceleration (directed along the vehicle's y axis, Figure 1) and yaw angular velocity (rotational velocity about the vehicle's z axis, Figure 1) have been used in this study for comparing the response characteristics of different values of speed, road-condition, super-elevation and radius in left and right curve directions during turning (overtaking).

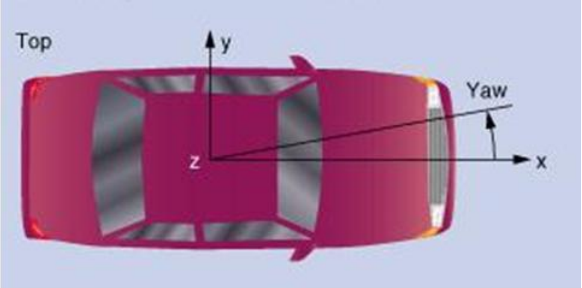

Figure 1- Yaw Angular Velocity

OBJECTIVES OF THE STUDY

The goals of this study were to find road geometry parameters that affect the stability of vehicles during negotiating curves and to analyze vehicle dynamics parameters (lateral acceleration and yaw angular velocity) when driving through right and left curves. The last goal was to identify connections between road parameters and vehicle responses with the driver's behavior in different curve directions focusing on longitudinal speed and acceleration.

PREVIOUS STUDIES

There are many studies investigating crash types and safety-related features in curves. However, there are limited studies that distinguish between right and left curves when investigating crashes. In particular, the authors of this study could not find any studies investigating overtaking maneuver behavior in left and right curves. The nearest investigations are two undated citations by Taylor et al. and Stimpson et al. cited in two studies [Krammes, 1993; Steyer, 2006] which state that one of the operating measures identified as a contributing factor to crash risk on horizontal curves is vehicle lateral placement. Lateral placement is defined as the lateral position of vehicles in the original travel lane. This indicates how good is the driver in keeping the vehicle between lane boundaries during negotiating curves. According to Miller [Miller, 1982] it is a function of vehicle size, lane width and lane type. Steyer [Steyer, 2006] also investigated lateral placement, though not the overtaking maneuver, between right and left curves. The study noted that one of the important safety-related features in curve negotiation is vehicle lateral placement. It also states that the driving path should be considered when investigating crashes on curves. Moreover, the study makes a distinction between right and left curves and offers some suggestions as to why centre-line encroachments occur. Centre-line encroachments on curves to the driver's near-side (that is, left curves in right hand traffic and right curves in left hand traffic) may be considered 'controlled' or 'intentional' encroachments where some drivers intentionally 'cut the corner' or 'straighten the curve' when it is possible to be done safely. The study argues that these types of encroachments are mainly associated with the radius of the curve, curve length, grade and available sight distance. Centre-line encroachments on curves on the driver's far-side (that is right curves in right hand traffic and vice versa) may be due to speed and a tendency for drivers to steer away from roadside hazards [Steyer, 2006]. An analysis in France highlighted some infrastructure characteristics, for all type of roads, which increase the risk of severe crashes involving a heavy goods vehicle (HGV). The results showed twice as many HGV crashes on right-hand curves than on left-hand curves (25% and 13% respectively) when two vehicles are involved [Gothié, 2008].

As it has been mentioned earlier, research on overtaking crashes is comparatively rare, despite the frequency and severity of these types of crashes. Clarke, Ward and Jones [Clarke, 1998] reported that overtaking crashes accounted for eight percent of fatal crashes on rural roads in Nottinghamshire, England and that their crash severity index (the proportion of cases resulting in death or serious injury) was over twenty percent. In Australia, Armour [Armour, 1984] found that overtaking accounts for about ten percent of rural casualty crashes. In a study of separated roads in Sweden [Othman, 2009], overtaking crashes represented eight percent of 3000 investigated crashes. Another study in Denmark [Nielsen, 2000] identified the overtaking maneuver as a major cause of head-on collisions with severe consequences. Other studies found that the rate of overtaking crashes is related to the provision and geometric design of passing lanes according to Hughes [Hughes, 1992] and Polus [Polus, 2000].

From the review of the limited studies available for overtaking crashes which distinguish between left and right curves, there is a lack of investigations that link vehicle dynamics, road geometry and driver behavior when addressing road safety. Thus, a focus of this study is on infrastructure features and driver behavior in curves that can fundamentally affect vehicle dynamics during negotiating and overtaking in right and left curves.

METHODOLOGY

The aim of this study was to find road geometry parameters that affect vehicle stability when driving through curves. The approach was to use numerical simulation of vehicle maneuvers in different curves using a controlled parametric study. The results were compared to previously derived results from crash analyses and volunteer driving studies. These results could then be used to study the parameters producing different effects for different curve directions and could be further linked to human behavior while negotiating curves. Driver behavior information was obtained from a field test study [Alonso, 2007]. The field test was conducted in parallel to the accident analysis study [Othman, 2009] by a collaborative partner in a European project called RANKERS (RANKing for European Road Safety) [RANKERS, 2007].

Vehicle Dynamics Simulation

A vehicle dynamic simulation program was needed that could capture the dynamic response of a vehicle using the travel speed and steering angle as inputs. The program should also be able to model road geometry features that affect vehicle dynamic responses. The desired outputs of the model were lateral acceleration and yaw angular velocity which should indicate the stability of the vehicle. The desired outputs can be achieved using a simple vehicle model, the “bicycle model”, with 3 degrees of freedom [Wong, 2001] or a more complicated system modeling more mechanical components with many more degrees of freedom.

PC-Crash [Datentechnik, 2007], initially developed for the simulation of motor vehicle crashes, was selected for the simulations. PC-Crash can configure a vehicle model based on the data from the vehicle manufacturer (and user) and provides the facilities to define a road section according to the user’s specifications. The simulation runs can be configured to drive the vehicle along a predefined path and record the dynamic responses. PC-Crash has been tested and validated for professional traffic accident reconstruction [Moser, 1999]. Validation of the vehicle dynamics model in PC-Crash is demonstrated in a study testing extreme turning conditions (vehicle yaw) in order to examine the accuracy of the computer simulation [Cliff, 2004]. The yaw maneuvers in [Cliff 2004] were more severe than the simulations anticipated for this study.

A SEAT León passenger car has been used in the PC-Crash simulations to be consistent with the instrumented vehicle used in the field study. It should be noted that the goal of the simulations was to compare a vehicle’s response in left and right curves under similar conditions and not the detailed simulation of a specific vehicle model.

Lane Changing Maneuver

The crash analysis conducted earlier [Othman 2009] has identified overtaking as one of the collision types in curves. It was important to choose a relatively severe maneuver to identify any vehicle stability issues. It was also critical to have a repeatable test method that can be used to compare vehicle performance in different curves.

A severe double lane-change maneuver has been chosen for the evaluation of vehicle dynamics in the simulations to represent conditions leading to overtaking crashes found in [Othman 2009]. The maneuver consists of rapidly driving a vehicle from its initial lane to a parallel lane, and returning to the initial lane, without exceeding lane boundaries. Track dimensions of the double lane-change are according to ISO 3888 specification [ISO, 1999]. The total length of the maneuver was 125 m. The maneuver was modified to curves as it was originally described for straight line operation.

Experimental Design for PC-Crash Simulation

Based on the prioritization of a study’s objectives, experimental design guides the selection of the test parameters. The main functions of the experimental design in this study were to define a model for the effects of road features on vehicle dynamic responses and to determine differences in vehicle dynamic responses between left and right curves.

Before running the simulations in PC-Crash, factors of interest needed to be identified to determine how the runs should be conducted. Four factors that most likely affect lateral acceleration and yaw angular velocity during overtaking have been chosen. Three of the factors (speed, super elevation, radius) have three levels – or values - and the remaining factor, road condition (or friction), two levels. Table 1 shows these factors, their levels and chosen codes.

Table 1. Factors that may Affect Lateral Acceleration and Yaw Angular Velocity

Factor	Levels	Value	Code
Speed [km/h]	3	(70, 90, 110)	(-1, 0, 1)
Super elevation [%]	3	(5.5, 2.5, -2.5)	(-1, 0, 1)
Curve radius [m]	3	(300, 600, 800)	(-1, 0, 1)
Road condition [μ]	2	wet [μ=0.5] dry [μ= 0.8]	(-1, 1)

Different levels for each factor will have a great effect on the vehicle's lateral acceleration/yaw angular velocity. For example, it is clear that there are large differences in lateral acceleration when driving at 70 or 110 km/h. These differences are not interesting for the comparison and should be eliminated from the study. Therefore a two sided randomized block design has been chosen to reduce (or eliminate) these effects [Box, 2005]. Left and right curves were one side of the design, while runs within each curve type were defined as the other side of the design (i.e. blocks). The runs within each curve were made randomly in order to reduce/eliminate block differences. A full run for all factors was calculated to consist of $3 \times 3 \times 3 \times 2 = 54$ for one curve direction (i.e. a total of 108 runs were conducted for both left and right curves).

Field Test

The field test experiment was conducted by a partner in the European Project called RANKERS. The field tests focused on road-driver interaction and its impact on road infrastructure design, particularly addressing road layout influence on driver behavior [Alonso, 2007]. The field studies of real traffic driving situations were performed on the AP-66 motorway of the Spanish road network. In the tests, an instrumented vehicle (SEAT León) and a set of drivers was used. The sample of thirty-two licensed drivers, from age 21 to 57 years old, was recruited as experimental subjects. Driver characteristics were equally distributed between the variables: gender, experience, and familiarity with the road. Special attention was made on the selection of appropriate road locations where analysis of the driver-infrastructure interaction could be carried out. The following list of variables defined the experimental design for the field test:

- Independent Variables or Factor:
  - Radius of curvature
    - Small radius (≤ 500m)
    - Large radius (> 500m)
  - Curve direction
    - Left-hand
    - Right- hand
- Dependent Variables
  - Speed
  - Longitudinal acceleration and gas / brake pedal (secondary variables)

ANALYSIS

The analysis of the simulation output was divided into two parts. The first part investigates and identifies parameters which have a significant effect on the lateral acceleration and yaw angular velocity during overtaking on curves. The second part analyzed differences of lateral acceleration/yaw angular velocity between driving on right and left curves. The field test has been used to link the simulations to human behavior in curves.

Part I: Finding Road Parameters

The starting point in this part of the analysis was to find a model for the chosen factors. The model is shown in Equation 1 and, apart from effect of the mean of factors (b_0), includes effects of each factor and any first order interaction between them. Moreover the model considers second order interactions of speed, x_1, and super elevation, x_2.

The model, as shown in equation 1, considers a total of 13 parameters, one from the mean, four from the factors alone, six from first order interaction and two from second order interaction.

$$y = b_0 + \sum_{i=1}^{4} b_i x_i + b_{11} x_1^2 + b_{22} x_2^2 + \sum_{i \neq j} b_{ij} x_i x_j \qquad (1)$$

Where:

x_1 = speed

x_2 = super elevation

x_3 = curve radius

x_4 = road condition

b = coefficient of the factors in the model (to be determined)

To estimate the coefficients of the factors in the model in equation 1, $\mathbf{b_i}$, the inverse of the system of equations $(y = Ab)$ has been applied, using the design matrix in the appendix as the coefficient matrix, A, and using the simulation output, lateral acceleration, as the outcome, y, from the model. Since the system of equations is overestimated (i.e. 54 equations to find 13 parameters) a least square approximation has been used to find the unknowns, which is the best solution for the mean of the system

The next step was to find and check the significance of the factors (95% confidence interval) by finding the variance (equations 3, 4 & 5).

$$\boldsymbol{Var(b_i) = \sigma^2 \cdot C_{ii}} \qquad \textbf{(3)}$$

Where:

$$\boldsymbol{\sigma^2 = MS_R = \frac{\sum_{i=1}^{54}(y-\hat{y})^2}{DoF_R}} \qquad \textbf{(4)}$$

$$\boldsymbol{C = (X^T X)^{-1}} \qquad \textbf{(5)}$$

MS_R is mean of squares

$\hat{y}$ is the grand average.

DoF_R is degrees of freedom of the residual vector = 54 – 13 = 41.

Part II: Analyzing Vehicle Dynamic Responses

In order to analyze vehicle dynamic responses and see if there is any evidence for significant differences between different curve directions and blocks, respectively, an analysis of variances was performed. The calculations are presented in Table 2. It was assumed that the block and curve affects were additive (i.e. no interaction between blocks and curves) and the errors were Normally, Independently, and Identically Distributed (NIID).

Table 2- Equations used in ANOVA-Table where "n" is number of blocks or runs (54 runs) and "k" is number of curve directions = 2

Source of variation	Sum of squares	Degrees of freedom	Mean squares	F-ratio
Between blocks	$S_B =$ $\sum(\bar{y}_b - \bar{y})^2$	$\nu_B =$ $(n-1)$	$m_B = S_B / m_B$	$F_{\nu_B,\nu_R} = \frac{m_B}{m_R}$
Between curves	$S_C =$ $\sum(\bar{y}_c - \bar{y})^2$	$\nu_C =$ $(k-1)$	$m_C = S_C / \nu_C$	$F_{\nu_C,\nu_R} = \frac{m_C}{m_R}$
Residuals	$S_R =$ $\sum(y_{bc} - \bar{y}_b - \bar{y}_c + \bar{y})^2$	$\nu_R =$ $(n-1)(k-1)$	$m_R = S_R / \nu_R$	
Deviations from grand average	$S_D =$ $\sum(y_{bc} - \bar{y})^2$	$\nu_D =$ $(nk-1)$		

Part III: Field Test

Two statistical analysis techniques were used with the data collected in the field studies. The first one was the Analysis of Covariance (ANCOVA) to know how the radius of curvature influences speed. The second was a Factorial Multivariate Analysis of Covariance (MANCOVA) to determine how curvature direction and radius of curvature could influence speed, longitudinal acceleration, accelerator and brake pedal use when driving along the curves. Prior to the actual execution of the statistical study, a pretreatment of the registered data was necessary in order to prepare and organize the variables for analysis. Each curve was divided into 9 sections and was also given a curve identifier representing the number of the curve under the study [Alonso, 2007].

RESULTS

The main goals of the simulations were to define road features affecting vehicle dynamic responses and determine differences in the responses corresponding to curve directions. The results are presented separately for lateral acceleration and yaw angular velocity. The last subsection shows results from the field test review.

The vehicle dynamic responses differed along the curve for left and right curves when overtaking maneuvers were introduced. On left curves there were three, equally high, peaks at the beginning, middle and the end of the curves. On right curves there was one high peak in the middle with two small peaks at the ends. Figures 2 and 3 show lateral accelerations and yaw angular velocities for overtaking on curves with radius of 500 m, super elevation equal to 3%, and a travel speed of 70 km/h. The first peak (before 20 m in all cases) is when the vehicle starts to leave the initial lane and when the vehicle crosses the lane boundary the values approach zero. The second peak coincides with the start of steering back to the initial lane. Again, crossing the lane boundary is associated with the curves approaching zero values. Finally the third peaks arise when the driver straightens out the vehicle when returning to the initial lane after completing the maneuver. In the following subsections only the absolute maximum values of the lateral accelerations and yaw angular velocities are plotted and compared in detail. The maximum value is the closest value to the grip margin [Klomp, 2007] when loss of control is expected, regardless of when the maximum value is found during the maneuver. However, the responses of the vehicle along the curve will be also explained and compared between curve directions in the discussion section.

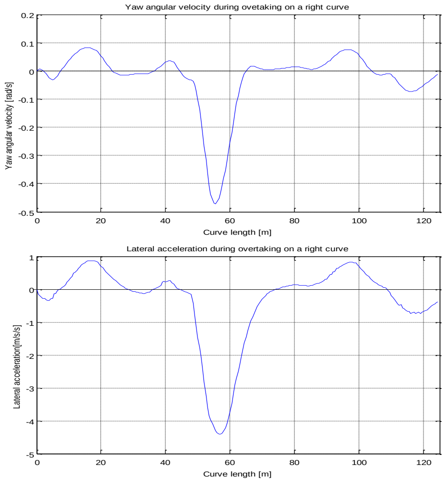

Figure 2- Lateral Acceleration and Yaw Angular Velocity on right curves [Radius = 500 m, Speed = 70 km/h]

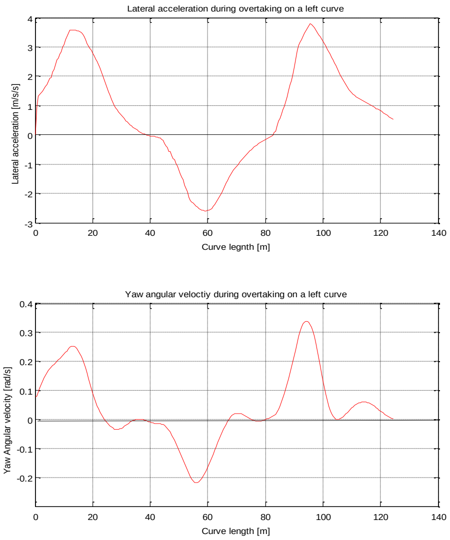

Figure 3- Lateral Acceleration and Yaw Angular Velocity on left curves [Radius = 500 m, Speed = 70 km/h]

Lateral Acceleration

The acquired variance results from Equation 4 that have been estimated for absolute maximum lateral acceleration were 0.0945 and 0.1978 which were Estimated Pooled Variances for right and left curves respectively. They are used for calculation purposes and the remaining estimations for right and left curves are shown in Tables 3 and 4 and illustrated in Figure 4.

The parameters b1, b2, b3 and b4 represent confidence intervals of the factors speed, super elevation, curve radius and road condition, respectively, and the remaining coefficients are the first order interaction between the factors (e.g. b12 is the speed – super elevation interaction and b11 is second order interaction of the speed). The parameter, b0 is the effect due to the mean of all factors and is not of interest when studying the influence of individual parameters.

Table 3 Parameter Estimation for Right Curves, with b, the Variance of b, and the Upper and Lower Bounds of a 95% Confidence Interval

Right	B	Var(b)	Upper	Lower
b0	**4,87**	0,0088	5,06	4,69
b1	**1,57**	0,0026	1,67	1,47
b2	-0,06	0,0026	0,04	-0,16
b3	**-0,44**	0,0026	-0,34	-0,54
b4	**0,24**	0,0018	0,32	0,16
b11	-0,10	0,0079	0,08	-0,27
b12	-0,11	0,0039	0,01	-0,23
b13	0,03	0,0039	0,15	-0,10
b14	**0,36**	0,0026	0,46	0,26
b22	-0,06	0,0079	0,11	-0,24
b23	0,04	0,0039	0,16	-0,09
b24	0,08	0,0026	0,18	-0,02
b34	**-0,13**	0,0026	-0,03	-0,23

Table 4- Parameter Estimation for Left Curves, with b, the Variance of b, and the Upper and Lower Bounds of a 95% Confidence Interval

Left	b	Var(b)	Upper	Lower
b0	**5,63**	0,0183	5,89	5,36
b1	**1,16**	0,0055	1,30	1,01
b2	**-0,64**	0,0055	-0,49	-0,78
b3	-0,14	0,0055	0,01	-0,28
b4	**0,35**	0,0037	0,47	0,23
b11	-0,24	0,0165	0,01	-0,49
b12	-0,14	0,0082	0,04	-0,31
b13	-0,05	0,0082	0,13	-0,23
b14	**0,35**	0,0055	0,50	0,21
b22	0,08	0,0165	0,33	-0,17
b23	0,07	0,0082	0,25	-0,10
b24	-0,05	0,0055	0,09	-0,20
b34	-0,04	0,0055	0,11	-0,18

The estimates of the factors and their associated confidence limits are shown in Tables 3 and 4; the factors which have a significant effect on the output are in bold text. If the confidence interval does not span the zero line, the factor is significant. These intervals are presented graphically in the error plot (Figure 4). The single factors affecting lateral acceleration in right curves are speed, radius and road condition. Furthermore, affects of two interacting factors, speed – road condition and radius – road condition, were significant and their affect on lateral acceleration could not be explained by noise. On the other hand, single factors affecting lateral acceleration in left curves were speed, super elevation and road condition, while only the interaction between speed and road condition had a significant effect.

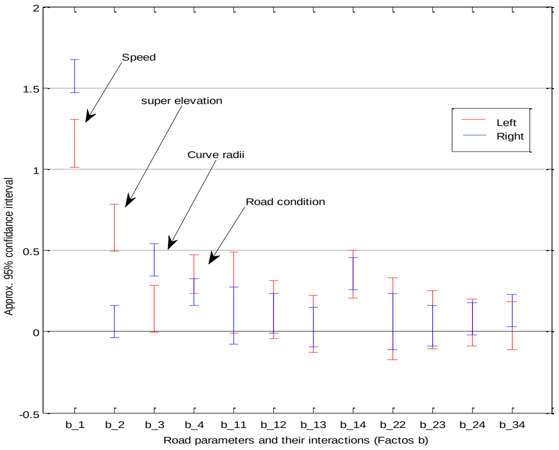

Figure 4- An error plot of the confidence intervals of factors b that affect lateral acceleration for left and right curves

One objective was to determine if there are differences in lateral accelerations and yaw angular velocities between left and right curves. Analysis of variance (ANOVA) was used to compare lateral acceleration in left and right curves to each other. The ANOVA results are shown below in Table 5 Where SS is the sum of squares, Df is degrees of freedom, MS is mean of squares and Prob(F) is the p value from the F distribution. Curve directions are relevant for stating that there is a difference and the low probability value, when compared to the F-distribution; make it very unlikely that the differences between the curves can be explained by noise. Thus, the different lateral acceleration between right and left curves is significant during overtaking maneuvers.

Table 5- ANOVA-Table

Source	SS	Df	MS	F	Prob(F)
Curves	15.412	1	15.4209	54.18	1.184 E-09
Block	178.404	53	3.3661	11.83	3.331 E-16
Error	15.084	53	0.2846		
Total	208.909	107			

Yaw Angular Velocity

As explained in the previous section, confidence intervals for the analysis parameters are presented in the error plot below, Figure 5, which shows the confidence intervals of the factors, and whether or not they span zero and thus are significant. The single factors affecting yaw angular velocity in right curves were speed, radius and road condition while only speed had an effect on yaw angular velocity in left curves. In addition, yaw angular velocity in both left and right curves were sensitive to second order interactions of speed and to the interaction between speed and road condition.

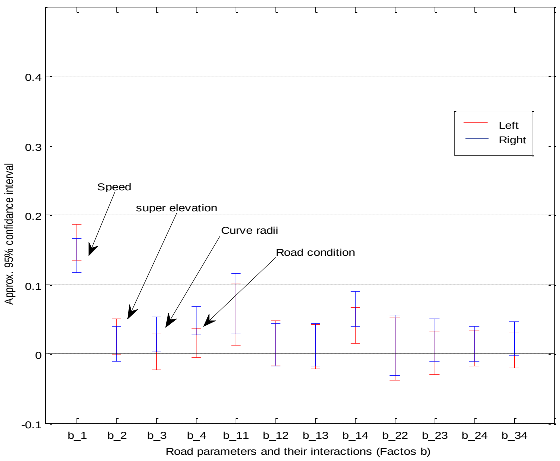

Figure 5- An error plot of the confidence intervals of factors b that affect yaw angular velocity for right and left curves

The ANOVA analysis was done to prove or refute that there is difference in vehicle responses when comparing results for left and right curves. The low probability value, when compared to the F-distribution, makes it very unlikely that the differences between the curves can be explained by noise. This means that the difference of yaw angular velocity between right and left curves, during overtaking, is significant.

Field Test

The results of the field test identified interesting differences in longitudinal speed and acceleration between left and right curves (Figure 6). On the large radii curves, speed is nearly constant when curves are left, but for curves to the right, speed decreases in the middle and increases in the last third of the curve.

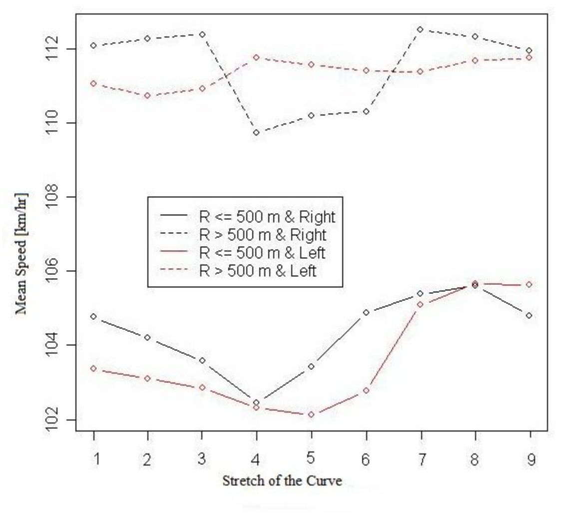

Figure 6- Longitudinal speeds for left and right curves. (Adapted from [Alonso, 2007]).

Figure 7 shows how longitudinal acceleration is negative at the beginning of the curves when the curve is to the right and R ≤ 500 m. Moreover, when curve is to the right but R > 500 m, longitudinal acceleration is more regular along the curves. The results from the data recorded in the driving studies indicate that drivers behave differently when negotiating left and right curves.

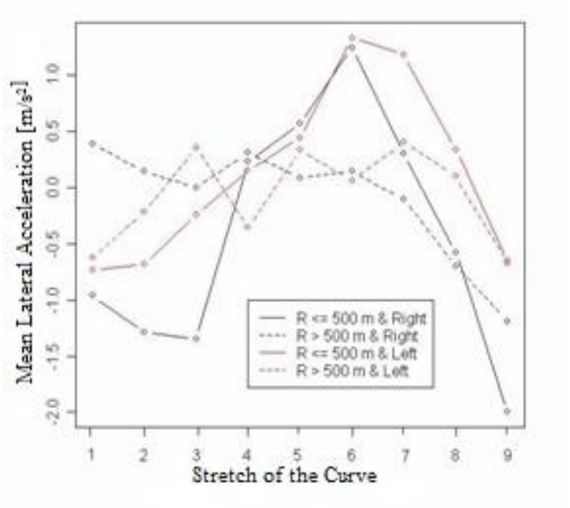

Figure 7- Longitudinal acceleration for left and right curves. (Adapted from [Alonso, 2007]).

DISCUSSION

The objective of this investigation was to find how vehicles and drivers perform on curves. In particular, why overtaking crash types are over-represented on right curves compared to left curves [Othman, 2009]. Thus, it is worth mentioning that, although finding factors affecting lateral acceleration/yaw angular velocity is interesting and one of the goals of this study, it is of greater concern to find road factors that affect overtaking maneuvers in left and right curves differently. That is, factors that affect vehicle behavior in both right and left curves indicate that vehicle stability is sensitive to associated curve geometry features regardless curve direction. For the second goal finding if there are any significant differences of lateral acceleration and yaw angular velocity was not the only desired result. It was important to also determine the curve directions that produce the highest values. However, in comparing absolute maximum values both lateral acceleration and yaw angular velocity were significantly higher on left curves than on right curves. That was a statistical result and not the case for the all simulation combinations. These findings alone do not reflect results of the crash history analysis where right curves are more dangerous than left curves in overtaking [Othman, 2009]. However peak accelerations occurred at different times in the curve during lane changes for different curve directions. The magnitude of the peak values was more consistent in left curves than right curves. In right curves, little acceleration is observed when driving from the initial lane to the parallel lane. However, accelerations are severe in the middle when returning to the initial lane. This is a result that steering at this point in the maneuver must compensate both for the curve direction and the lane changing. The three peaks in left and right curves for all cases (Figures 2 and 3), showed that first and third peaks in left curves were higher than in right curves. More detail and effects of other road features on lateral acceleration and yaw angular velocity are described in the following sections.

Lateral Acceleration

The significant factors affecting vehicle response have been established in Tables 3 and 4, and visualized in Figure 4. It is interesting to note that they are different for left and right curves. Right curves were sensitive to radius and interaction of radius – road condition, while left curves were sensitive to super-elevation. The common active factors between right and left curves were speed, road condition and speed-road condition interaction. These common factors could be expected to be explained from basic vehicle dynamics. It is also relevant to see that there are no quadratic terms in the model that were significant for lateral acceleration response. The significant factors in left curves were sensitive to radius when initiating overtaking (leaving initial lane) while right curves were sensitive to radius when returning back to the initial lane (Figures 2 and 3). This rapid change of lateral forces through the curve is a result of the vehicle experiencing a transient "curve radius" much smaller than indicated by the curve design radius. This can yield higher lateral force than the road design code has considered [Granlund, 2010], which may reach or exceed a limit condition. Thus, the results clearly demonstrate that vehicle performance is different between right and left curves during overtaking.

In Table 5, the data from the ANOVA results show that the difference between left and right curves is statistically significant at the 99% level with p-value of 1.18×10^{-9}. This is highly significant and explains that overtaking produces different responses in left and right curves. However, lateral acceleration is higher for left curves than on right curves. The mean lateral acceleration of all 54 runs in left curves was 0.08*g* (16%) higher than in right curves. This result is not consistent with the result of the earlier crash analysis [Othman, 2009]. Thus, the over-representation of overtaking crashes on right curves cannot be explained by vehicle dynamics characteristics when considering only maximum absolute lateral acceleration. This was found when identical driving conditions were given for left and right curves. However, right curves were more sensitive, to radius and interaction of radius – road condition, than left curves. At the same time, left curves were more sensitive to super-elevation. This indicates that right curves generally are sensitive to more road geometry parameters than left curves. Moreover, right curves induce a severe lateral acceleration in the middle of overtaking. In other words more steering input is required by the driver to perform the overtaking. When comparing peak values between curve directions, the differences were also statistically significant. Lateral accelerations at the start and finish of overtaking were higher on left curves than right curves, but lower in the middle of the maneuver.

The field test revealed that the driver chooses higher speeds in right curves than in left curves. The results of the field test were only analyzed as normal driving through the curves and overtaking was not identified. Thus, these results cannot be compared directly with the overtaking simulations. However, driving through curves without overtaking has been simulated with PC-Crash both with constant and variable speeds. The results did not show differences in vehicle dynamic behavior between left and right curves. The simulation results confirm that differences between left and right curves observed in the field tests are mainly due to human behavior. The fact that higher speeds were observed in right curves is interesting, even though the field tests were not investigating overtaking. Higher speed induces higher lateral acceleration and is additive to the transient effect of decreasing radius in overtaking (discussed previously) in right curves.

The field test results linked to simulation show that the driver influences the vehicle performance and stability differently for right and left curves during overtaking. Stability is used in the context of defining how close the vehicle is to its limit condition for lateral forces.

Yaw Angular Velocity

As found in the analysis of lateral acceleration, there are significant effects of road parameters on yaw angular velocity and producing clear differences between right and left curves. The difference of yaw angular velocity was highly significant with p-value of 7.74×10^{-11}. But, similar to lateral acceleration, left curves had much higher mean yaw angular velocity than right curves when comparing maximum values. In analyzing peak values of the yaw angular velocity, the middle peak of right curves was significantly higher than at the start and end of the maneuver.

For both lateral acceleration and yaw angular velocity results in overtaking maneuvers, higher absolute values were observed in left curves which contradict the results from the crash analysis [Othman, 2009]. However, these results are for constant speed maneuvers. The sensitivity of right curves to speed and radius suggests that the driver behavior in the curve can result in more critical vehicle responses. The type of driver responses observed in the field test [Alonso, 2007] identified one type of behavior (higher speed) in right curves that can potentially produce vehicle responses that can explain the safety issues observed in [Othman, 2009].

CONCLUSION

These simulation analyses have given insight into how road geometry factors and curve direction affect vehicle stability during overtaking maneuvers. Left curves were sensitive to super elevation while right curves to radius. The simulation showed also how variations in radius decreased vehicle stability. This occurs in the middle of overtaking maneuvers during right curves but occurs at the start and finish of overtaking maneuvers in the left curves. This behavior can contribute to the severity and frequency of overtaking crashes [Clarke, 1998]. Road design guidelines and road safety monitoring programs should reconsider the influence of road characteristics on traffic safety in curves. Parameters that have a negative influence on safety should be identified so that potential countermeasures are developed. Parameters that are sensitive to driver behavior are of particular interest.

Future work should focus on combined effect of vehicle dynamic responses, environment and human behavior during overtaking and driving through curves. This work needs to be based on more reliable data sources to define simulation inputs such as data from Field Operational Test (FOT) and Naturalistic Driving Studies (NDS).

REFERENCES

Alonso M, Vega H, Plaza J. (2007). Human Factors in road infrastructure design: analysis of road layout influence in driver behavior. Department of Human Factors, CIDAUT Foundation, Valladolid, Spain. International Conference Road Safety and Simulation (RSS). 2007.

Armour M. (1984). *A description of casualty accidents on Australian rural highways*. Report No. AIR 1120-3. Melbourne, Australia: ARRB Transport Research.

Box G E P, Hunter W G, Hunter J S. *Statistics for Experimenters*, John Wiley & Sons, New York. 2005.

Clarke D, Ward P, Jones J. (1998). *Overtaking road accidents: Differences in maneuver as a function of driver age.* Accident Analysis and Prevention, 30, 455-467

Cliff W, Lawrence J, Heinrichs B, el at. (2004). *Yaw Testing of an Instrumented Vehicle with and without Braking.* . SAE Paper No. 2004-01-1187.

Datentechnik S. (2007). PC Crash version 7.0 - A Simulation program for Vehicle Accidents, English Manual. Linz Austria 2002.

Gothié M, Cerezo V, Conche F. (2008). *Relationship between road infrastructure characteristics and hgv accidents.* CETE de Lyon Bron, France. International Conference on Heavy Vehicles. Paris 2008. Paper Nr. 86

Granlund J. (2010). *Safer Curves on Multiple Lane Roads.* Vectura Consulting, Sweden. Transport Research Arena Europe 2010, Brussels

Hughes W, Joshua S, McGee H. (1992). *Study designs for passing sight distance requirements*. (Publication No.FHWA-RD-91-078). Washington DC: US Department of Transportation, Federal Highway Administration.

ISO (1999). *International Organization for Standardization*. International Standard ISO 3888-1. Technical Committee ISO/TC 22, Road vehicles, Subcommittee SC 9, Vehicle dynamics and road-holding ability.

Klomp M. (2007). On Driver Force Distribution and Road Vehicle Handling. A Study of Understeer and Lateral Grip. Licentiate Thesis. Department of Applied Mechanics. Chalmers University of Technology. Göteborg. Sweden.

Krammes R, Brackett R, Shafer M, el at. (1993). *Horizontal alignment design consistency for rural two-lane highways*. (Report No. FHWA-RD-94-034). Washington DC: Federal Highway Administration, US Department of Transport.

Leonard J, Bilse D, Recker W. (1994). *Super-elevation rates at rural highway intersections*. (Report No. RTA-53P434). Irvine, CA: University of Carolina Institute of Transportation Studies.

Miller E, Steuart G. (1982). Vehicle Lateral Placements on Urban Roads. *Transportation Engineering Journal*, Vol. 108, No. 5, September/October 1982, pp. 495-508

Moser A, Steffan H, Kasanický G. (1999). The Pedestrian Model in PC-Crash – The Introduction of a Multi Body System and its Validation. SAE Paper No. 1999-01-0445.

Nielsen M. (2000). *Accidents on rural roads in Denmark.* VTI Conferees, 13A, 7. Linköping, Sweden: Swedish National Road and Transport Research Institute.

Othman S, Thomson R, Lannér G. (2009). Identifying Critical Road Geometry Parameters Affecting Crash Rate and Crash Type. Chalmers University of Technology, Gothenburg, Sweden. 53rd AAAM Annual Scientific Conference, October 4-7, 2009, Baltimore, MD. Vol 53 · *October 2009, pp 155 -165.*

Oxley J, Corben B, Koppel S, el at. (2003). *Cost-Effective Infrastructure Measures on Rural Roads.* Monash University Accident Research Centre. Australia.

Polus A, Livneh M, & Frischer B. (2000). *Evaluation of the passing process on two-lane rural highways.* Transportation Research Record, 1701, 53-60.

RANKERS Project. Ranking for European Road Safety. Homepage http://rankers.cidaut.es. Spain; 2008.

Steyer R, Sossoumihen A, Weise G. (2000). *Traffic safety on two-lane rural roads: New concepts and findings*. Proceedings of the 2nd International Symposium on Highway Geometric Design (pp 299-312). Cologne, Germany: Road and Transportation Research Association.

Wong J Y. (2001). *Theory of Ground Vehicles*. Department of Mechanical Aerospace Engineering. Carleton University. Ottawa. Canada.

Appendix

Design Matrix A

													Lateral Acc.		Yaw Angular Vel.	
b0	**b1**	**b2**	**b3**	**b4**	**b11**	**b12**	**b13**	**b14**	**b22**	**b23**	**b24**	**b34**	**Left**	**Right**	**Left**	**Right**
1	-1	-1	-1	-1	1	1	1	1	1	1	1	1	5.25	3.56	0,26	0,18
1	0	-1	-1	-1	0	0	0	0	1	1	1	1	6.42	5.65	0,35	0,25
1	1	-1	-1	-1	1	-1	-1	-1	1	1	1	1	6.64	6.02	0,71	0,85
1	-1	0	-1	-1	1	0	1	1	0	0	0	1	4.74	3.58	0,27	0,19
1	0	0	-1	-1	0	0	0	0	0	0	0	1	5.84	5.56	0,35	0,26
1	1	0	-1	-1	1	0	-1	-1	0	0	0	1	6.06	5.68	0,73	0,64
1	-1	1	-1	-1	1	-1	1	1	1	-1	-1	1	3.94	3.62	0,28	0,19
1	0	1	-1	-1	0	0	0	0	1	-1	-1	1	5.09	5.16	0,38	0,41
1	1	1	-1	-1	1	1	-1	-1	1	-1	-1	1	5.16	5.14	0,91	0,49
1	-1	-1	0	-1	1	1	0	1	1	0	1	0	4.19	2.98	0,22	0,15
1	0	-1	0	-1	0	0	0	0	1	0	1	0	5.45	4.64	0,2	0,22
1	1	-1	0	-1	1	-1	0	-1	1	0	1	0	6.31	5.96	0,45	0,42
1	-1	0	0	-1	1	0	0	1	0	0	0	0	3.53	3.11	0,22	0,16
1	0	0	0	-1	0	0	0	0	0	0	0	0	4.92	4.65	0,31	0,22
1	1	0	0	-1	1	0	0	-1	0	0	0	0	5.99	5.65	0,5	0,56
1	-1	1	0	-1	1	-1	0	1	1	0	-1	0	3.32	3.04	0,24	0,16
1	0	1	0	-1	0	0	0	0	1	0	-1	0	4.37	4.67	0,33	0,22
1	1	1	0	-1	1	1	0	-1	1	0	-1	0	5.03	5.16	0,5	0,8
1	-1	-1	1	-1	1	1	-1	1	1	-1	1	-1	4.96	2.78	0,26	0,16
1	0	-1	1	-1	0	0	0	0	1	-1	1	-1	6.08	4.33	0,36	0,22
1	1	-1	1	-1	1	-1	1	-1	1	-1	1	-1	6.37	5.86	0,69	0,34
1	-1	0	1	-1	1	0	-1	1	0	0	0	-1	4.21	2.79	0,26	0,15
1	0	0	1	-1	0	0	0	0	0	0	0	-1	5.32	4.51	0,37	0,22
1	1	0	1	-1	1	0	1	-1	0	0	0	-1	6.08	5.62	0,7	0,43
1	-1	1	1	-1	1	-1	-1	1	1	1	-1	-1	4.24	2.92	0,31	0,16
1	0	1	1	-1	0	0	0	0	1	1	-1	-1	4.79	4.38	0,39	0,21
1	1	1	1	-1	1	1	1	-1	1	1	-1	-1	5.22	5.14	0,75	0,67
1	-1	-1	-1	1	1	1	1	-1	1	1	-1	-1	5.32	3.66	0,28	0,18
1	0	-1	-1	1	0	0	0	0	1	1	-1	-1	7.30	5.42	0,4	0,23
1	1	-1	-1	1	1	-1	-1	1	1	1	-1	-1	8.93	7.80	0,5	0,3
1	-1	0	-1	1	1	0	1	-1	0	0	0	-1	4.47	3.68	0,27	0,19
1	0	0	-1	1	0	0	0	0	0	0	0	-1	6.51	5.60	0,41	0,23
1	1	0	-1	1	1	0	-1	1	0	0	0	-1	7.78	7.89	0,52	0,3
1	-1	1	-1	1	1	-1	1	-1	1	-1	1	-1	3.95	3.60	0,29	0,19
1	0	1	-1	1	0	0	0	0	1	-1	1	-1	5.77	5.65	0,41	0,24
1	1	1	-1	1	1	1	-1	1	1	-1	1	-1	7.03	7.76	0,56	0,31
1	-1	-1	0	1	1	1	0	-1	1	0	-1	0	4.22	3.09	0,23	0,16
1	0	-1	0	1	0	0	0	0	1	0	-1	0	6.18	4.60	0,35	0,21
1	1	-1	0	1	1	-1	0	1	1	0	-1	0	7.52	6.76	0,44	0,35
1	-1	0	0	1	1	0	0	-1	0	0	0	0	3.61	3.09	0,23	0,16
1	0	0	0	1	0	0	0	0	0	0	0	0	5.27	4.60	0,34	0,22
1	1	0	0	1	1	0	0	1	0	0	0	0	6.63	6.75	0,46	0,34
1	-1	1	0	1	1	-1	0	-1	1	0	1	0	3.55	3.02	0,25	0,15
1	0	1	0	1	0	0	0	0	1	0	1	0	4.77	4.64	0,34	0,22
1	1	1	0	1	1	1	0	1	1	0	1	0	5.89	6.77	0,49	0,34
1	-1	-1	1	1	1	1	-1	-1	1	-1	-1	1	5.12	2.68	0,27	0,15
1	0	-1	1	1	0	0	0	0	1	-1	-1	1	6.72	4.29	0,39	0,22
1	1	-1	1	1	1	-1	1	1	1	-1	-1	1	8.37	6.44	0,48	0,32
1	-1	0	1	1	1	0	-1	-1	0	0	0	1	4.36	2.89	0,28	0,16
1	0	0	1	1	0	0	0	0	0	0	0	1	5.94	4.28	0,43	0,22
1	1	0	1	1	1	0	1	1	0	0	0	1	7.16	6.59	0,52	0,31
1	-1	1	1	1	1	-1	-1	-1	1	1	1	1	4.12	2.81	0,28	0,15
1	0	1	1	1	0	0	0	0	1	1	1	1	5.52	4.33	0,46	0,22
1	1	1	1	1	1	1	1	1	1	1	1	1	6.60	6.47	0,56	0,31

Paper III

USING NATURALISTIC FIELD OPERATIONAL TEST (FOT) DATA TO IDENTIFY HORIZONTAL CURVES

Sarbaz Othman[1]; Robert Thomson[2]; Gunnar Lannér[3]

ABSTRACT

Investigations to identify relationships between crashes and road features usually deal with effects of only one or two of the main three pillars of traffic safety - human, vehicle and infrastructure performance. There are usually several contributing factors from all three pillars which together lead to the crash. This study develops an approach to include information from all three systems by using field operational test (FOT) data that are recorded from real-life and natural driving data that is different from traffic simulations and on-site data sources. The study focuses on identifying horizontal curves from real traffic data and provides access to vehicle and human response data on curves as the vehicle was driven there. This information is needed to compare FOT to crash data obtained from retrospective analyses.

A method has been developed to derive the driving path radius for a curve using naturalistic driving data. In addition, the start and end points for the curve are also identified. With this information, vehicle response signals and human behavior data can then be arranged on a common axis referenced to the curve. The approach also identifies lane changing maneuvers on curves which can be used to evaluate potential crash triggers. The application of this method allows for reviewing changes in the regulatory speed limit, curve geometry, or crash history and thus evaluates the design of curves and choosing appropriate countermeasures.

Key Words: Traffic safety, Horizontal curves, Curve radius, FOT data, Vehicle dynamic responses

INTRODUCTION

Background

Addressing safety issues for the three major traffic safety pillars: human, vehicle, and infrastructure performance is still a challenge that faces road safety engineers. All three aspects must be part of a traffic safety plan and dealt with subject to budget limitations. Consequently, the cost efficiency of systems and countermeasures are decisive factors for policy making and design decisions. Road safety researchers are still continuously working to develop and establish relationships between collisions and geometric features such as curves.

Traditional methods such as accident analysis and controlled experiment methods until recently were effective in improving traffic safety (Neale et al., 2005), Moreover, there were not any better analysis approaches due to limited advances in technology and data collection

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systems from traffic safety perspective (Victor et al., 2010 b; Dingus et al., 2006). The traditional methods usually deal with linear effects without a comprehensive investigation to understand mechanism behind occurring accidents (Fink and Krammes, 1995; Sakshaug, 2000). A comprehensive study requires considering road-users, vehicles and traffic environment separately (Sandin 2008) because there is rarely a simple or single cause that leads to a crash. Instead, there are several contributing factors from the three main pillars of traffic safety which together lead to the crash. Correcting one of the many problem factors may prevent the crash and its serious consequences (Hollnagel, 2004; EuroRAP, 2005). Safety components are used together in systems for example in black spot analysis (Dupré, 2007) or investigating specific countermeasure (Bonneson et al, 2007).

On all roads, curves are complex but unavoidable features. Most of the crash studies indicate that road curves experience a higher crash risk (Othman et al. 2009) and a greater proportion of severe crashes that straight segments (Gibreel et al, 2001). Even on properly designed curves, many vehicles do not follow the exact alignment of the curve (Glennon & Weaver, 1972). Vehicles move either outward or inward relative to the centerline of the road while negotiating a curve. This lateral positioning of a vehicle is a deviation from a basic assumption of driving in the middle of the lane, used when designing horizontal curves, and can be a contributing factor in loss-of-control crashes. Safe driving along a curve requires an appropriate approach speed and adequate lateral positioning in the curve (Staplin et al, 1997).

It is important to create a safety evaluation method which combines the parameters of specific road segments together with vehicle dynamic responses and human behavior. More specifically, the method should be able to observe vehicle responses as well as driver behavior for a road segment for further analysis. One of the most reliable sources is data recorded and stored during natural driving conditions Field Operational Tests (FOT) which is Naturalistic Driving (ND). In FOT, driver behaviors and vehicle responses are recorded and stored during regular operations. The issue with FOT is that the data collected does not consider road geometry parameters explicitly. In addition, the dataset is large and complex, which creates many practical difficulties in analyzing simultaneous data sets. One approach to include road data and overcome data complexity is to focus on critical road segments. For example, extracting vehicle response data can be extracted when the vehicle is operated on specific road elements, which can be characterized in terms of specific design parameters.

In light of the studies mentioned earlier, horizontal curves were chosen for further study because they are one of the most important geometric features that can affect a road's level of service and safety. Finding the curve characteristics (radius, start-end points) from natural driving data is fundamental for analyzing vehicle responses in curves. It is essential because the travel path radius of a curve is different from real radius of the curve (Bonneson 2007). The radius from road design drawings is the physical radius which may be different from the driving radius that drivers follow when negotiating curves. It is the driving path that is more important than physical radius when connecting human behavior with curve information.

Figure 1 shows elements of a simple horizontal curve including the point of curvature (PC the point where the curve starts), point of tangency (PT the point where curve ends), and point of curve (POC any point along the curve) (Murgel and Hamilton 1999).

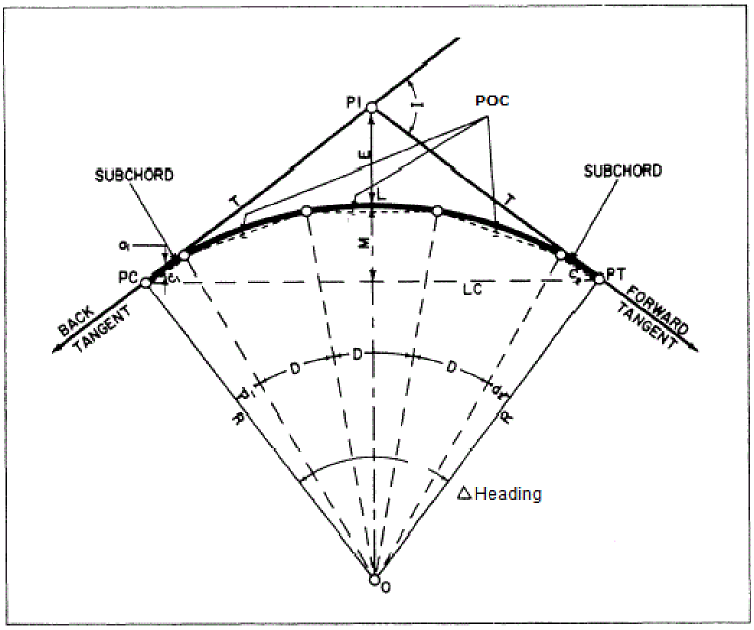

Figure 1 Elements of a horizontal curve. (Murgel, 1999)

Objective of the Study

The objective of the study is to find an approach able to identify horizontal curves from FOT data including the radius (R) and associated start-end points of the driving path curves and then combine the curve information of several safety related parameters on a common axis. More specifically, the method should synchronize vehicle responses and human behavior on identified horizontal curves for subsequent analysis purposes.

Previous Studies

There are considerable research activities investigating horizontal curves focusing on different aspects of service and safety-related features of curves. All reviewed safety investigations agree in pointing out curves as a black spot for traffic safety. However, they are not always agreeing on the ranking of factors that cause high crash rates in curves. In the USA, Fink and Krammes (1995) showed that the degree of curvature is a good predictor of crash rate on horizontal curves. The effects of approach tangent length and sight distance were not as clear and the results suggest that the adverse safety effects of long approach tangent lengths and short approach sight distances become more pronounced on sharp curves (Fink and Krammes 1995). A study by Dupré (2007) revealed that insufficient super-elevation, in combination with sharp curves, is the main factor of crashes on motorway access ramps. However, Sakshaug (2000) claimed the opposite, stating that there was a tendency towards higher crash risk for curves with high super-elevation than with low super-elevation.

In a crash history analysis (Othman et al. 2009) showed that crash rate increases with decreasing curve radii. Furthermore, overtaking crashes are more frequent in right curves compared with left curves. Steyer et al. (2000) noted that one of the important safety-related features in curve negotiation is vehicle lateral placement. They stated that the driving path should be considered when investigating crashes on curves. Moreover, the study makes a distinction between right and left curves and offers some suggestions as to why centre-line encroachments occur. Lateral placement is defined as the lateral position of vehicles in the original travel lane. This indicates how well the driver keeps the vehicle between lane boundaries while negotiating curves. According to Miller and Steuart (1982), lane keeping is a function of vehicle size, lane width and lane type. Othman et al. (2010) in another study simulated vehicle-road interaction in different curve directions. The results showed that vehicle responses in terms of lateral accelerations and yaw angular velocity are significantly different between lane-changing on left and right curves. However, maximum values of lateral acceleration and yaw velocity could not explain differences in the crash rate between left and right curves. Leonard et al. (1994) concluded that curves induce lateral acceleration and higher crash rates are expected when vehicles experience higher lateral accelerations.

With respect to speed on curves, a study was undertaken by Glennon et al (1985) to determine when drivers start their deceleration and reach the curve speed, relative to the point of curvature (PC) shown in Figure 1. The study indicates that drivers maintain their speed on the tangent up to a point about 3 s travel time from the PC. At this point, they begin to decelerate at a constant rate until they reach the mid-point of the curve. The deceleration rate increases with decreasing radius. Subsequent research has shown that this behavior is consistent among drivers and is generally independent of tangent speed and radius (Bonneson 2000). The implications of the findings by Glennon et al. (1985) are that drivers wait until they are close to the curve before they begin to adjust their speed, regardless of the curve’s radius. It has been speculated that this behavior reflects the drivers’ desire to estimate an appropriate curve speed based on their assessment of curve sharpness. However, they are unable to make this judgment until they are very close to, or traveling along, the curve (Krammes et al. 1995). This behavior suggests that advance information about an upcoming curve, as provided by a curve warning sign, may heighten driver awareness of the curve, but it does not appear to cause them to begin slowing sooner. All studies mentioned above are based on crash history analysis, simulations, field tests or theoretical calculations. These types of data sources and studies are subject to a high degree of experimental control. Moreover, the studies may include interactions between only two of the three main safety factors.

There are a variety of curve radius-estimation methods to identify horizontal curves with different level of accuracy, precision, cost, ease of use, and safety. The recommendations, according to a comparison study (Carlson et al (2005), are based on the expected needs of three different groups that use radii information: transportation agencies, crash investigators and transportation researchers. The study compares ten radius estimations techniques for horizontal curves. The results showed that using plan sheet and Global Positioning System (GPS) had the smallest average relative error: -0.9% and 1.2%, respectively. Another study (Imran and Hassan 2006) presents also a global positioning system – geographic information system (GPS–GIS) based procedure for the deduction of the horizontal alignment of a road based on the path of a control vehicle. The results showed that the procedure could produce the horizontal alignment of a road quickly, accurately, and for a relatively low cost. Thus, GPS based signals are promising to estimate curve radius especially when the GPS errors are minimized, for example, by taking the mean of several radii estimations using different trips (Box et al. 2005).

From the review of the studies available there is a lack of research connecting all three safety pillars in a method which is the aim of this study. The reliability and availability of input data is another important factor due to complexity of connecting all three factors together on common time axes. This study uses Field Operation Test (FOT) data in its approach. In FOT; driver behavior and vehicle responses are recorded and stored during natural driving settings.

MATERIAL

The methodologies that have been used in most of the investigations to address traffic safety deficiencies are usually based on data collected from simulations, field test or crash databases. However, these data sources have limitations due to questions regarding bias, precision and accuracy in interpreting natural driving situations. The data used in the following approach was mined from the SeMiFOT FOT. In comparison to the other mentioned data sources such as simulations and field tests, which are smaller studies with a higher degree of experimental control, the FOT is a quasi-experiment with drivers using vehicles during their daily routines without special instructions about how and where to drive. The study period typically extends over at least a few weeks and data logging works autonomously (Victor 2010 a).

Data Flow from Vehicle to Analysis

The data flow from vehicle to analysis is described in Figure 2. The data was stored locally in the vehicle while summary/status information was uploaded remotely via wireless 3G/GPRS. When the status information was uploaded, it was transferred into a database and displayed in a web interface for quality and status checks (for example, available hard drive space left). Video was stored separately and synchronized with data in the database. The analysts can then access both the database and the video data synchronously, either via the analysis viewer or directly from Matlab^{TM}. As for the installed data acquisition units, different vehicles had different hardware configurations.

An Oracle database was chosen for SeMiFOT together with the UMTRI (University of Michigan Transportation Research Institute) inspired database. A 10Hz sample frequency was used for most channels except those with high sampling frequency such as accelerometers with 100 Hz and EyeTracker (SmartEye & SeeingMachines) with 50/60Hz. Map data attributes were added to the database based on map matching of GPS-positions.

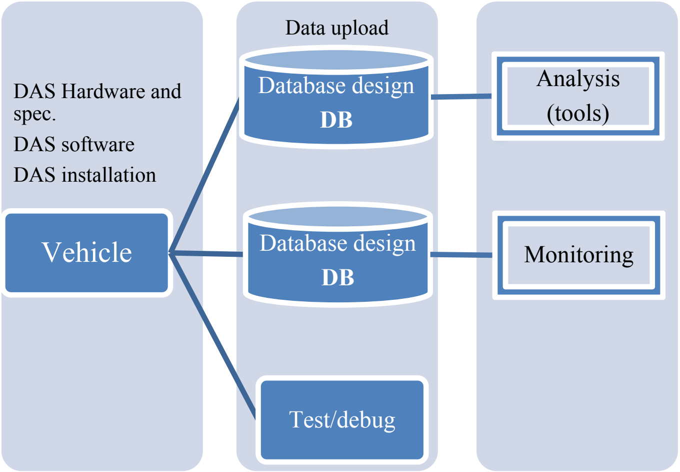

Figure 2: An overview of the data management process

The data acquisition system (DAS) in the SeMiFOT includes all aspects of the data acquisition, sensing and interfaces that are parts of collecting data from the vehicles, as shown in Figure 3, where CAN (Controller–Area Network) is the vehicle bus standard designed to allow microcontrollers and devices to communicate with each other within a vehicle without a host computer and CAM is a video camera. Moreover, other road data specifications were included in the database such as road width, road type, legal speed limit, time dependent driving speed, junction (distance to nearest node + id), functional road class, roundabout, urban area, traffic flow (ADT, axle pair, trucks, vehicles, state roads only), road name/number, on-ramp, off-ramp, junction class, and speed cameras.

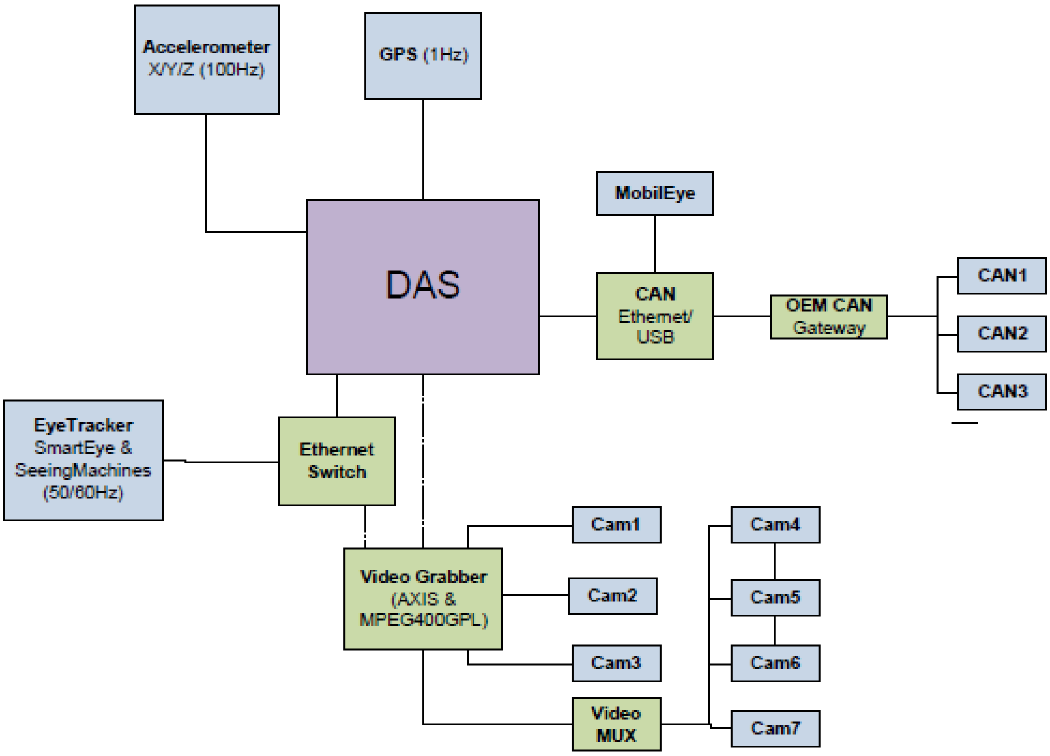

Figure 3: An overview of the DAS with its components (Bärgman and Svanberg 2010)

In the naturalistic FOT study , the drivers of 14 vehicles (including 7 Volvo cars) logged a total of 2944 hrs of data over a distance of 171440 km during 7934 trips and a data collection period of about 6 months (collected over a period from December 2008 to June 2009).

The approach developed in this study was developed using data limited to 7 Volvo cars. The following study focuses on the methodology and the intention is to include all vehicles and analyze any signal of interest. The parameters used in designing this tool were vehicle type, GPS coordinates, yaw rate, diving speed, speed limit, and vehicle heading. Driving speed signals have been used to test the method. Other signals such as steering angle, lane positioning, accelerations etc should easily be analyzed with the tool.

Data Quality

It is essential to make sure that this work has a proper data source. FOT data has been checked in a data quality analysis (Victor, 2010 b) to guarantee that the data fulfils all requirements related to the addressed objectives of this study. The approach for data quality analysis was developed in FESTA (2008) and consists of four steps shown in Figure 4.

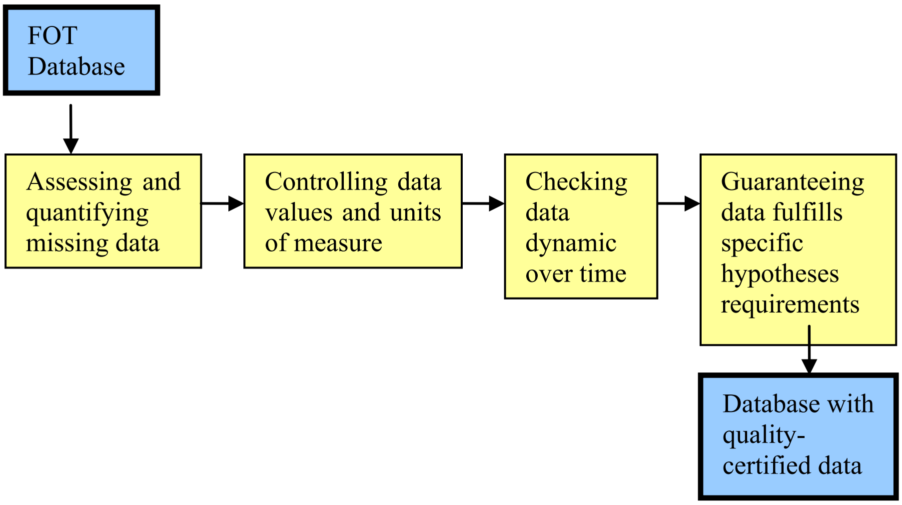

Figure 4: Data quality analysis (Victor et al., 2010)

In the first step the data is controlled for missing data and in the second step quantity and units of all measures are investigated (for example by checking if the data is within a reasonable range). These two steps need to be conducted during the upload procedure. In the third step the dynamics of the data is checked such as checking the amplitude range and the derivatives of measures. The last step considers checking whether the data fulfils all requirements related to the addressed hypotheses related to SeMiFOT.

RESULTS

The approach to identify horizontal curves from FOT data and then combining them with other safety factors on a common axis consists of several steps as shown in Figure 5. Matlab scripts have been used in implementing the steps. The process starts by plotting GPS data in the FOT database to define the FOT road network and then selecting road sections of interest. In the second step the curves are identified and their radii are estimated from the selected road section while in the last step data signals are synchronized on the curve sections for further analysis.

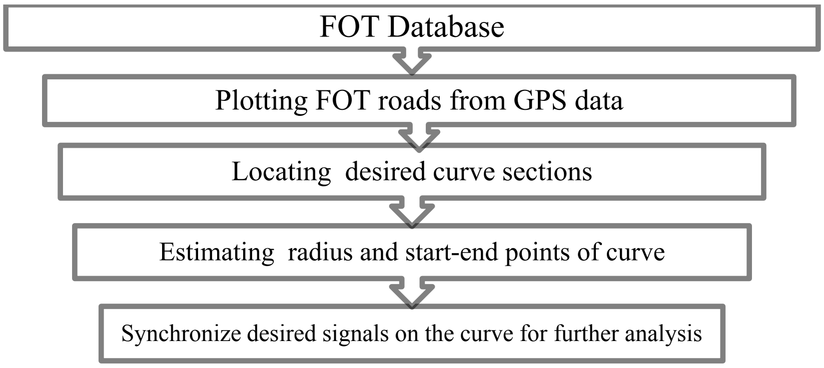

Figure 5: Processing and filtering FOT data

Plotting Roads and Collecting Trips

Roads are plotted from GPS coordinates in the FOT database according to the roads' speed limit. The GPS position is expressed in longitude (east-west) and latitude (north-south). The unit is decimal degrees and the resolution is 0.00001 deg which corresponds to approximately

1.1 m for the latitude and 0.56 m for longitude. GPS position has an original sampling frequency of 1 Hz but it has been resampled to 10 Hz (by repeating each value 10 times) (Bärgman and Svanberg 2010). The Volvo cars were driven by 29 different drivers and a total of 6950 trips of 91504 kilometers during 1700 h of have been collected. The trips were on different road types including dual roadways, 2+1 road, motorways, etc. The 2+1 road is a Swedish concept of converting unsafe non separated rural motorways to '2+1' roadways. In this configuration, a third lane is created with a median barrier between the opposing travel lanes and is used as a passing lane that alternates about every 1 to 3 km for the different directions of travel.

Specifying and separating the roads according to their speed limits 50, 70, 90 and 110 km/hr, as shown in Figure 6, simplifies the choosing curves that have the same or different speed limits in both curve directions (i.e. left and right). It is also possible to choose left or right curves where the speed limit changes within the curve due to approaching a residential area, change of road type, etc. Curve sections of interest are chosen subjectively from the figures by reading GPS coordinates of the section and using them as input to collect trips on that specific section. The GPS plot shows also if there are enough trips on the road section. A minimum number of 5 trips was the threshold for analyzing a road section.

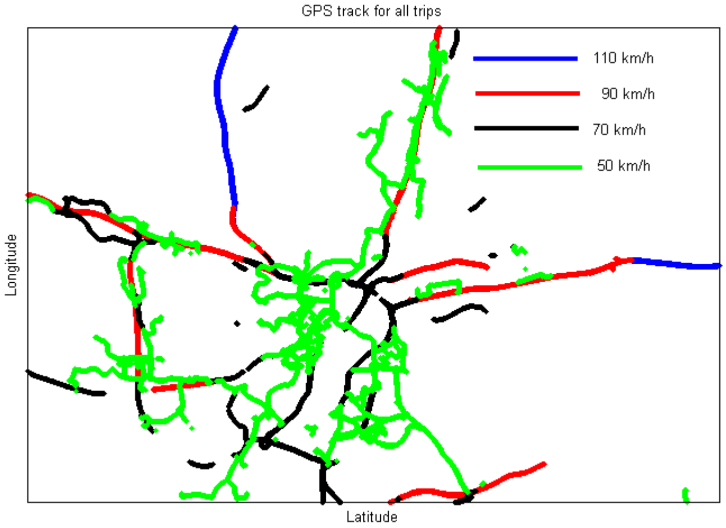

Figure 6 GPS track for all trips

Since SeMiFOT is a naturalistic driving study, the number of trips on each road section is different. Figure 7 shows, for example, trips by only one vehicle on a curve section of the highway E20 (49 and 60 trips on the left and right curve directions respectively). The trips are separated and plotted according to left and right turn directions where red lines represent left curves while blue lines represent right curves. The sum of yaw rate data has been used to decide the driving direction of the trip on the curve. If the sum is less than zero (negative) the turn is to the right while it is a left turn if the sum is greater than zero (positive). The variation of vehicle paths across the road section shown in the figure is a combination of GPS measurement errors (Ardeshiri and Kharrazi 2006) and the different driving path for each trip on the roadway that is explained later in Section Start-End Points of the Path Curve.

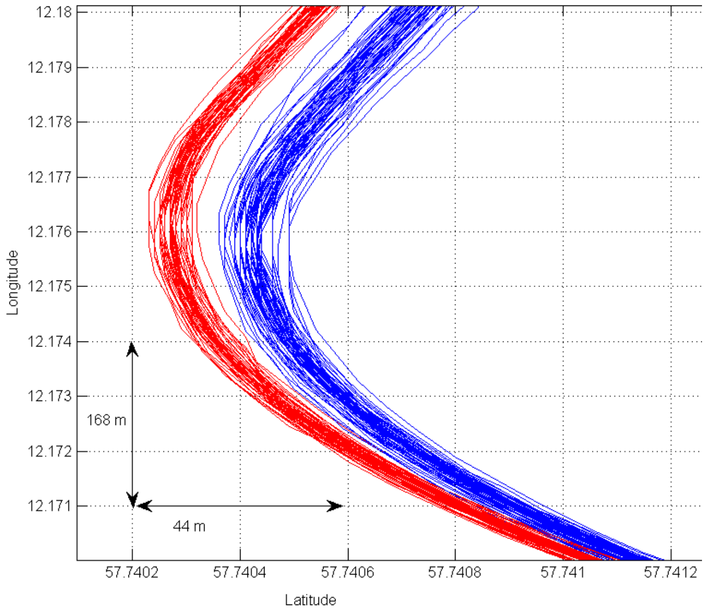

Figure 7 Trips occured on a curve section

After separating trips, data quality is checked by removing trips with low quality or with no data and the corresponding data signals on the section such as heading, yaw rate, speed, etc. are collected.

Locating the Curve

To precisely locate the curve and its endpoints on the selected road sections, both yaw rate and heading have been tested. Yaw rate is the angular velocity of the vehicle rotation which is sensitive to steering input (Wong 2001), while heading is the travel direction derived from the GPS signal. The results with yaw rate data were not promising for defining curve ends. Sudden changes in yaw rate along the curve section introduced peaks in the curvature profile of the section as the curvature is function of yaw rate. Consequently, the number of identified curves on the same road section varied depending on driving pattern and travel path of the trips as shown in Figure 8 and Figure 9. The red lines in the figures are an indicator to separate curves and straight sections (zero “Off” for curves and one “On” for straight sections). They are used to identify curves and to define where each of the curves start and end. The blue lines in the figures represent curvature of the path found from yaw rate of the vehicles. A curvature of one rad/s was tested, as a threshold, to separate curve and straight sections. This implies a curve section starts when curvature exceeds one rad/s and ends when it falls below one rad/ sec. In Figure 8, from one trip, one curve has been defined where the curvature, blue line, is above one. The indicator line is then “Off” or zero along the curve section.

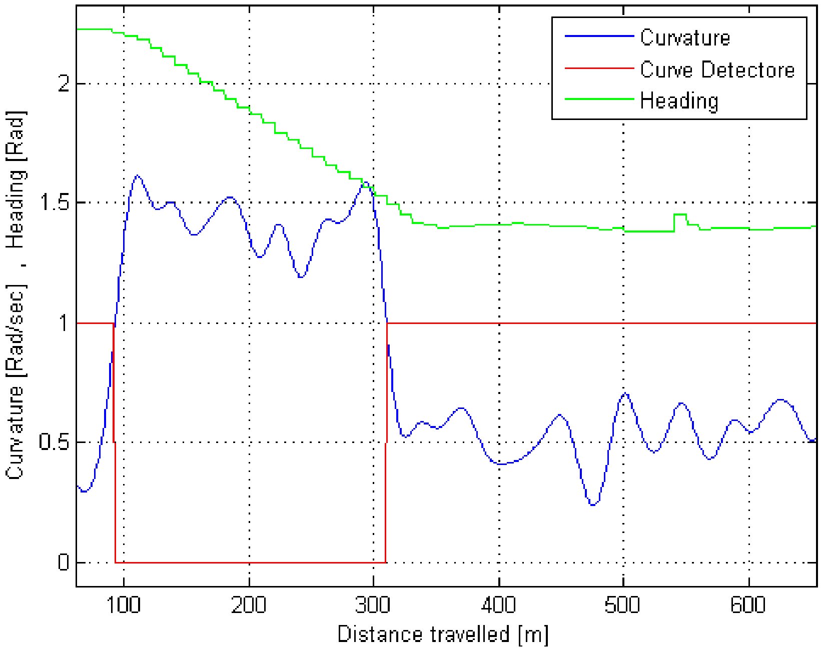

Figure 8 Locating one curve using yaw rate to separate curves and straight road sections

Another trip of the same vehicle but with a different driving path had three curves identified on the same road section instead of only one curve, as shown in Figure 9, despite that there is only one curve on this road section. This split the curve in Figure 8 to three shorter chord curves. Different trips gave different numbers of curve sections depending on the driving path. This problem does not occur when using vehicle heading, which is based on GPS signals to locate curves. Heading is less sensitive to driving course in locating the curve. Figure 10 shows plotted headings for all trips of the car along the same curve section where each of the trips identify only one curve.

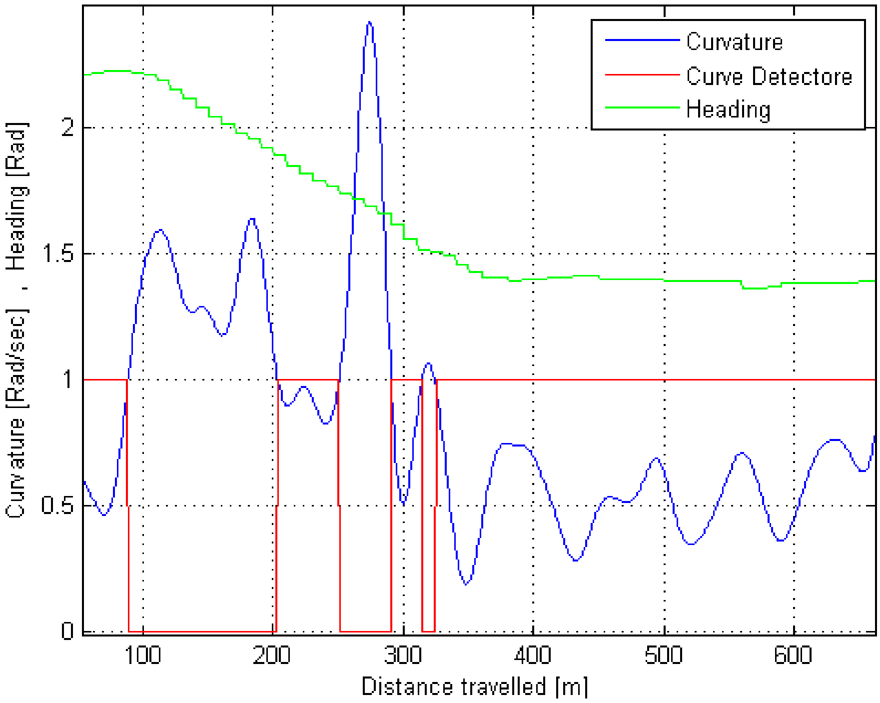

Figure 9 Dividing one curve to several by using yaw rate to separate curves and straight road sections

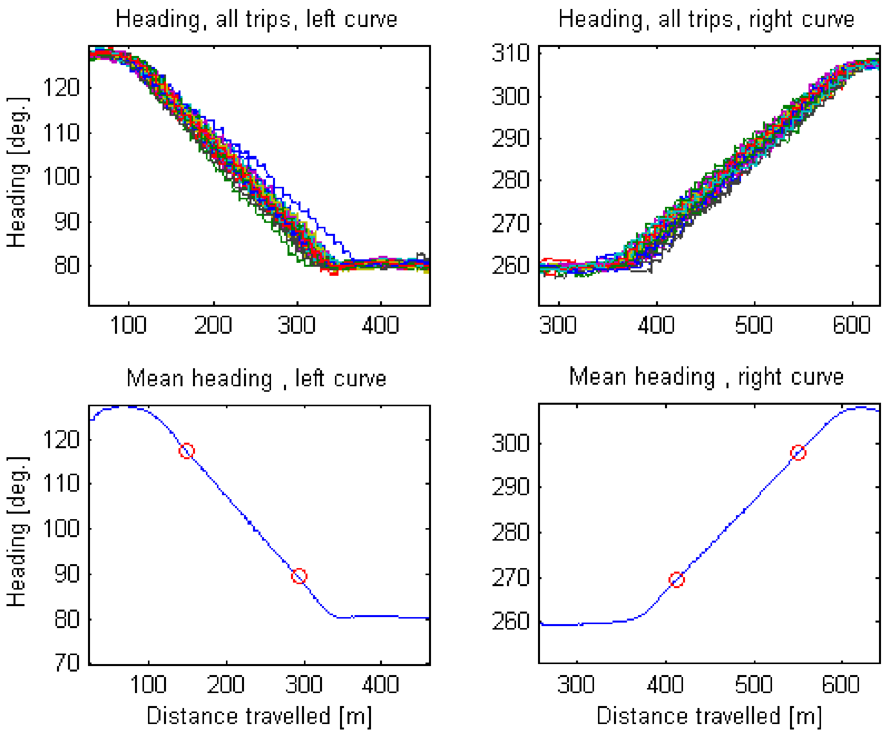

Figure 10 Heading for all trips on a curve section

Estimating Curve Radius

Equation 1 has been implemented to estimate path radii of each trip, shown in Figure 7, using heading of the vehicle and distance travelled. From the heading signal of the vehicle ΔHeading in Equation 2 is calculated. The ΔHeading is the change in heading of the vehicle between two points on the curve as shown below in Figure 11. The distanced travelled is found from the velocity of the vehicle and time between the two points (Equation 2).

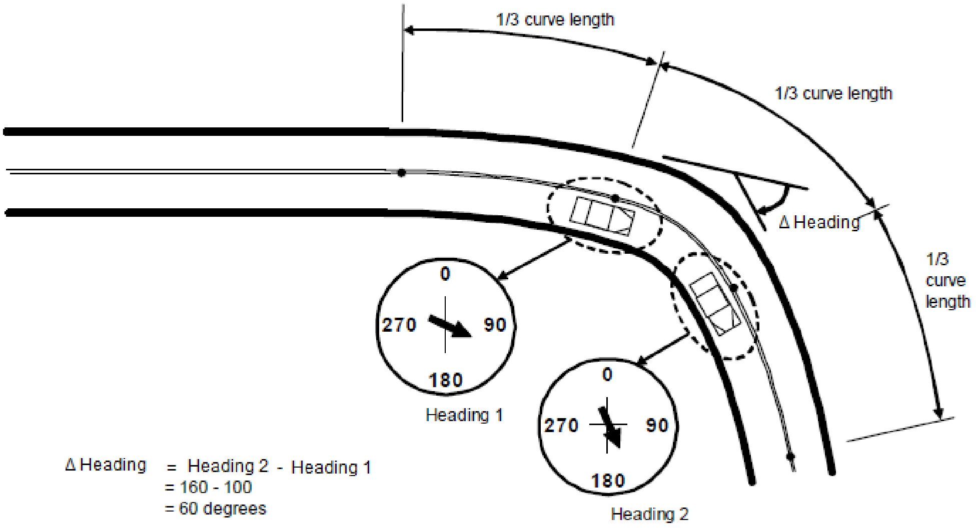

Figure 11 Finding angle of change of the curve using heading

$$R = \frac{180° * L}{\pi * \Delta\, Heading} \qquad (1)$$

Where:

R = Radius of the curve

Δ Heading = change in the heading between two point on the curve

L = distance the vehicle travelled which is length of the curve chord between the two chosen points

$$L = \sum_{k=0}^{n} V_k * dt \qquad (2)$$

Where:

V = Vehicle speed

n = number of measured vehicle speeds

dt = time interval between measured vehicle speeds

Theoretically, the estimated radii using any two points along a circular curve (Figure 1) should be the same for any two different points along the selected curve section from FOT. However the challenge is to make sure that the points lie on the curve section and the estimation is correct. ΔHeading is used, with a threshold, to define the two points on the curve where the first point is set when ΔHeading, referenced from beginning of the analysis section, reaches the threshold. Similarly the second point is set when ΔHeading, referenced from the first point, reaches the threshold. In order to determine an optimal threshold in deciding curve radius, different threshold limits, between 5 to 22 degrees, have been tested. The results of radius estimation using different limits of ΔHeading were similar with low standard deviation as long the two points laid on the curve as shown in Table 1. When the limit was high, the distance between the two points became very short and the result was sensitive to errors. The latter case lead to a radius found from Equation 1 becoming either zero when the chord is zero or very large when the ΔHeading is very small. This is shown in Figure 12 where the middle two red points located when ΔHeading is 22 degrees. When the limit is low then one or both points could lie outside the curve section in which case the sections outside the curve are also included and leads to errors in estimating radius as the first and last two points in Figure 12. Mainly ΔHeading values within the range of 8.5 – 11.5 degrees (green points in Figure 12) can be used. The selected points can be checked from the heading plot to determine whether they are on the road curve and are suitable points. After radii were estimated for all trips, outliers were removed (when the radius is two standard deviations away from the mean of the sampled radii).

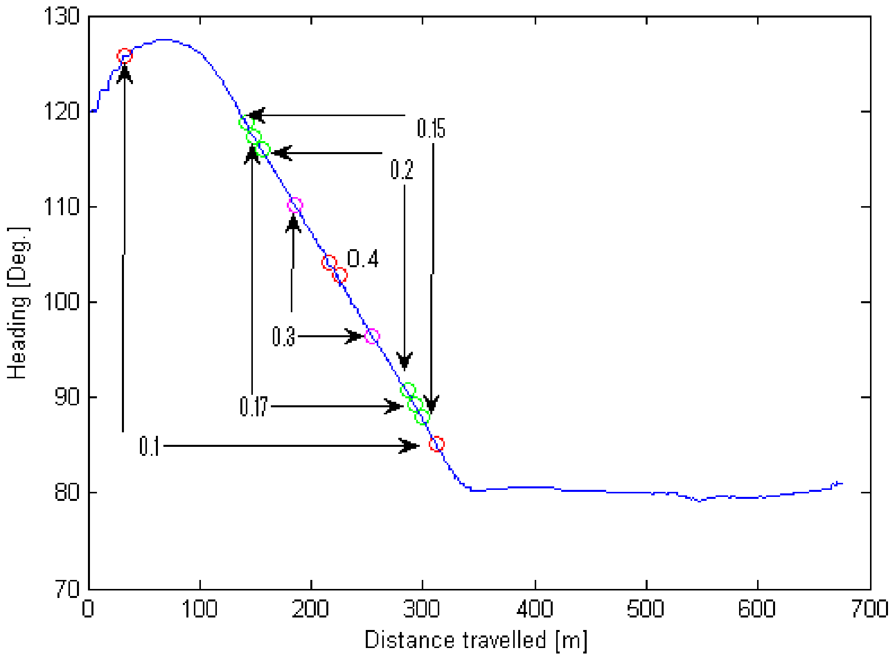

Figure 12 Choosing two points using change of heading to estimating path radius

Table 1 Curve radius estimations using different Δ Heading

ΔHeading [rad] (deg)	Curve1		Curve2	
	Radius [m]	STD	Radius [m]	STD
0.1 (5.7)	1017	94	524	87
0.15 (8.5)	888	22	436	17
0.17 (9.7)	896	20	422	22
0.2 (11.5)	901	19	422	28
0.3 (17.2)	951	40	462	60
0.4 (22.9)	666	884	0	0

Despite using same Δ Heading, there are small differences in radii estimations from different trips of the same curve which is a combination of the errors from the measurements of vehicle heading signals, GPS dependent, and different driving paths. Driving through a curve is different and subject to individual drivers as the drivers follows different paths in curves depending on their steering skill, the dynamic behavior of their vehicle, and from their anticipation of the road layout (Raymond et al. 2001). It is worth mentioning again that the curve radii in Table 1 are the estimated radii of the vehicle travel path which could be different from the designed curve radii. The difference is, for example, because the drivers usually shift their vehicle laterally in the traffic lane such that they flatten the curve slightly. This behaviour allows them to limit the speed reduction required by the curve. A demonstration of possible difference between the radius of a curve and the travel path radius is shown in Figure 13 (Bonneson et al. 2007).

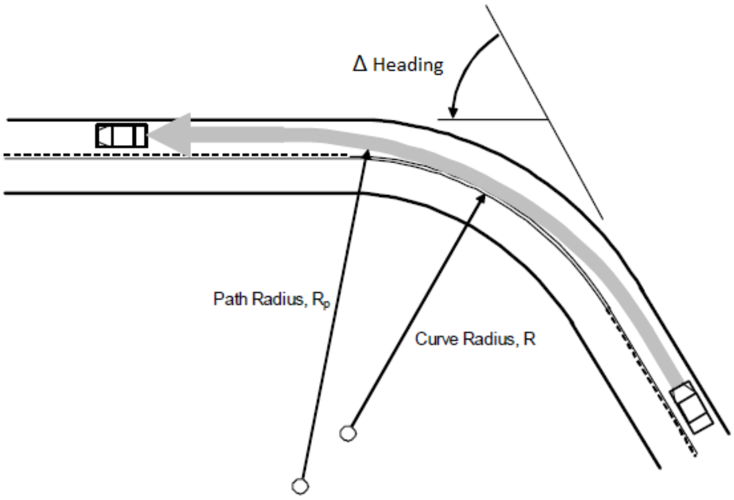

Figure 13 Effect of lateral shift on travel path radius (Bonneson et al, 2007)

Start-End Points of the Path Curve

Finding the start- end points of the driving path is critical in curve analysis since they are essential to locate and find the curve length and, moreover, to combine the curve with related vehicle dynamic and human behavior factors. The two heading points, used previously to estimate R, including measurements between them are used to model the curve. From the initial measurements, coefficients of a first degree polynomial has been evaluated which represents the simple curve. A residual vector is calculated from differences between the values of modeled polynomial and the measured heading data of the selected section including the curve. The start-end points are estimated, from the residual vector, when the vehicle changes direction by one degree during entrance or exiting the curve. This is shown in Figure 14 where the red points are those used to estimate R and model the polynomial while the green points are start-end point of the curve when direction is changed by one degree.

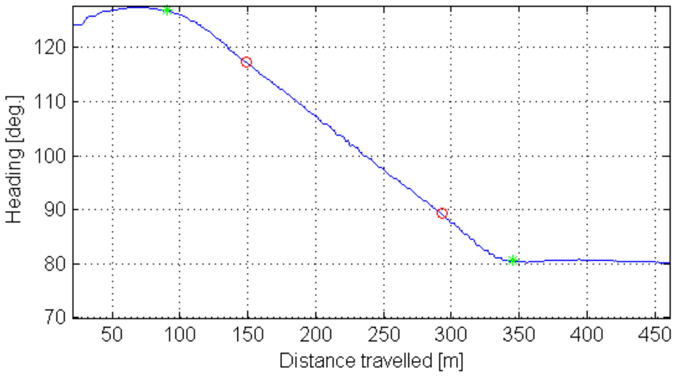

Figure 14 Start-end points of the curve

Depending on the driving course of trips start-end points of the same curve could be slightly different. One start-end point (PC and PT) has been determined for each curve by taking the mean of (PC and PT) of all trips on that curve. This is demonstrated in Figure 15 where a zero point called PC has been set as reference start point (PC) for all trips and the end point (PT).

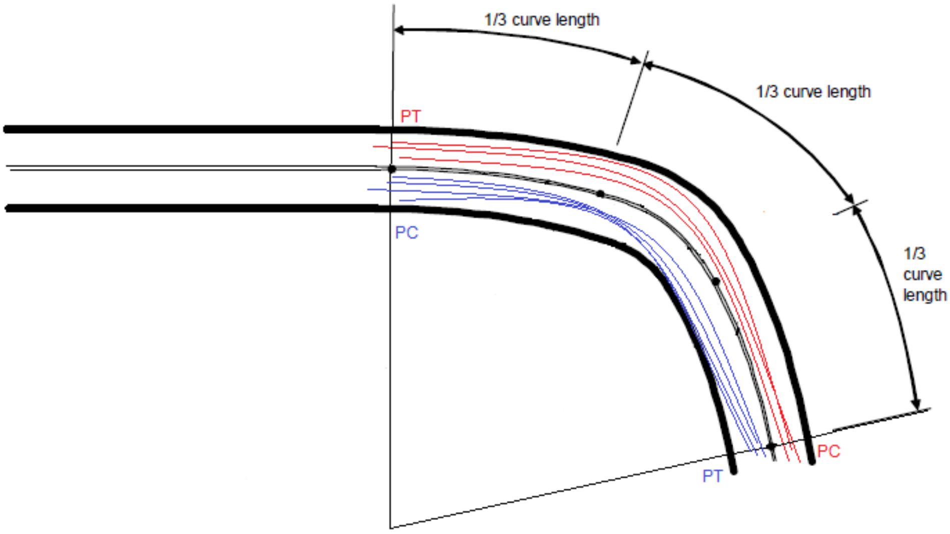

Figure 15 Two points has been set as start and end of all trips

Signal Treatment and Analysis Possibility with the Method

After estimating radius and start-end points of the curve, the signals of interest can be synchronized along the curve for analysis and further treatment. For example the profile of signals such as speed, lateral position, yaw rate, lateral acceleration, and steering angle can be analyzed. The profiles show trends and characteristics such as signal dynamics, amplitude range and derivatives of the measures along the curve. Furthermore, the signals are collected depending on which information is of interest. Reference signals always needed to define curve sections such as GPS coordinates, vehicle heading, driving speed, time index and yaw rate.

The main concern in analysing different data signals along the curve is that the vehicles have different driving speeds which lead to different numbers of sample points for each trip. Hence, it is not possible to use a time index as a reference to compare and analyze the trips. However, travelled distance along the road section can be used as a reference instead. A Fourier Transform based interpolation has been used to fit trips on the travelled distance. The original vector is transformed using Fast Fourier Transforms (FFT) and then transformed back with extended or shortened signal vectors keeping their information content as shown in Figure 16. The red lines, shown in Figure 16, are the driving speed along the curve, with different length, plotted relative to the number of measured speed points. The measured speed vectors then have been changed to fit the curve chord. These are delineated in blue lines in Figure 16 where the blue lines have same length and plotted with respect to transformed numbered of speed points to fit the travelled distance of the vehicle.

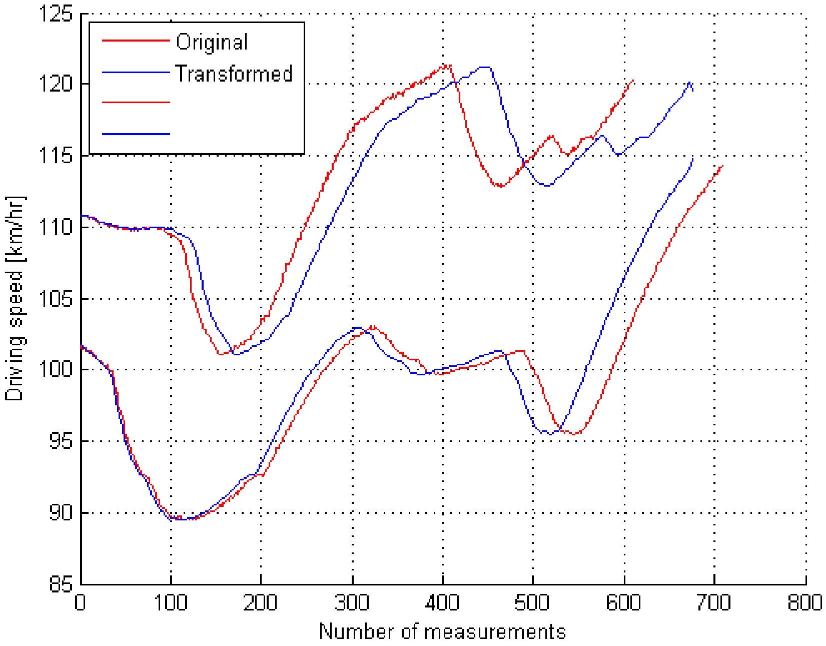

Figure 16 Original and transformed speed signals on a curve section

This technique makes it possible to synchronize trips with different speeds on the curve and analyze the signals together along the road section. Moreover, the possibility of analyzing signals from a single trip for the same curve is facilitated. In Figure 17, for example, trips that have maximum and minimum speed on a curve section have been identified for further analysis.

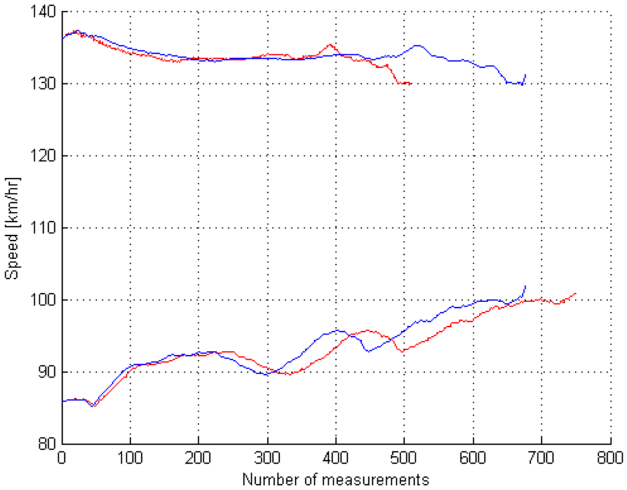

Figure 17 Maximum and minimum speed trips

Another example of an analysis is shown in Figure 18, the original and transformed speed profiles of all trips on the left and right direction of the same curve section are plotted. The pattern of the driving speed along the curve has been calculated by taking the mean speed of the trips, where the speed profile on the same road section indicates different characteristics between left and right direction.

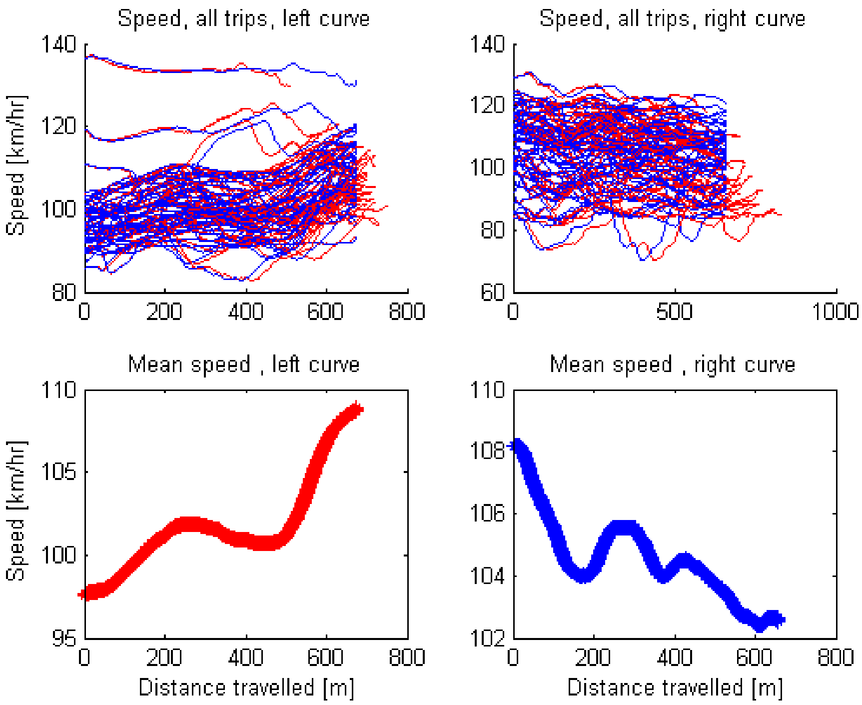

Figure 18 Speed profile for all trips along a curve section

DISCUSSION

This section discusses specific results in this study. The importance of the study including usage in any subsequent analysis is explained later in the summary section.

Plotting Roads and Collecting Trips

The GPS track plots were used in selecting road sections with respect to their speed limit with sufficient accuracy according to the SeMiFOT quality report (Vector et al. 2010 b). In addition, the GPS based heading signal used to estimate R for each of the trips does not affect the angle of curvature because the systematic GPS error within each trip is the same (Ardeshiri and Kharrazi 2006). Trips with low quality or no data have been removed during collecting the trips. The remaining number of trips on selected curve sections was important though, an accurate path curve radius cannot be found if there are few trips on the curve. An insufficient number of trips on the curve will also not allow analyzing and comparing signals from single trips on the curve section and a minimum limit of 5 trips was chosen for further analyzing a curve section. The number of trips can be counted at the start of the process using the GPS track map when selecting the curves for analysis. In this way selecting curves with insufficient trips can be avoided since analyzing these curves will then not be feasible. This is one of the limitations using FOT data in which it is not possible to influence the driving route of the vehicles.

Separating trips to left and right curves, i.e. driving and back along the curve, was essential in order to classify curves and corresponding signals according to curve direction. Separating trips can be used, in subsequent analysis, to compare signals of interest on left and right curves such as driving speed, lateral positioning, etc. Another advantage of separating trips is to determine trends of the signals on each curve direction. Accumulated yaw rate along the curve is used to separate left and right trips, right turns when yaw rate is negative and left turns when it is positive. This can be used to identify trips on the incoming lane (i.e. on wrong side direction), for example when the yaw is positive but the GPS plot of the trip is on the right turn lane. It is more likely to find this type of events on non separated two-way roads when there is oncoming traffic. This is more accurate when using accurate GPS coordinates such as differential GPS. Driver behavior and vehicle signals before entering the curve of such trips can be analyzed to find reasons for driving on the wrong side of non-separated roads. For example the reason, among others, could be a high speed entering the curve and cutting the curve to attempt to maintain travel speed (Bonneson et al. 2007).

Estimating Curve Radius and Start-End Points

Finding the driving path radius of a curve from real traffic was one of the main tasks in this study. According to most of the studies, curve radius has a great affect on crash rate (Othman et al. 2009). Results of estimated the radii of only two curves, using Equation 1, are presented in Table 1. In any subsequent analysis it is essential to classify curves with respect to their radius. The approach in this study considers all curves as simple and does not distinguish between type of curves, such as simple, compound, reverse and spiral, which is another limitation of this study approach. However, simple curves which have single (constant) radius are the most common type of horizontal alignment curve (Donnell et al. 2009).

The path radius calculated with the developed method was compared to the physical radius measured from aerial photographs of the data collection areas. As seen in Table 2, there was good agreement between the estimated driving radii and the physical curve radii for the road centerline. This indicates that the method was able to appropriately classify the curve radii into different bins for future analysis purposes.

Table 2 Driving path radius estimates compared to physical curve radius

Calculated		Aerial Photography [m]
Left Curve [m]	Right Curve [m]	
1105	1124	1115
1177	1124	1560
779	782	716
560	532	430
897	868	872

Yaw rate could not be used to define curves and their ends because it was very sensitive to the steering input as explained in Section 0 However, yaw rate is interesting to define events/incidents or other driving maneuvers on curves such as lane changing and overtaking. Using heading to determine path radius gave reasonable results in terms of standard deviation of radii found from trips on the curve. Estimating path radius is essential to classify curves into groups for analysis reason. From changes in heading, two points on the curve were identified to estimate radius and to find a polynomial representing heading along the curve section. The polynomial was used to define the start – end points of the curve where the vehicle enters and exits the curve. Using the change in heading between start (PC) and end (PT), points to calculate radius was not accurate because start and end points of the trips are different along the same curve depending on where the driver started turning and change direction. This led to radius estimations of the same curve diverging considerably depending on trips and ΔHeading threshold. Different start-end points are interesting for analyzing how trips differ in terms of how drivers enter, driving along and exit curves and what these differences depend on. This information is needed to determine how driver behavior, driving speed, vehicle type, curve type or their combinations influence curve paths. To analyze corresponding signals and reduce the effect of individual drivers, common references for start and end points for the curves were needed to put all trips on a common axis. Putting trips on a common axis allows analyses of individual trips on the same curve. It also allows mean values of different signals on individual curves to be compared to corresponding data on other curves. The reference points are also important to determine differences of PC and PT between paths for the trips and the physical road curve. The start-end points of driving path are determined when the vehicles turn and change their course which could be different from the PC and PT designed for the road.

Analysis Possibilities using this Method

Radius estimation and defining start-end points are the most important outputs of this approach study. The radius of the path can be estimated from any two points on the curve with some reservations explained in Section 0. The two points can then be used to model and estimate start-end points of the curve. Finding curve parameters, along with signal profiles for the trips (Figure 17 and Figure 18) and driver behavior factors that what they can be used to explain signal characteristics and driver behavior along curve sections. This can be implemented in any subsequent data analysis to scan the curve sections available in FOT data (Figure 6). Depending on the results, effects of other factors can be studied and added to the identified critical curves such as presence of super-elevation, view distance, sunshine, roadside, road way environment, etc. Figure 18, for example, shows different speeds along the curve section as well as different speed profiles between left and right curve directions. To study this variation of the signals, it is important to subdivide curve into sub-chords which is a further classification beyond the division of curves according to curve radii-and directions mentioned previously. The subdivision should include at least entrance, middle and end of the curve or to finer parts such as in a field study (Alonso et al. 2007) that divided a curve to 9 sub chords. The number of sub-chords can be decided according to the variations in the signal profiles and it needs to be consistent for comparison reasons, at least, in curve groups that have same or similar curve radius. It is also relevant that the analysis includes road sections, together with corresponding signals, before and after the curves. Different type of road segments, before and after a curve, such as straight section, vertical curves or another horizontal curve may affect driver's behavior and vehicle responses on the curve that need to be analyzed.

Summary

FOT data that has been used in this study was initially collected for evaluating active safety devices (Vector et al. 2010 b). A key challenge in the analysis of naturalistic data, such as FOT, is how to enhance the data so one can infer the influence of driver, vehicle, and roadway characteristics on driving safety. However, naturalistic databases usually contain large quantities of data that are complex and imperfect and require a multidisciplinary approach to draw conclusions regarding traffic safety. To study roadway features, it was important to limit and choose road segments of interest and then combine them with other traffic safety factors and was the purpose of this study. The current focus is limited to horizontal road curves where, according to large number of studies, are considered as safety black spots

(Othman et al. 2009; Bonneson et al. 2007).To achieve the purpose of this analysis, the methodology shown in Figure 5 has been implemented.

A small-scale test was performed in order to assess the application of the methodology in any subsequent large-scale analysis. What makes this approach important is the possibility of choosing curve sections on the GPS map and analyzing their safety components. For example, lane changing maneuvers can be identified which can be used to define abnormal traffic events or a trigger for a crash on the curve sections. Using the method in this study, it is possible to look at several parameters at the same time to explain the reason or causes beyond the event or potential crash triggers. For example, the vehicle in the trip shown in Figure 9 experienced sudden changes in yaw rate along the curve section, which can be considered as an event and is essential to explain why the vehicle trajectory is not consistent along the curve. Using the approach in this study allows for the simultaneous analysis of several parameters when the sudden changes in the yaw rate occurred. Variables of interest can be curve dimensions, vehicle dynamics signals, the driver's behavior (eye tracking, in-vehicle distractions, etc.) and environmental circumstances as weather, day time. Locating a curve section on the FOT road network and analyzing its safety is not possible without knowledge about the curve ends and radius, otherwise it is not possible to know whether driving situations are according to the curve dimensions. Although curve dimensions could be found from drawings and added to the other data collected in FOTs, the information must be referenced to the dynamic signals from the vehicle and driver extracted from FOT. Furthermore, the radius from drawings is the physical radius which is different from the driving radius that drivers follow when negotiating curves.

The method in this study is useful to analyze curve safety based on FOT data, especially when the curve functionality and other curve-related traffic control devices should be checked periodically to ensure that they are appropriate for the prevailing conditions. Changes in the regulatory speed limit, driving curve geometry, or crash history may justify the conduct of an engineering study to re-evaluate the appropriateness of the curve functionality and the choice of an appropriate countermeasure.

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REFERENCES

Alonso, M., Plaza, J. and Vega, H. (2007). "Human Factors in road infrastructure design: analysis of road layout influence on driver behavior." Road Safety and Simulation Conference, RSS 2007, Rome, Italy.

Ardeshiri, T., and Kharrazi, S. (2006). "Sensor Fusion for Vehicle Positioning in Intersection Active Safety Applications." M.Sc. thesis at Chalmers university of Technology. ISBN/ISSN:986-00-5947-0. Published at the 8th International Symposium on Advanced Vehicle Control.

Bärgman, J., and Svanberg, E. (2010). “Sweden-Michigan Naturalistic Field Operational Test (SeMiFOT) Phase 1. WP 3 Data Management- Final Report.” SAFER REPORT 2010:05

Bonneson, J. (2000). “Superelevation Distribution Methods and Transition Designs.” Transportation Research Board, National Research Council, Washington, D.C., NCHRP Report 439.

Bonneson, J., Pratt, M., Miles, J., and Carlson, P. (2007). “Horizontal Curve Signing Handbook.”, Texas Transportation Institute. The Texas A&M University System College Station. Product 0-54339, p 18-19.

Box, G. E. P., Hunter, W. G. and Hunter J. S. (2005). “Statistics for Experimenters.” John Wiley & Sons, New York, ch 2 p 25-27, 41.

Carlson, P., Burris, M., Black, K., Rose, E., (2005). “Comparison of Radius-EstimatingTechniques for Horizontal Curves”, Transportation Research Record: No. 1918, pp. 76–83.

Dingus, T. A., Klauer, S.G., Neale, V. L., Petersen, A., Lee, S. E., Sudweeks, J., Perez, M. A., Hankey, J., Ramsey, D., Gupta, S., Bucher, C., Doerzaph, Z. R., Jermeland, J., Knipling, R.R. The 100-Car Naturalistic Driving Study, Phase II – Results of the 100-Car Field Experiment [Report]. - Virginia : Virginia Tech Transportation Institute, 2006. - DOT HS 810 593.

Donnell, E., Hines, S., Mahoney, K., Porter, R., and McGee, H. (2009). “Speed Concepts: Informational Guide. U.S. Department of Transportation.” Federal Highway Administration. P 14.

Dupré, G., & Bisson, O. (2007). *Safety in curves on urban express roads.* Internal Report for Deliverable 2.1, European Commission 6th Framework Project Ranking for European Road Safety (RANKERS), Contract No. S07.36996/001678.

EuroRAP. (2005). “EuroRAP-First Pan-European Progress Report”. Published by EuroRAP AISBL, 6

FESTA, C. (2008). *FESTA Handbook: Field opErational teSt supporT Action.* Handbook, Deliverable 6.4, European Commission 7th Framework Project FESTA, Contract No.214853.

Fink, K. L., and Krammes, R. A. (1995). “Tangent Length and Sight Distance Effects on Crash Rates at Horizontal Curves on Rural Two-Lane Highways.” J. Transportation Research Record. No. 1500, p. 162-168.

Gibreel, G. M., Easa, S. M. and El-Dimeery, I. A. (2001) “ Prediction of operating speed on three-dimensional highway alignments.” J. Transp. Eng., **127**(1), 21–30.

Glennon, C. J. and Weaver, D. G. (1972). “Highway curve design for safe vehicle operations.” J. Highway Research Record, **390**, 15–26.

Glennon, J.C., T.R. Neuman, and J.E. Leisch. (1985). “Safety and Operational Considerations for Design of Rural Highway Curves.” FHWA/RD-86/035. Federal Highway Administration, U.S. Department of Transportation.

Hollnagel, E. (2004). “Barriers and Accident Prevention.” University of Linköping. Sweden, ISBN 13:9780754643012.

Imran, M. and Hassan Y. (2006). “GPS–GIS-Based Procedure for Tracking Vehicle Path on Horizontal Alignments.” Proc. Computer-Aided Civil and Infrastructure Engineering **21** (2006) 383–394

Krammes, R.A., Brackett R.Q., Shafer M.A., Ottesen J.L., Anderson I.B., Fink K.L., Collins K.M., Pendleton O.J. and Messer, C. J. (1995). “Horizontal Alignment Design Consistency for Rural Two-Lane Highways.” FHWA-RD-94-034. Federal Highway Administration, U.S. Department of Transportation.

Leonard, J., Bilse, D., and Recker, W.(1994). “Super-elevation rates at rural highway intersections.” (Report No. RTA-53P434). Irvine, CA: University of Carolina Institute of Transportation Studies.

Miller, E. and Steuart, G. (1982).“Vehicle Lateral Placements on Urban Roads.” J. Transportation Engineering Journal, Vol. 108, No. 5, September/October 1982, pp. 495-508.

Murgel, G. and Hamilton, R., (1999). “– Engineering Surveying Laboratory Manual.” ,CE 211. Boise State University, Boise, Idaho. p65-68.

Neale, N., Dingus, T., Klauer, S., Sudweeks, J., Goodman, M.,(2005). AN OVERVIEW OF THE 100-CAR NATURALISTIC STUDY AND FINDINGS. Proc. 19th International Technical Conference on the Enhanced Safety of Vehicles. – Washington, 05-0400.

Othman, S., Thomson R. and Lannér G. (2009). “Identifying Critical Road Geometry Parameters Affecting Crash Rate and Crash Type.” Proc., Annals of Advances in Automotive Medicine- 53rd AAAM, Baltimore, MD. Vol 53 · October 2009, pp 155 -165.

Othman, S., Thomson, R., and Lannér, G. (2010). “Are Driving and Overtaking on Right Curves More Dangerous than on Left Curves?” Annals of Advances in Automotive Medicine - 54th Annual Scientific Conference; Las Vegas, USA; 17-20 October 2010, pp. 253-264.

Reymond, G., Kemeny, A., Droulez, J. and Berthoz A (2001). “Role of Lateral Acceleration in Curve Driving: Driver Model and Experiments on a Real Vehicle and a Driving Simulator.” Human Factors: The Journal of the Human factors and Ergonomics Society 2001 43: 483

Sakshaug, K. (2000). “Overhøydens innvirkning på ulykkesfrekvens i kurver.” SINTEF rapport STF22 A00562. Trondheim. Norway; 2000.

Sandin, J. (2008). “Aggregating Case Studies of Vehicle Crashes by Means of Causation Charts.” Ph.D. thesis, ISSN 0346-718X. Department of Applied Mechanics, Chalmers University of Technology.

Staplin, L., Gish, K., Decina, L., Lococo, K., Harkey, D., Mohammed, S., Tarawneh, M., Lyles, R., Mace, D. and Garvey P. (1997). "Synthesis of Human Factors and Highway Safety Research." Volume 2, Publication No. FHWA-RD-97-095.,

Steyer, R., Sossoumihen, A., Weise, G. (2000). "Traffic safety on two-lane rural roads: New concepts and findings." Proceedings of the 2nd International Symposium on Highway Geometric Design (pp 299-312). Cologne, Germany: Road and Transportation Research Association.

Victor, T., Bärgman, J., Hjälmdahl, M., Kircher, K., Svanberg, E., Hurtig, S.,Gellerman, H., Moeschli, F (2010 a). "Sweden-Michigan Naturalistic Field Operational Test (SeMiFOT) Phase 1. **WP 5** Evaluation of Methodology" Final Report. SAFER REPORT 2010:02

Victor, T., Moeschlin, F., Hjälmdahl, M., Ahlström, C. (2010 b). "Sweden-Michigan Naturalistic Field Operational Test (SeMiFOT) Phase 1. **WP 5** Evaluation of Methodology" Final Report. SAFER REPORT 2010:06

Wong J. Y. (2001). "Theory of Ground Vehicles." Department of Mechanical Aerospace Engineering. Carleton University. Ottawa. Canada, 2001, ch 5, p 281-282.

Paper IV

SAFETY ANALYSIS OF HORIZONTAL CURVES USING REAL TRAFFIC DATA

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ABSTRACT

Researchers are still seeking a better understanding of the parameters that affect safety in horizontal curves. Curves are one the most critical sections of the road network contributing to a high percentage of serious run off accidents and lane changing crashes. Moreover, driving in curves requires combined control of both steering and speed, taking into account the dynamic response and limits of the car. The objectives of this study were to evaluate the safety performance of horizontal curves through analyzing vehicle dynamic signals such as lateral acceleration and speed as well as quantitative analysis of lane changing maneuvers. The study uses real traffic environments where driver behavior and vehicle response data were recorded and stored during regular operations without subjecting the driver to any experimental controls. A total of 96 curves, equally distributed for left and right turn directions, have been collected and grouped according to their radii. The results showed that the curve entrance is the most critical element when negotiating curves regardless of curves radius and that the safety risk decreases along the curve. Lane changes occurred more frequently as curve radius increased. The results showed how road design influences the driver’s strategy by establishing links between curve features, vehicle dynamic responses, and the driver’s behavior.

Key Words: Traffic safety, Horizontal curves, Curve radius, FOT data, Vehicle dynamic responses

INTRODUCTION

Horizontal curves are necessary components of the road networkbut they tend to be associated with a disproportionate number of crashes. Crash rates in curves have been found to be typically 2 to 4.5 times higher than on straight road sections (Johnston, 1982; Leonard et al, 1994). A study in the United States showed that each year about 38000 fatal crashes occur on the highway system with 25% of the fatalities found to occur on horizontal curves (Torbic et al, 2004). Another study by Gupta & Jain (1975) found that curvature actually is a more important factor than road width, vertical clearance as well as sight distance after analyzing 34000 road crashes. They also noted that head-on collisions, collisions with fixed objects and rollover crashes occur disproportionately on curved road sections. There is also good

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agreement in the road safety research community that sharper curves cause more accidents (Othman et al, 2009; Charlton & de Pont, 2007). A crash history study that analyzed 3000 accidents in Sweden showed that overtaking accidents are more frequent on large right curves (radius > 700 m) while run off accidents are more frequent on sharp (radius < 500 m) right curves (Othman et al, 2009).

Almost all previous studies are based on crash history, field tests, or simulations which show the increased accident rate on horizontal curves. However these approaches are deficient in analyzing and linking effects of other factors that may also influence safety on curves. This is essential to enable examining the main safety factors -infrastructure, vehicle, human- methodically by separating the components and studying their interrelations at the same time during the same driving conditions.

In field operational tests (FOT) and naturalistic driving studies (NDS), driver behavior and vehicle response data are recorded and stored during regular operations without subjecting the driver to any experimental controls. This approach promotes FOT as a potential dataset for analyzing the influence of infrastructure on traffic safety. However the FOT dataset is complex and very large. To access the data and overcome the dataset difficulties, an effective tool (Othman et al, 2011) has been developed to identify curves and mine associated data. The safety analyses of the collected curve data have been performed through different statistical hypotheses such as effects of different curve features on vehicle dynamic responses (lateral acceleration and yaw rate) and modeling lane changing maneuvers with respect to curve radius, and studying longitudinal speed patterns on the curves.

OBJECTIVE AND SCOPE

The goal of this study was to identify and evaluate the safety performance of horizontal curves using recorded naturalistic driving data. The evaluations are based on vehicle responses - lateral acceleration, yaw rate, and speed - which are an output of the driver behaviour. . The objectives were achieved through evaluation of several research questions: (1) Are safety risks of curves, in terms of lateral acceleration, yaw rate and operating speed, influenced by radius and travel direction along the curve segments. (2) Are lane changing maneuvers influenced by radius, speed, direction and road width of the curves? (3) Are longitudinal acceleration and speed differential influenced by radius, travel direction and vertical grade of curve segments?

The proposed study uses data stored from FOT studies where no instructions, experimental designs, or special conditions were given to the vehicle drivers. The results of this study can also be used to evaluate the further application of FOT data to road safety studies of road infrastructure.

METHODOLOGY AND MATERIAL

Data Collection

The data used in this study was mined from the SeMiFOT database, which is a quasi-experiment with drivers using vehicles during their daily routines without special instructions about how and where to drive (Victor, 2010). The duration of data collection was 6 months starting from November 2008 and the data logging was autonomous. The data examined for the following study was limited to 5922 trips of 7 Volvo cars driven by 28 different drivers. Data mining was conducted using a tool that was developed to identify driving path and lane changing maneuvers on horizontal curves from naturalistic driving (Othman et al, 2011). The method synchronizes vehicle responses and human behavior on identified horizontal curve segments. Specifically, the tool is able to identify and characterize horizontal curves from FOT data including radius (R), establishes the start and end points of the curve path, and then combines the curve information with other safety relevant data on a common axis. More specifically, A total of 96 curve sections from 3526 trips have been identified including corresponding information of environment, vehicle and driver factors during driving on the curves. The regulatory speed-limits of the curves are 70, 90, and 110 km/h. Furthermore, the selected curves were amenable to studying travel in both directions. The variables collected for each of the curves are shown in Table 1**.** The variables capture elements of the road, vehicle, and driver characteristics response needed for the intended analyses. To draw a boundary between vehicle and driver variables the data that has been recorded directly from the vehicle are considered as vehicle variables including those dependent on human inputs such as speed, lateral acceleration, etc.

Table 1 Variables for each of the curves

Infrastructure	Vehicle	Driver
Curve radius [m]	Speed [km/hr]	Path radius [m]
Curve direction	Speed of lane	Total number of trips
Curve length m]	Speed of non lane	Number of lane change
Road width [m]	Maximum speed trip	Id of lane changing
Road type	Lateral acceleration	Trip id of maximum
Speed-limit [km/hr]	Longitudinal	Video films of lane
Traffic flow [pair of	Yaw rate [1/sec]	Start-end time of the
Grade [m]	Steering angle[rad]	
	Heading [rad]	

Analysis Variables

To identify variables highly influencing the predicted safety performance of horizontal curves between the listed variables in Table 1, a review of several previous studies (Granlund, 2010; Othman et al, 2010; Fitzpatrick et al, 2010; Aram, 2010) was conducted. The interesting independent factors selected for this study are degree of curvature, curve direction, grade, speed-limit, and roadway width while the dependent variables were operational speed, lateral acceleration, yaw rate and lane changing. The independent variables are parameters that are determined by the road designer or road operator while the dependent variables are those that can be associated vehicle and traffic safety thereby and lead to assessment of safety risk. All variables presented in Table 1 were analyzed in this study. Only those variables of particular interest (road design) or statistically significant were studied in detail. The data collection and treatment of the variables prior to analysis are described in the following subsections.

Road Curve information

Curve characteristics which are the independent factors in the statistical analysis, are listed and described in the following subsections.

- Curve Radius

The radius found using the tool (Othman et al, 2011), mentioned in Section 0, is the path radius which was the driver's choice for negotiating the curve. Past observations of driver behavior while negotiating curves indicate that vehicles shift laterally inward relative to the centerline while cornering (Bonneson et al, 2007b; Emmerson, 1969) and results in a path radius larger than the curve radius (physical radius of the curve). The driver chooses this shift in lane position as it reduces the side friction demand and allows them to limit the speed reduction in the curve. Figure 1shows the driving path of the vehicle as it negotiates a horizontal curve. This path pointed as Path Radius, R_p in the figure. The vehicle is turning left, flattening the curve by shifting toward the centerline in the middle segment of the curve. The difference between this driving path and curve radius *R* is shown in the figure.

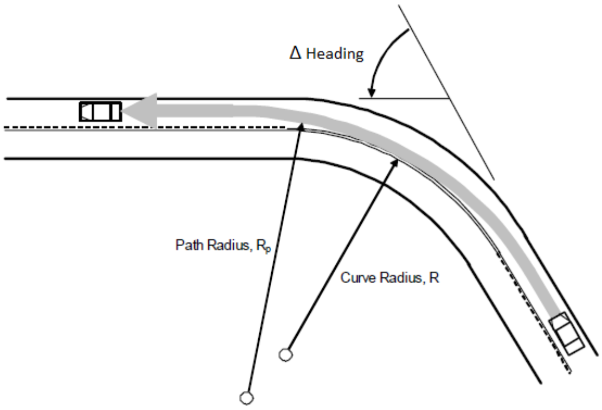

Figure 1 Effect of lateral shift on travel path radius (Bonneson et al, 2007b)

The geometry indicated in Figure 1 has been used for computing the effective increase in radius due to a lateral shift within the lane. The results shown in Table 2 have been used in this study to transform path radius to curve radius depending on the curve deflection angle degree. However, in this study both path and curve radii have been considered in the analysis.

Table 2 Increase in Curve Radius Due to a Lateral Shift in Lane Position (Bonneson et al, 2007b)

	Curve deflection angle, degrees											
Increase in Radius, m	5	10	15	20	25	30	35	40	45	50	55	60
	961	240	107	60	39	27	20	15	12	10	8	7

A wide range of curve radii were included in the data collection to insure that the analysis and resulting criteria reflected the consideration of a wide range of radii up to 1350 m. The curves were considered as simple curves which have a single (constant) radius and are the most common type of horizontal alignment curve (Donnell et al, 2009). The radii have been divided into four groups so that the number of curves in the groups is distributed as evenly as possible. The groups were curves with radius less than 400 m, 400 – 650, 650 – 900 and 900 – 1350 m.

- Curve Length

The curve length is the computed distance travelled between the identified start and end points of the driving path. For the analyses, the curve length was divided into three equal segments: entrance, middle and exit. Dividing curves to segments was used to identify the critical parts of the curve being those curve segments exhibiting the largest lateral acceleration and yaw rate.

- Grade and Road Width

Vertical grades of the curves were determined from the difference in altitude between the start and end points of the driving path, i.e. the same points on the road used to determine curve length. Grades of the curve segments (entrance, middle and exit) have also been found separately. The estimated grade was classified into three categories: level, uphill, and downhill sections. The section is considered level when the slope is between -2% and +2%. These thresholds for longitudinal slope are the required longitudinal slopes for drainage of raining water when the cross slope is zero. A positive grade, greater than +2%, denotes an uphill condition as the vehicle travels toward, or through, the curve while negative slope, less than -2%, denotes a downhill. Road width (RW) has been classified to three groups: $RW \leq 7.5$, $7.5 < RW \leq 10.5$ and $RW > 10.5$. Road width is considered to be the distance between the outer lane markings and not the entire paved carriageway width.

Vehicle Signals and Human Behavior

The following dependent signal variables have been collected point wise along the curve length. However, the mean values of the signals for the curve segments have been the main input data in the analysis. The variables have been tested against the fixed factors mentioned in Section 0 to address the objectives and evaluate hypotheses of this study.

- Lateral Acceleration and Yaw Rate

The influence of independent factors on lateral acceleration and yaw rate variables were analyzed, where these vehicle response variables have been used as traffic safety indicators of the curves. The dependent factors tested were segments, direction and radius of the curves. The mean value of the variable measurements along the curve segments have been used in the analysis but without regard to their sign (absolute value). This eliminates issues due to the opposite signs recorded during turning on a curve depending on direction, i.e. left or right.

- Lane Changing Maneuvers

Trips containing lane changing maneuvers on the curves were identified and separated from trips with non-lane changing. Moreover, lane changing trips on different curves have been normalized by considering the total number of trips. Lane changing trips have been used to find correlations between lane changing and different fixed factors such as curve radius, direction and speed-limit. Furthermore, the separated trips can be used in further studies when analyzing human behavior using the video films for example to explain where, how, and why maneuvers occur.

The human behavior variables are only analyzed implicitly in this study in terms of outcomes like speed, lateral acceleration, yaw rate and lane changing maneuvers. Thus, the video films were not analyzed although the data is collected and identified for further analysis. Analyzing video films to study in-vehicle distractions, for example, is outside the scope and area covered by this investigation and requires different research specialties.

- Speed and Longitudinal Acceleration

Effects of the independent factors on operational speed, for three different speed configurations, have been used in the analysis as one indicator of curve safety. The speed configurations that have been calculated separately were mean speed and speed differential between the curve segments as well as speed of the lane changing maneuvers. The speed differential refers to the difference between speeds when entering and exiting a road segment. Moreover, the speeds of trips with and without lane changing maneuvers have been calculated separately for the analysis. Longitudinal acceleration along the curve segments has been used in the analysis to complete the analysis of vehicle speeds along the curve directions and segments. More specifically, longitudinal acceleration was used to analyze when and where drivers change speed along curve sections.

Statistical Considerations

The SPSS Univariate general linear model (GLM) was used when analyzing variables and allows modeling the value of a dependent scale variable based on its relationship to categorical and scaling predictors. For the purposes of testing hypotheses concerning parameter estimates, GLM Univariate assumes that the values of errors are independent of each other and the variables in the model. Moreover, the variability of errors is constant across cells. This can be particularly important when there are unequal cell sizes; that is, different numbers of observations across factor-level combinations. The last assumption is that the errors have a normal distribution with a mean of zero. Table 3 shows the dependent variables (i.e. vehicle signal) that have been tested against the fixed factors i.e. curve parameters. Furthermore, the table shows the numbers of levels and subgroups of the factors. In the analysis, mean values of the signals recorded from all trips on the curve segments have been used in order to minimize effects of individual drivers on the results. The lane changing variable in the table is the number of trips with lane changing maneuvers with respect to total numbers of trips on the curve. The curves have been collected in pairs to determine if a difference in a roadway element varies in how it affects dependent variables such as lateral acceleration and operating speed. The attributes within each pair are similar except for the difference in the attributes of interest, for example travel direction. By selecting pairs of matched sections, the effect of the selected attributes on safety is isolated and other factors are better controlled (Bonneson et al, 2007a). The results are considered statistically significant to the 95% level, i.e. p-value ≤ 0.05.

ANALYSIS AND RESULTS

The total number of collected curves was 96, equally distributed with regard to left and right travel directions. The distribution according to radius subgroup and speed-limit are shown in Table 4, where there are very limited sharp curves on roads with high speed-limit as expected. The path radii estimated using the tool (Othman et al, 2011) have been converted to curve radii according to corresponding degree of deflection using Table 2 and are shown in Table 4. Values in parenthesis indicate the distribution of curves by path radius. The distribution of curve radii among the sub-groups changed when curve radius used instead of path radius was used; however the new grouping does not affect the main results of the analysis due to the large span (250 m) within radius subgroups. Subsequently, the results generally do not distinguish between path and curve radius since both produced the same results with slight differences in significance degree and factor interactions. The following results are for road radius to facilitate future comparison to other studies.

Table 3 Test variables and their subgroups

Variables	Factors	Levels	Classes (Subgroups)	N
Lateral acceleration	Radius [m]	4	(R < 400), (400-650), (650-900), (900-1350)	288
	Direction	2	Left , Right	288
	Segment	3	Entrance, Middle, Exit	288
Yaw rate	Radius [m]	4	(R < 400), (400-650), (650-900), (900-1350)	288
	Direction	2	Left , Right	288
	Segment	3	Entrance, Middle, Exit	288
Lane changes	Radius [m]	4	(R < 400), (400-650), (650-900), (900-1350)	
	Direction	2	Left , Right	
	Road width [m]	3	(RW ≤ 7.5), (7.5 < RW ≤ 10.5), (RW > 10.5)	
	Speed-limit $[\frac{km}{hr}]$	3	70, 90, 110	
Operation speed	Radius [m]	4	(R < 400), (400-650), (650-900), (900-1350)	288
	Direction	2	Left , Right	288
	Segment	3	Entrance, Middle, Exit	288
Speed differential	Direction	2	Left , Right	288
	Segment	3	Entrance, Middle, Exit	288
	Grade	3	Straight, Uphill, Downhill	288
Longitudinal acceleration	Direction	2	Left , Right	288
	Segment	3	Entrance, Middle, Exit	288
	Grade	3	Straight, Uphill, Downhill	288

Table 4 Distribution of curves according to radius subgroup and speed-limit

	Radius	≥400	400 – 650	650 – 900	900 – 1350	
Speed						Total
70		24(15)	22(26)	3(8)	4(4)	53
90		2(0)	11(5)	4(11)	10(11)	27
110		0(0)	2(2)	4(4)	10(10)	16
	Total	26(15)	35(33)	11(23)	24(25)	96

The results of the statistical analysis are described in the following subsections according to the dependent variables, listed in Table 3. The results describe and evaluate effects of the factors mentioned in the study hypotheses on the dependent variables. All statements in the following results are statistically significant to 95% levels, unless the significance level is specifically mentioned.

Lateral Acceleration and Yaw Rate

As mentioned earlier, lateral acceleration and yaw rate are used as indicator signals to measure safety of operation on horizontal curves through examining the factors that influence these indicator signals. Safety is expected to be inversely related to lateral acceleration and yaw rate (Reymond et al, 2001; Leonard et al, 1994). The analyzed factors were radius, traveled direction, curve segment (entrance, middle and exit) and their interactions. The results of the factors and their interaction are described below.

Radius

The effect of radius on curve safety was very significant in which the assumed safety risk in terms of both lateral acceleration and yaw rate increased with decreasing curve radius and is in line with all reviewed curve safety studies. This result is illustrated in Figure 2 where it is also clear that the curve entrance is the most critical part for all curve radii groups followed by the middle section of the curves. At the curve exits, lateral accelerations and yaw rates for the three large radii groups converged to similar value. This is an interesting feature as the curve end points are determined when the heading angle deviates by 1 deg. from the steady state turning section seen in Figure 3. This point is not at the completion of the transition from curve to tangent section and one would still expect different vehicle dynamic states for the three different curve radii. However there is a noticeable difference in lateral acceleration and yaw rate for the smaller radii (R<400) and the larger curve radii.

To measure the strength of the linear relationship between the two variables (lateral acceleration and radius), the correlation coefficient, R^2 was calculated and defined in terms of the (sample) covariance of the variables divided by their (sample) standard deviations. The R^2 between lateral acceleration and radius was strong (0,73) considering all radius groups. When analyzing the three largest radii groups, the R^2 was very strong (0,92). Multiple comparisons procedures were used to control the error rate within radius groups by carrying out all pair wise comparisons of the group means. The results of multiple comparisons showed how risks among the four radius subgroups differ. The severity, in term of both lateral acceleration and yaw rate, was statistically different between nonadjacent radius groups. Only the smallest curves, i.e. R < 400 m were statistically different from the neighboring radii interval and these small curves were more dangerous than all other three larger radius groups in terms of magnitude of the dependent variables.

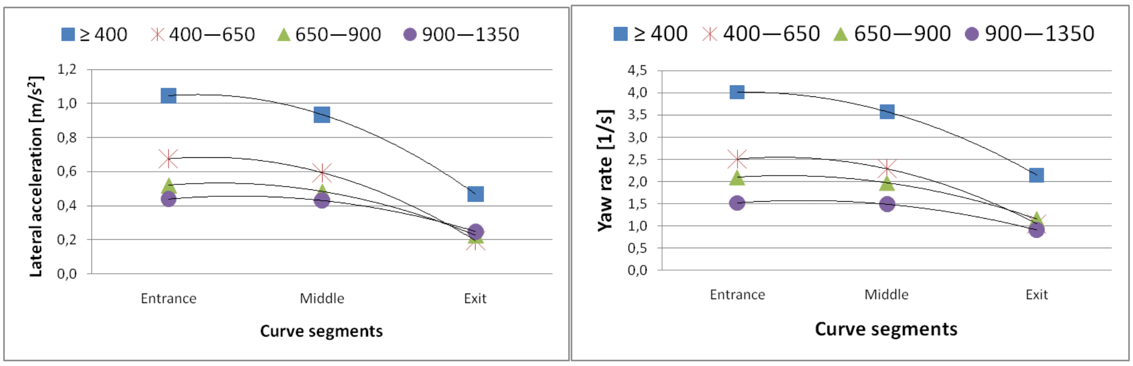

Figure 2 Lateral acceleration and yaw rate along horizontal curves for four radius groups

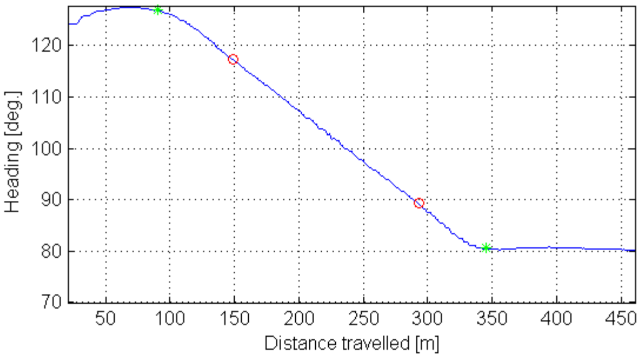

Figure 3 Curve endpoints determined by curve analysis tool (Othman et al, 2011)

Travel Direction

The difference between left and right travel directions was also significant where right curves were found to be more dangerous when using lateral acceleration as exposure. In general, there was no difference between left and right curves when yaw rate was used as a risk index. Thus, to have better understanding on how indicator signals look for different travel directions and to explain the different effects of travel direction on lateral acceleration and yaw rate, the outcomes have been split according to radius groups shown in Figure 4. The results of separate radius groups generally followed the same trend as the groups as a whole for both lateral and yaw rate signals. No difference between left and right curves, in terms of yaw rate, was observed while higher lateral accelerations for the right direction groups compared to the left direction can be seen in Figure 4.

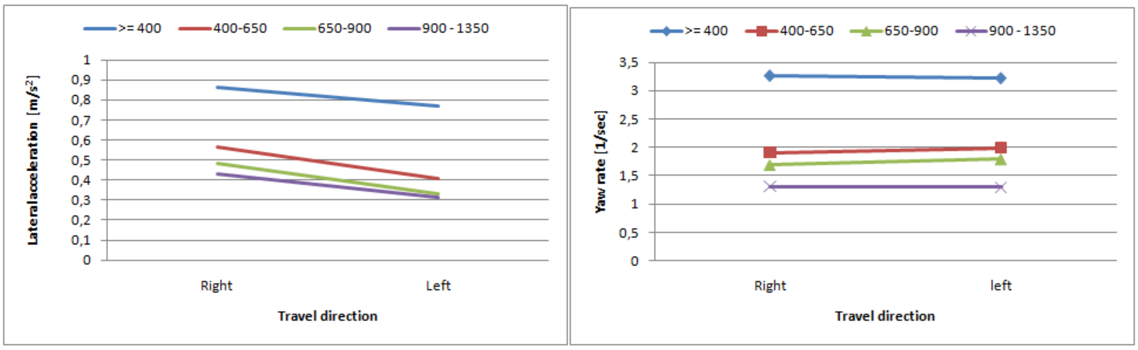

Figure 4. Lateral acceleration and yaw rate on right and left travel directions

Curve segments

Investigations to find the most critical portion of the curve length (entrance, middle and exit segments) showed that entering the curve is the most severe segment for both travel directions and all radius subgroups as shown Figure 2. Results of the curve segment analysis, taking into account radius groups, showed that the difference of the indicator signals was high among the entrance segments of the four radius groups while the difference was very low when exiting the curve groups.

Interactions

The results of examining lateral acceleration and yaw rate to explore how the three factors interact showed the only significant interaction that was between curve radius and segments. This means that a change in lateral acceleration, with respect to curve radius, is also dependent on curve segments. In other words, the simultaneous influence of curve radius and curve segment on lateral acceleration and yaw rate is not additive.

There were more significant interactions when considering path radius grouping instead of road radius. Thus, the interaction between curve direction and curve segments as well as between all three factors (direction, curve segment and radius) was significant for both lateral acceleration and yaw rate. However, only yaw rate was significant for curve radius and curve segments interaction in analyzing path radius grouping different from analyzing road radius.

Lane Changing Maneuvers

The rate of lane changing maneuvers observed on the curves was 11% of the total trips, in which 40 % occurred on left and 60% on right curves. Using the four curve factors mentioned in Table 3 showed that drivers change lane more frequently as the curve radius increases as shown in Figure 5. Furthermore the lane change frequency was affected significantly by interaction between curve radius and speed-limit. However, the relationship between lane changing and speed-limit was not significant.

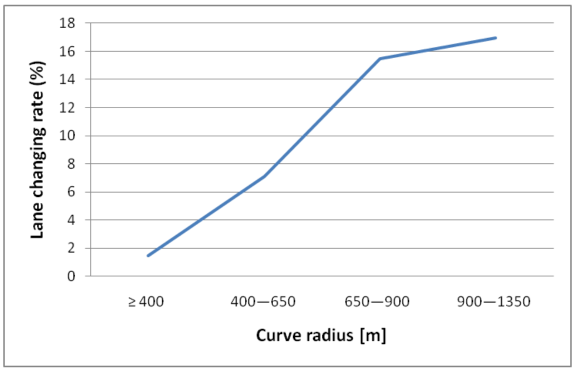

Figure 5. Rate of lane changing manoeuvres on horizontal curves for four curve radius groups where the rate is the proportion of lane changing trips to all trips

The linear model of correlation between lane changes and curve radius for both curve directions together shown very strong correlation with coefficient 0,89 as shown in equation 1 where X is curve radius and Y is rate of lane changes.

$$Y = 0.02X - 3 \qquad (1)$$

Speeds of trips with and without lane changing maneuvers have been compared to determine if lane changes are a method to “cut the corner” and maintain speed through the curve and/or speeding takes place and leads to the lane changing. The result showed that the speed of trips with lane changing maneuvers was higher than trips without lane changing although the difference was not statistically significant. Trips with lane changing have been considered as non-lane changing trips when the maneuvers occurred before or after the curve section. These maneuvers outside the curves were clear in the plots of the vehicle’s lane offset. Further analysis is needed to fully interpret the relationship between lane changing and safety risk.

Speed and Longitudinal Acceleration

There was no noticeable acceleration of the vehicle at the curve entrance. This was true independent of the radius group. In general, a slight deceleration was noticed at the curve entrance and then constant speed was observed generally in the middle and exit segments apart from the largest radius group where drivers accelerate in the entrance, maintain speed in the middle, and decelerate in the exit segments. However, none of these results were statistically significant and the maximum range of acceleration was between 0.02 and -0.05 m/s^2.

Operational speed also increased significantly as curve radius increased as shown in Figure 6 where speed is demonstrated along curve segments of the radius groups.

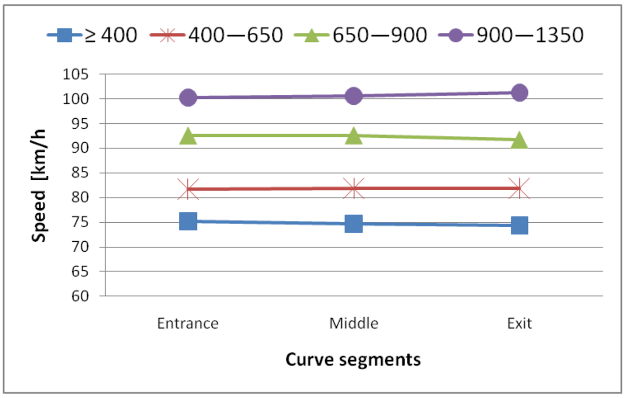

Figure 6 Operating speed along curves for four radius levels

To insure that no confounding factors in the analysis a study of a specific speed-limit in curves was conducted as shown in Table 5. The dataset of operational speeds with respect to speed-limits and radii, Table 5, revealed that operational speed generally increases with increasing curve radius regardless of speed-limit. However the difference between operational speed and speed-limits was inconsistent where the drivers keep their speed below the speed-limit on smaller radius curves and high speed-limit roads (90 & 110) while higher operational speed on road with speed-limit 70. This results show clearly that drivers take into account curve radius more than the speed-limits. This was more obvious when operational speed is 20 km/hr below the 110 speed-limit for curve radius 400 -650 while the speed is 15 km/hr above the 70 speed-limit level for radius 900 -1350.

Table 5 Operational speed for four radius levels and speed-limits

	Radius	≥400	400 – 650	650 – 900	900 – 1350
Speed-limit					
70		73.73	77.07	76.69	85.75
90		88.56	89.67	96.38	95.46
110		0	90.7	98.36	111.99

The linear model of correlation between speed and curve radius for both curve directions together showed a very strong correlation with coefficient 0.99 as shown in equation 2 where X_1 is the curve radius and Y_1 is the speed.

$$Y_1 = 0.032\,X_1 + 65 \qquad (2)$$

It was self-evident that longitudinal acceleration for different vertical grades varied significantly in which accelerations were zero, positive and negative for level, downhill and uphill curve sections, respectively. This result itself is not new information, it is used later when explaining results of speed differential as well as it is as a validation for the mined data that has been used to discover other findings of this study.

An examination of speed changes in the curves showed that drivers speed up along segments of right curves while they slow down on left curves. However this result is most likely biased since the distribution of uphill and downhill grades were not equal on right and left curves. As mentioned previously, grade significantly influences longitudinal acceleration. The null hypothesis in a nonparametric test has been rejected where the null hypothesis was uphill and downhill grades are equally distributed on left and right curves. The test showed right curves have more downhill and less uphill curves than left curves. This influences the results of speed differential when speed of right curves increases and left curve speeds decreases. Table 6 illustrates the unequal distribution of upp and downhill gradess in the curves on the travel directions.

Table 6 Distribution of vertical grade in the curves on travel direction

Grade	Right	Left
Level	31	30
Downhill	12	6
Uphill	5	12

DISCUSSION

The main purpose of this study has been to identify and evaluate the safety performance of horizontal curves using real traffic data. This was achieved through testing of several curve safety hypotheses related to road information and vehicle dynamic signals. The study investigated 96 curves, equally distributed for left and right travel directions, which were collected and grouped according to their radius. The radii estimated were path radius which is dependent on driving course and accuracy of the GPS track on the curve. To reduce errors from GPS coordinates and decrease the effects of individual drivers on the driving course, the path radii have been calculated from 3526 estimations with a minimum of 5 estimations to calculate mean value for each of the radius. Estimating the path radius was important since it is the path that the vehicle follows in reality from which the most dangerous curve segments can be identified. However, the estimated path radii, depending on deflection angle, have been re-estimated using Table 2 to find curve radii. Calculating curve radius was also essential to relate and validate the findings of this study in the light of previous curve research where most of them are based on curve radius (Othman et al 2009; Dupré, 2007). Vehicle responses along a curve section are different depending on the driving course (Rymond et al, 2001). Thus to have better understanding of the signals pattern along the curve sections, results are discussed according to curve segments, i.e. entrance, middle and exit. The major findings are arranged and discussed in the same order as subsections of the ANALYSIS AND RESULTS section.

Lateral Acceleration and Yaw Rate

Lateral acceleration and yaw rate indicated that as curve radius decreases, driving risk on the curves increase which is in line with all other reviewed previous studies. However, the risk was unequal along the curve length i.e. between curve segments. The highest record of lateral acceleration and yaw rate observed on the curve entrances, compared to middle and exit segments of the curves. This finding was valid for all radius groups in both travel direction. Although the true lateral acceleration measured on a vehicle is a function of velocity, yaw rate, and vehicle roll angles, for non-extreme maneuvers equation 3 can be considered to be valid if roll effects are ignored.

$$a_y = \frac{V^2}{R} \qquad (3)$$

As velocity was essentially constant in the curve, the lateral acceleration within the curve was mostly influenced by -the path radius, i.e. flattening the radius along the curve to keep the same speed. The last statement was confirmed when recalculating curve segment path radius, where both V and lateral acceleration are from measurements along the curves. The result of the re-estimation is revealed in Figure 7 where variations of path radius are plotted along the curve segments for different radius groups. This confirms that despite the same speed along the curve, entrances are the most dangerous part on the curve following by middle section with slight increase of radius and then a sharp grow of radius on the exit segment. An exception is small radii, R<400, when the increase of path radius was not extreme along the curves, but still following the same order of severity along the curve segments.

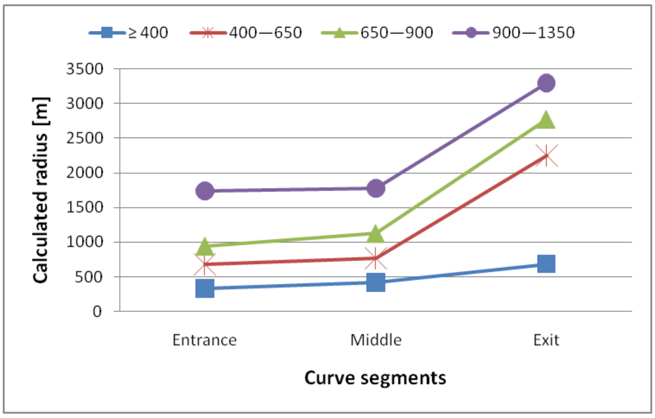

Figure 7 Calculating radii along curves using recorded lateral acceleration and speed

The results of travel direction suggest that right curves are more dangerous for all radius groups. One possible reason is that right curves are inner curves and they have smaller radii which increases lateral acceleration. Why yaw rate is the same on right and left directions needs to be further explained and studied. Vehicle speeds on left and right curves were rechecked to insure that it is not a speed factor that increased lateral acceleration and not yaw rate on right curves. Lateral acceleration is more sensitive to speed since it is calculated from ratio of speed squared (Equation 3) to radius while yaw velocity is ratio of velocity to the turning radius (Wong, 2001). The speed on left and right curves was not different, within 0.5 km/h, which make it less likely that speed caused severity of right curves. This result for speed does not support the crash history analysis (Othman et al, 2009) results that found more frequent overtaking accidents on right curves than on left curves. However, higher lateral acceleration on right curves could explain the more frequent overtaking accidents on right curves. Moreover, the 20 % greater lane change maneuvers observed on right curves in this study should also be considered in relating this study to the mentioned crash history analysis. This indicates that drivers tend to change lane (i.e. overtake) more often on right curves which could be a reason of higher representation of overtaking accidents on right curves. The safety risk for lane changes on a curve depends on direction, curve segment, and to which lane the change occurs. Othman et al (2010) in a simulation study analyzed overtaking in curves to explain the reason behind more frequent overtaking accidents on right curves than on left curves in the crash history analysis (Othman et al, 2009). The simulation results did not explain the crash history results. However it showed that lane changes on left curves are more dangerous in the entrance and exit of the curve while in the middle of right curves lateral acceleration and yaw rate are highest (Othman et al, 2010).

It can be noted that the radius groups generally follow the same pattern in terms of lateral acceleration, yaw rate and radius recalculation as shown in Figures 6 and 7. This makes theoretically possible to create new radius groups and finding corresponding vehicle responses through interpolating available results.

One limitation in discussing lateral acceleration and yaw rate is that super elevation as an important factor of safety and designing curves has not been included. That is because super elevation is not included in the national road database (NVDB) which is connected to FOT database. Moreover it is assumed that super elevation of left and right curves are constructed according to the norms.

Lane Changing Maneuvers

Drivers change lane more frequently as curve radius increases, this could be cutting the curves to increase radius or simply changing lanes due to overtaking. This was the opposite to what was reported previously. For example (Felipe & Navin, 1998) found that for curves with large radii the drivers followed the center of the lane in both directions. However, for smaller radii curves, the drivers “cut” the curves in both directions. In order to minimize the speed change, the drivers “flattened out the bends” by driving on the shoulder or in the other travel lane (Felipe & Navin, 1998). The reason for a higher lane changing rate on larger radius curves could be those larger radius curves are associated with motorway that have wider roads with multiple lanes which simplifies lane changing. Moreover, no oncoming traffic on such roads increases lane changing. Why drivers change lane has not been included in the analysis since it is out of the scope of this study. However, higher speed of trips with lane changing than without, though not significant, is an indicator that one reason is to keep a higher speed. The video films of the lane changes are identified and separated in the data collection process. The films need to be analyzed in order to better understand the behaviors behind lane changes.

Speed and Longitudinal Acceleration

Speeds along curve segments of the same radius groups were not different which confirms that the variations in path radius along curves are the main contributor of safety in curves. This is consistent with the study that found energy and side friction differential measures are proposed to be better indicators of curve severity than the speed differential measure (Bonneson et al, 2007b).

The expected result of longitudinal acceleration being influenced by vertical grade is an indicator for a good data collection quality and accuracy. Moreover, longitudinal accelerations explained why speed differential differed significantly between right and left curves. Right curves were associated with more downhill grades consequently more uphill left curves which lead to higher speed differential on right curves. The difference was only within 1 km/hr thus the higher lateral acceleration on right curves, discussed earlier, is not related to varying speed differentials for travel directions.

The grades of the curve pairs matched very well, 94%, when every downhill right curve should associate with an uphill left curve and vice versa. Only three pairs did not match in which two of them were close to the thresholds separating up and downhill. One curve had different start and end points for left and right directions. This caused large differences in curve length between directions, resulted in differences in inclination degree as well as radius estimation.

Interestingly, the speed choice behavior of drivers in curves was based on curve radius rather than the road's speed-limit. The speed choice could be as an adjustment of their perceived lateral acceleration according to a dynamic safety margin (Reymond et al, 2001), and/or the drivers simply predict radius and severity of the curves from foresight and selecting a suitable speed accordingly (Odhams & Cole, 2004).

The relevance of FOT as data and a tool for traffic safety research was successful in developing and implementing a method for extracting horizontal curves. Further, it produced important results by combining and analyzing road features with human behavior in terms of vehicle responses. However, the analysis encountered difficulties with the data quality as well as the design of statistical experiment. For example there was a bias in the grade for different curve directions. Despite this, using FOT data is promising and the safety analysis showed how naturalistic data can be used to assess infrastructure related research questions.

CONCLUSIONS

This analysis study evaluates several hypotheses accordingly several significant results. In response to the initial objectives:

1. Are safety risks of curves, in terms of lateral acceleration, yaw rate and operating speed, influenced by radius and travel direction along the curve segments?

    - The main conclusions related to the hypotheses are that safety along curves, indicated by vehicle responses like lateral acceleration and speed, is influenced by curve radius and direction. Although lateral accelerations at the end of larger curves converged to a value near zero, the smaller radii curves still had larger lateral accelerations near curve exits.

2. Are lane changing maneuvers influenced by radius, speed, direction and road width of the curves?

    - Drivers change lanes more frequently on larger curve radii and drivers adapt their speed in curves more by curve radius than speed-limit in choosing speed on curves. For the sample of trips analyzed, more lane changes occurred in right curves than in left curves.

3. Are longitudinal acceleration and speed differential influenced by radius, travel direction and vertical grade of curve segments?

    - Vehicle speeds were less influenced by curve segments however it was noticed that curve radius was more influential on operational speed than posted speed-limits.

The results are very useful combinations of traffic safety pillars which can be used as inputs to improve safety applications such as road design, vehicle active safety or/and human behavior analysis. Moreover, these analyses represent a valuable step in the development of the competence and methodology needed to analyze the explanatory factors in accident causation.

REFERENCES

Ali A., (2010), Effective Safety Factors on Horizontal Curves of Two-lane Highways. Journal of Applied Sciences 10 (22): pp.2814-2822.

Bonneson, J., Lord, D., Zimmerman, K., Fitzpatrick, K., and Pratt, M. (2007), “Development of tools for evaluating the safety implications of highway design decisions.” *FHWA/TX-07/0-4703-4,* Texas Transportation Institute, Texas, USA.

Bonneson, J., Pratt, M., Miles, J., & Carlson, P. (2007). *Development of Guidelines for Establishing Effective Curve Advisory Speeds.* Technical Report No. FHWA/TX-07/0-5439-1.Texas Transportation Institute.Texas, USA.

Charlton, S. G., & de Pont, J. J. (2007). *Curve speed management.* Land Transport New Zealand, Research Report 323. Internet access 2009-10-14: http://www.ltsa.govt.nz/research/reports/323.pdf

Donnell, E., Hines, S., Mahoney, K., Porter, R., & McGee, H. (2009). *Speed Concepts: Informational Guide.* Report No. FHWA-SA-10-001. U.S. Fedral Highway Administration. Department of Transportation. PA, USA.

Dupré, G., & Bisson, O. (2007). *Safety in curves on urban express roads.* Internal Report for Deliverable 2.1, European Commission 6th Framework Project Ranking for European Road Safety (RANKERS), Contract No. S07.36996/001678.

Emmerson, J. (1969) “Speeds of Cars on Sharp Horizontal Curves.” *Traffic Engineering & Control.* Vol. 11, No. 3, London (July1969) pp. 135–137.

Felipe, E., & Navin, F. (1998). Automobiles on Horizontal Curves: Experiments and Observations. *Journal of Transportation Research Record* , (1628), 50-56.

Granlund J. (2010). *Safer Curves on Multiple Lane Roads.* Vectura Consulting, Sweden. Transport Research Arena Europe 2010, Brussels

Gupta, R. C., & Jain, R. P. (1975). Effect of certain roadway characteristics on accident rates for two-lane roads in Connecticut. Transportation Research Record, 541, pp. 50−54.

Johnston, I. R. (1982). *Modifying driver behaviour on rural road curves: A review of recent research*. Proceedings of 11th Australian Road Research Board (ARRB) Conference, 11(4) pp. 115−24.

Fitzpatrick, K., Lord, D., Park, B-J, (2010), Horizontal Curve Accident Modification Factor with Consideration of Driveway Density on Rural Four-Lane Highways in Texas, Journal of Transportation Engineering, Vol. 136, No. 9

Leonard, J., Bilse, D., & Recker, W. (1994). *Super-elevation rates at rural highway intersections.* Report: No. RTA-53P434. University of Carolina, Institute of Transportation Studies, DE, USA

Odhams, A., & Cole, D. (2004). Models of Driver Speed Choice in Curves. *Proceeding:7th International Symposium on Advanced Vehicle Control, (AVEC 04), 23-27 August 2004,* Arnhem, Netherlands.

Othman, S., Thomson, R., Lannér, G. (2009). Identifying Critical Road Geometry Parameters Affecting Crash Rate and Crash Type. 53rd AAAM Annual Scientific Conference, October 4-7, 2009, Baltimore, MD. Vol 53· *pp 155 -165.*

Othman, S., Thomson, R., Lannér, G. (2011).Using Naturalistic Field Operational Test (Fot) Data to Identify Horizontal Curves. Journal of Transportation Engineering. Accepted.

Reymond, G., Kemeny, A., Droulez, J. and Berthoz A (2001). “Role of Lateral Acceleration in Curve Driving: Driver Model and Experiments on a Real Vehicle and a Driving Simulator.” Human Factors: The Journal of the Human factors and Ergonomics Society 2001 43: 483 DOI: 10.1518/001872001775898188, 2001). The online version: http://hfs.sagepub.com/content/43/3/483

Torbic, D.J., Harwood, D.W., Gilmore, D.K. , Pfefer, R., Neuman, T.R., Slack, K.L., and Hardy K.K., (2004). NCHRP Report 500: Guidance for Implemention of the AASHTO Strategic Highway Safety Plan - Volume 7: A Guide for Reducing Collisions on Horizontal Curves. Transportation Research Board, Washington, D.C.,

Victor, T., Moeschlin, F., Hjälmdahl, M., & Ahlström, C. (2010). *Sweden-Michigan Naturalistic Field Operational Test (SeMiFOT). Evaluation of Methodology.* Report: Safer2010:06, Göteborg, Sweden.

Wong, J. Y. (2001). *Theory of Ground Vehicles*. Department of Mechanical Aerospace Engineering. Carleton University. Ottawa. Canada.