Methodology for Driver Behaviour Data Collection and Analysis for Integration in Geometric Design of Highways

Dalia Said, Ph.D.
Department of Civil and Environmental Engineering
Carleton University
1125 Colonel By Drive
Ottawa, Ontario, Canada, K1S 5B6
Tel: (613) 520-2600
Fax: (613) 520-3951
E-mail: dsaid@connect.carleton.ca

Abd El Halim O. Abd El Halim
Chair, Professor
Department of Civil and Environmental Engineering
Carleton University
1125 Colonel By Drive
Ottawa, Ontario, Canada, K1S 5B6
Tel: (613) 520-2600X5789
Fax: (613) 520-3951
E-mail: a_halim@carleton.ca

Yasser Hassan (corresponding author)
Associate Professor
Department of Civil and Environmental Engineering
Carleton University
1125 Colonel By Drive
Ottawa, Ontario, Canada, K1S 5B6
Tel: (613) 520-2600X8625
Fax: (613) 520-3951
E-mail: yasser_hassan@carleton.ca

Word count:

Manuscript	4,714
Figures (8*250)	2,000
Total	6,714

Paper submitted for presentation in the 4th International Symposium on Highway Geometric Design.

November 2009

Methodology for Driver Behaviour Data Collection and Analysis for Integration in Geometric Design of Highways

Topic Area: Human Factors in Geometric Design

Dalia Said, Abd El Halim O. Abd El Halim, and Yasser Hassan

Carleton University, Department of Civil and Environmental Engineering
Ottawa, Ontario, Canada, K1S 5B6
Tel: (613) 520-2600
Fax: (613) 520-3951

Email: dsaid@connect.carleton.ca ; ahalim@connect.carleton.ca; yasser_hassan@carleton.ca;

Abstract

The overall objective of the research conducted at Carleton University was to update the current geometric guidelines to accommodate the driver behaviour in a quantitative manner. This was accomplished through focusing on the road user as a main element in highway design in order to create a consistent geometric design. To realize this objective, an experiment was designed to collect driver behaviour data using a test vehicle equipped with various instruments. Thirty volunteers were recruited to drive the test vehicle on a test route. The driver behaviour data collected included vehicle path, steering angle, speed, and lateral and longitudinal accelerations on different road classifications. These data along with the geometric alignment of the highways traversed in the experiment formed a huge database. This database was used to evaluate driver behaviour and analyse the interaction between it and geometric design and safety. This research has provided significant recommendations to the design guidelines for updating the design of horizontal curves and evaluation of design consistency. Examples of the aspects of horizontal curve design covered in this research include determining desirable lengths of spiral curves, driver comfort thresholds on horizontal curves, and recommended values for deceleration and acceleration rates at the entrance and exits of the curve. This paper summarizes the data collection methodology and presents the main contributions of this research.

INTRODUCTION

Over the years, handling driver behaviour in highway and traffic engineering has changed from merely focusing on the mechanistic side of the design and the relation between the vehicle and the road to designing with the road users in mind in order to conform to their expectations (Kanellaidis 1996). Initially, the understanding of driver behaviour and characteristics was through research findings from social sciences. However, engineers should have a clear quantitative understanding of the road drivers including their behaviour, performance, characteristics, and interaction with the highway environment. This approach, where the designer provides for a forgiving road environment, reduces the probability of driver error and provides for a safer design (Dimitropoulos and Kanellaidis 1995, Kanellaidis 1996).

Good coordination between the driver, the road, and the vehicle allow for a comprehensive evaluation of the interrelationships of traffic safety and these three components (Lamm et al. 1999). Since the introduction of the motor vehicle in early 1900's, vehicle technology has experienced a great evolution, and vehicle characteristics have continually improved. Traffic volumes and speeds and dimensions of vehicles have also greatly increased. Providing a progressive design is important to satisfy this evolution in characteristics and growth in volumes, speeds, and sizes (Messer 1980).

In addition, the driving experience, and hence the driving behaviour, has evolved greatly since the rural highway system in North America was built. During the early 1920's, a high percentage of roads were low design and poorly coordinated. In addition, drivers had little experience with long distance driving on rural highways and speeds were relatively low. After World War II and with the continuous change in the highway conditions and vehicle performances, the driving experience also changed and by the 1960's drivers began to a great extent to expect better roads (Messer 1980). Among the basic expectations of drivers is higher design speeds on the highways, and it has become important for designers to conform to the expectations of drivers.

On the other hand, North American highway design guides as AASHTO Green Book (2004) and TAC Guide (1999) are based mostly on characteristics of vehicles designed in 1930's and 1940's and have not, to a large extent, kept pace with modern vehicle design and driver behavior. This could be attributed to the lack of research to update the fundamentals and criteria to consider the on-going developments in vehicles and driving behavior. Such revisions can be carried out only if designers have a clear, quantitative understanding of driver behaviour and performance.

The relationship between highway design and the driver behaviour is best explained through the framework shown in Figure 1. The highway features including the geometrics, roadside environment, traffic control devices, weather, and traffic conditions are the inputs to the driving task. This information is processed given the driver's physiological characteristics including reaction time, visual abilities, and fatigue level. These characteristics form the mental characteristics such as the expectancy level, attention level, and workload capacity. The result is how the driver will behave, translated through the vehicle operations characterized by the speed, and tangential and lateral acceleration rates, steering position, throttle and braking pedal positions, and lateral placement.

Therefore, one of the main factors that form the driving behaviour is the road geometry. This interaction between road geometry and driving behaviour should be studied to find points of deficiency in geometric design and increase safety on highways. This way a better conformance to driving behaviour could be achieved.

As part of a research initiative to bridge this gap of the knowledge base in driver behavior, an experiment was designed and conducted at Carleton University to collect driver behavior data including vehicle path, steering angle, speed, and lateral acceleration on different road classifications using a test vehicle. Then using this analysis for the overall objective of this research which is to update the current geometric guidelines to accommodate the driver behaviour in a quantitative manner.

METHODOLOGY FOR DRIVER BEHAVIOUR DATA COLLECTION

An experiment was designed to collect driver behaviour data using a test vehicle equipped with various instruments. Thirty volunteers were recruited to drive the test vehicle on a test route consisting of different functional classes of highways in Ottawa and including different types of geometric features. The driver behaviour data collected included driver's choice of vehicle path, speed, lateral and longitudinal accelerations, and steering angle. These data along with the geometric alignment of the highways traversed in the experiment formed a huge database. This database was used to evaluate driver behaviour and analyse the interaction between it and geometric design and safety.

An advantage of this experiment over other methods of investigation is that it collects true reliable data under true driving conditions and on many classes of roads. This is opposed to experiments performed on simulators or on special test routes designed for only the test vehicle to drive on. In addition, most experiments studying driver behaviour were based on subjective measures such as questionnaires, ratings, or secondary task.

The research methodology, shown in Figure 2, involved the following steps:

1. Preparation for the experiment included designing and planning of the experimental study, installation of the measuring equipment on the instrumented vehicle, recruiting volunteers for the experiment and training them on the procedure, and selection of the test route. The alignment was composed of both urban and rural freeways and two-lane highways.

2. The second component involved the actual experimenting phase. It was concerned with collecting reliable data about driver behaviour along the test route's alignment.
3. The third component was the preparation of the database used for analysis. This database included the synchronized driver behaviour data collected during the experiment and geometric alignment data of the roads traversed.
4. The fourth component involved examining, analysing, and modelling the interaction between the road's alignment and the human behaviour derived from these experiments.
5. The final outcome of this research was concerned with revising and updating the current geometric design guidelines in order to accommodate driver behaviour in a more accurate and quantitative manner.

The experiment was performed during the summer and fall months, which are favourable conditions. These are also the months where drivers would drive less conservatively causing the geometric features of the road to be a direct influence on driver behaviour.

TEST VEHICLE SET-UP

The test vehicle used in this study, shown in Figure 3, was a Ford minivan owned by Carleton University and used by the Department of Civil and Environmental Engineering in performing experiments related to highway design and traffic studies. The vehicle could be easily adapted to install different types of measuring equipment. The seat beside the driver was removed and a board was installed with angles that could hold the various instruments. The different instruments installed are shown in Figure 4. . The data collection process was explained in detail in other references (Said et al. 2006, Said et al. 2007) and is presented here only briefly.

1. GPS receivers to record the vehicle path during the test.
2. Corsa data acquisition box to record the vehicle speed, steering angle, and lateral and longitudinal accelerations.
3. Two laser guns to measure the distance between the test vehicle and the vehicles in front and behind the test vehicle to determine the presence of free-flow conditions.
4. Video camera mounted beside the driver to record the driver's view during the test course. This is important to have a permanent record of the outside events that might have effects on the driver's behaviour.

VOLUNTEER RECRUITMENT

Thirty volunteers were recruited for this experiment. The sample size was chosen as thirty to obtain a normal distribution. Figure 5 shows the different characteristics of the driver sample. Most of the volunteers were in the mid-age group ranging from around 20-50 years of age. The volunteers were undergraduate students, graduate students, friends of the team members, and professors Results of the filled questionnaires, as well as the experiment, showed that the sample contained different driving behaviours ranging from slightly cautious, moderately cautious, extremely cautious, and slightly aggressive. In addition, the sample contained various driving experiences ranging from less than 5 to more than 16 years of driving experience.

The main task of the volunteers was to drive the same way they drive on the road, and they were not asked to do specific manoeuvres. All volunteers were fully licensed drivers. The task involved no confusion and drivers were faced with the same usual risks of everyday driving. The drivers were given explanation and instructions on the procedure before starting the experiment and elements of the experiment were made clear to them. The experiment was performed during the summer and fall months so that the drivers are not exposed to the more dangerous conditions of snow or freezing ice, which could be perceived as potential danger.

DRIVING DATA SYNCHRONIZATION

Using the data collected from all pieces of equipment, a database for each driver was built including the following:

1. Vehicle’s trajectory (Northing and Easting) obtained from corrected GPS data after post-processing.
2. Vehicle’s speed, lateral acceleration, longitudinal acceleration, steering, throttle, and braking positions obtained from the Corsa Box.
3. Side friction value or the centrifugal force minus the weight component of the vehicle due to the superelevation in degrees.
4. The distance and speed difference between the test vehicle and the vehicles in front and behind it from the front and back laser guns.

More data regarding the synchronization process is available in Said et al. (2006, 2007). Figure 6 shows an example of integrating the alignment data with the speed data and the driver’s view on one of the roads traversed in the experiment. The horizontal axis represents the distance and the first and second axes from the bottom represent the curve radii (m) and speed (km/h) respectively.

ANALYSIS OF DRIVER BEHAVIOUR DATA FOR UPDATING HORIZONTAL CURVE DESIGN

The data collected made up a huge database that could be used for examining, analysing, and modelling driver behaviour given the road geometry, traffic conditions, and vehicle dynamics. The focus of this paper is to show the main results of this major research at Carleton University. Topics covered in this paper are:

1. Analysis of vehicle path,
2. Modelling desirable spiral lengths for horizontal curves based on driver steering behaviour,
3. Modelling driver comfort thresholds on horizontal curves based on driver lateral acceleration,
4. Modelling deceleration and acceleration rates at entrance and exits of horizontal curves of two-lane rural roads and ramps, and
5. Relating driver behaviour to safety performance on highway horizontal curves.

Analysis of Vehicle Path

On horizontal curves, the parameter that describes the vehicle path is the instantaneous curvature (1/*R*). It can be calculated for every three points on the driver's path using Equations (1) and (2). Where *R* is the curve's radius, (x_1, y_1), (x_2, y_2), and (x_3, y_3) are three points on the circumference of a circle, and (x_0, y_0) are the coordinates of the circle's center (Math Forum 2000).

$$x_0 = \frac{\begin{vmatrix} x_1^2 + y_1^2 & y_1 & 1 \\ x_2^2 + y_2^2 & y_2 & 1 \\ x_3^2 + y_3^2 & y_3 & 1 \end{vmatrix}}{2 \times \begin{vmatrix} x_1 & y_1 & 1 \\ x_2 & y_2 & 1 \\ x_3 & y_3 & 1 \end{vmatrix}}, \quad y_0 = -\frac{\begin{vmatrix} x_1 & x_1^2 + y_1^2 & 1 \\ x_2 & x_2^2 + y_2^2 & 1 \\ x_3 & x_3^2 + y_3^2 & 1 \end{vmatrix}}{2 \times \begin{vmatrix} x_1 & y_1 & 1 \\ x_2 & y_2 & 1 \\ x_3 & y_3 & 1 \end{vmatrix}} \tag{1}$$

$$R = \sqrt{(x_1 - x_0)^2 + (y_1 - y_0)^2} \tag{2}$$

For the evaluation of the vehicle's path, the 85th percentile curvature for the thirty volunteers were plotted for each curve in the study database and compared to the curvature of the geometric alignment. The analysis found that the spiral transition followed by the drivers was different from the actual alignment. This may be attributed to the drivers beginning the change in their path to match the alignment's curvature after perceiving the beginning of the curve. Therefore, by the beginning of the curve, the curvature of the vehicle path did not reach the curvature of the true alignment. To compensate for this situation, the vehicle path had a greater curvature in the middle of the curve than the alignment's actual curvature. This is called curve-cutting behaviour, and was also reported in previous studies (Johnston 1983, Glennon and Weaver 1971, Shinar et al. 1974).

The interrelation between curve radii and differences in curvature between the vehicle path and the alignment is shown in Figure 7. Regression analysis produced the following model:

$$\Delta Curve = -0.00057 \ln(R) + 0.0047 \qquad \text{adjusted } R^2=0.689 \tag{3}$$

Where:

$$\Delta Curve = \left(\frac{1}{R}\right)_{VP\_85} - \left(\frac{1}{R}\right)_{C} \tag{4}$$

Where $\left(\frac{1}{R}\right)_{VP\_85}$ = the 85th percentile vehicle path curvature at the point of maximum curvature for a certain curve, and $\left(\frac{1}{R}\right)_{C}$ = the alignment's curvature.

It is noticed that a similar trend exists for both two-lane highways and freeways, and that generally higher differences in curvature are observed on sharper curves. Therefore, this relationship is more pronounced on two-lane highways. It should be noted that having the greater differences in curvature on sharper curves, which are generally less safe than flatter curves, raises even more safety concerns. Hence further investigation was carried out using the steering behaviour data and lateral acceleration data which are summarized in the following sections and the details of the results are presented in Said et al. (2008, 2009).

Modelling Desirable Spiral Lengths for Horizontal Curves Based on Driver Steering Behaviour

Studying the steering behaviour should allow a comparison between the vehicle path and the built alignment. This should in turn facilitate improving the design of horizontal curves through determining the spiral length that conforms to the drivers' steering behaviour. In this context, the steering behaviour is quantified here using the steering angle, which is the angle the steering wheel makes with the straight position. Theoretically, this angle ranges from 0° at the straight position to ±360° with the sign convention indicating positive angles for right turns, and vice versa.

The term steering length is introduced as the length the driver takes to adjust the vehicle path from a tangent section to the curve section and is used to compare the vehicle path to the built alignment and to determine the desirable spiral length. For each curve in the test route, the steering length was measured using the steering angle profile for each of the 30 drivers in the test sample. Then the 85th percentile was calculated and compared to the actual spiral length of the alignment.

Two models were found for two-lane highways and ramps and for freeways, and are shown here in Equations 5 and 6 respectively.

For two-lane highways and ramps:

$$L_{85} = 5.97\times10^{-7} R^3 - 1.0127\times10^{-3} R^2 + 0.472R + +62.940$$

$$L_{85} = 1.01\times10^{-6} R^3 - 0.0018\times R^2 + 0.8393R + 23.922 \qquad df=588 \qquad R^2_{adj}=0.86 \qquad (5)$$

For freeways:

$$L_{85} = -0.02818 \; R + 169.355 \qquad df=474 \qquad R^2_{adj}=0.89 \qquad (6)$$

where L_{85} is the 85th percentile steering length in meters.

To complete the analysis, a closer look was taken at the current practice of the North American guides (AASHTO 2004, TAC 1999). The desirable spiral length was compared to the different recommended minimum and maximum spiral lengths from the different control criteria defined by the Green Book and TAC. In this analysis, the comparison with the guides will be done using only the relation for the two-lane highways. The results are shown in Figure 8 (a) for the Green Book controls and Figure 8 (b) for the TAC controls.

The design speeds used in the comparison are the maximum design speeds allowable for these radii as specified by the guidelines and ranged from 50 to 110 km/h. Methodology of calculating each of the controls can be found in Said et al. (2009). From Figure 8, it is obvious that the desirable spiral length represented by the drivers steering behaviour follows the same trend as the minimum comfort control. The steering length increases with increase in radius in the lower range of radii, then decreases with increase in radii in the upper range. This proves the validity of the model, especially that the comfort control is based on theoretical derivation. However, the desirable spiral length exceeds all minimum controls at the 85th percentile level. The difference between the minimum controls and the desirable length is significantly large, which is especially critical in the lower range of radii and leads to safety concerns.

The comparison shows that there is a difference in the values adopted in the guidelines and that of driving behaviour. Another concern is the value of *c* taken in the Green Book which is 1.2 m/sec^3. This value is higher than the value found by 85% of the drivers for sharp curves. The highest value observed was 0.75 m/sec^3 for the sharpest curve of R= 86 m. Moreover, using constant comfort values of *c* for a wide range of radii unrealistic.

On the other hand, the value taken by the Canadian Guidelines (c=0.6 m/sec^3) is closer to driver behaviour especially in the range of smoother curves (R> 500 m). However, there still remains the main safety control of designing sharp curves with design speeds much less than the operating speed. This is the main reason behind the difference between the driving behaviour and that of the design. Therefore, to design spiral curves conforming to driver behaviour it is recommended to use Equation 5 derived in this research which is based on driver behaviour under true driving conditions.

Modelling Driver Comfort Thresholds on Horizontal Curves Based on Driver Lateral Acceleration

The objective of this component in the research was to develop a model that quantifies the upper limit of driver comfort thresholds based on actual road driving data. Details of this section as well as calculation methods are found in Said et al. (2008). Previous studies have shown that the comfort threshold describes the desire of the drivers to minimize their speed reduction as they move from the approach tangent to the curve (Chowdhury et al. 1991, Bonneson 1999, Bonneson 2000). As a result, it was suggested that drivers tend to accept greater side fiction demands when facing greater speed reductions (Chowdhury et al. 1991). This implies that drivers may end up negotiating curves at higher speeds and higher side friction than what they are designed for, which raises two concerns:

1. The margin of safety between the side friction demanded ($f_{s,d}$) and that supplied at the interaction between the tires and the road is reduced, and therefore the risk of skidding increases.
2. Drivers' operating speeds exceed the design speed, which may cause inconsistency in the design of highways.

One of the important findings of this study was that there was significant difference between the right and left turn curves. The validity of this observation was tested through a control test which was performed on a route with eight horizontal curves. Four runs were made with a constant speed of 70 km/h which was the safe speed on curves including the sharp ones. The first two runs were in opposite directions with the accelerometer facing a certain direction. The following two runs were similar to the first two runs but the accelerometer was rotated 180º. Therefore, four sets of lateral acceleration measurements were available for each curve: (1) right turn, (2) left turn, (3) right turn with the accelerometer rotated 180º, and (4) left turn with the accelerometer rotated 180º.

The significance of the difference between the lateral acceleration data for the four runs was tested using three sets of the *t*-test of two independent samples at 5% level of significance. In each of these sets, the right turns experienced greater lateral acceleration values than the left turns. Therefore, it was concluded that when negotiating right turns, drivers experience higher values of lateral acceleration, making it the critical direction. Further regression analysis was consequently performed using right turns only.

A model was developed to describe lateral acceleration on horizontal curves for rural roads and ramps. Eight curves were used for the analysis, five rural and three ramps. The regression analysis was performed using the software SPSS v15, and produced:

$$a_{85} = 0.7634 - 0.0688\, I_R - 0.006207\, V_{A\_85} + 0.006514\, \Delta V_{85} \qquad \text{df=151} \qquad R^2_{adj}\text{=0.996} \quad (7)$$

Where a_{85} is the 85th percentile lateral acceleration value (m/s^2), I_R = dummy variable (=1 for a ramp, =0 for rural roads), V_{A_85} is the 85th percentile approach speed (km/h) and ΔV_{85} is the 85th percentile of speed reduction from tangent to curve (km/h).

The developed model could be used with the point-mass formula to determine the minimum radius of a horizontal curve for a specific speed environment, which would replace the approach speed in the model formulation. In addition, the model could be used in evaluation of design consistency for horizontal curves. For a specific radius and superelevation rate, an inferred curve operating speed could be predicted and compared to the design speed. Moreover, the inferred speeds of a series of horizontal curves could be predicted using this model and hence a check could be made for uniformity of speeds to ensure design consistency.

Modelling Deceleration and Acceleration Rates at Entrance and Exits of Horizontal Curves of Two-lane Rural Roads and Ramps

Operating speed profiles are used to address inconsistencies in speeds and therefore in the road design. They are used to trace the change of speed between tangents and curves. In order to find the length of speed reduction or increase, the deceleration and acceleration rates entering and exiting the curve respectively are required along with the operating speeds on the curves and tangents. Several models have been developed to predict the speeds on horizontal curves and tangents for two-lane rural roads. However, the acceleration and deceleration rates have not been sufficiently investigated. Most studies adopt a constant value for these rates. On the other hand, review of driver behaviour in this study, found that using a constant rate on different curve radii does not reflect true driver behaviour.

To validate the values used in previous studies, two *t*-tests were made. First, a single sample *t*-test was performed to test if the 85th percentile deceleration rate (d_{85}) was significantly different from the value proposed in previous studies (0.85 m/s^2) at 5% significant level. The average 85th percentile deceleration rate of the studied sample was 0.72 m/s^2. The result of the test showed that the average is not significantly different from 0.85 m/s^2 (*p*-value= 0.206). This is the same conclusion made by Collins and

Krammes (1996). However, the wide range of d_{85} with the change in radius (0.06 m/s^2 – 1.53 m/s^2) suggests that a single value should not represent all deceleration rates on all curves regardless of their radii.

Another single sample *t*-test was performed to test if the 85th percentile acceleration rate (a_{85}) was significantly different 0.85 m/s^2 at 5% significant level. The rate of the studied sample was 0.51 m/s^2. The result of the *t*-test showed that there was a significant difference between a_{85} and 0.85 m/s^2 (*p*-value <0.001). This also conforms to results of Collins and Krammes (1996) and Fitzpatrick et al. (2000). Therefore, using this value in the speed-profile underestimates the deceleration length. In addition, the wide range of the acceleration rate (0.18 m/s^2 – 0.94 m/s^2) also shows that the geometric characteristics of the curve affect the acceleration rate adopted by the drivers.

Therefore, regression analysis was performed to develop two models that relate both the acceleration and deceleration rates to the geometric characteristics of the curve. Eleven curves, eight rural and three ramps, were used in the deceleration rate analysis. Twelve curves, eight rural and four ramps, were used in the acceleration rate analysis. The models show that there is a significant relation between the deceleration rate when entering the curve and the inverse of the curve radius. In addition, there is a significant relation between the acceleration rate when exiting the curve and the inverse of the curve radius and the curve length.

$$d_{85} = 0.636 + \frac{237.573}{R} I_T - 0.602 I_T \qquad \text{df=246} \qquad R^2_{adj}\text{=0.95} \qquad (8)$$

$$a_{85} = 0.275 + \frac{44.563}{R} + 0.046 I_{TF} \qquad \text{df=265} \qquad R^2_{adj}\text{=0.83} \qquad (9)$$

Where d_{85} and a_{85} are the 85th percentile deceleration and acceleration rates respectively (m/s^2), R = curve radius (m), I_T = dummy variable (=1 for independent tangent preceding the curve, =0 for nonindependent tangent), and I_{TF} = dummy variable (=1 for independent tangent following the curve, =0 for nonindependent tangent).

The developed model can be used, in combination with the operating speed models, in drawing speed profiles for use in the evaluation of design consistency on two-lane rural roads. It should be noted here that even though the study used a relatively small number of sites, it has the unique advantage of utilizing measured deceleration and acceleration rates under actual driving conditions.

CONCLUSIONS

This paper summarized a methodology used to collect driver behaviour data under true driving conditions. An experiment was designed and carried out at Carleton University, where a test vehicle was equipped with numerous instruments that could measure vehicle path, speed, accelerations, steering positions, and throttle and braking pad positions. Thirty volunteers were recruited to drive the test vehicle. Using the collect driving data and integrating them with the geometric characteristics of the road, several analyses were performed. The analyses described in this paper cover the evaluation of the vehicle's path, modelling the desired spiral length based on driver steering behaviour, modelling the driver comfort thresholds on horizontal curves, and modelling the acceleration and deceleration rates adopted by drivers on horizontal curves. Incorporating driver behavior in the control criteria of the design guides would provide a design for highways with the road user in mind. It is recommended that this methodology be used with a larger driver sample along with a larger sample of horizontal curves. In doing so, the models developed in this research could be refined. In addition, this study was based on a minivan passenger car as a test vehicle. Further analysis with different types of passenger cars and heavy trucks would be valuable in covering a wider range of vehicles on the road.

ACKNOWLEDGMENTS

The authors would like to express their gratitude to the Natural Sciences and Engineering Council (NSERC) for financial support to conduct this research. The equipment used in the research was acquired through funding from the Canada Foundation for Innovation (CFI) and Ontario Innovation Trust (OIT). Additional financial support was provided by the Ontario Graduate Scholarship (OGS) and Transportation Association of Canada (TAC). The alignment data for this study were provided by the Planning and Design Section of the Eastern Region of the Ontario Ministry of Transportation and the Mapping Department of the City of Ottawa. The authors would also like to thank the volunteers who helped in the driving experiment.

REFERENCES

American Association of State Highway and Transportation Officials. 2004. A Policy on Geometric Design of Highways and Streets. Washington, D.C.

Bonneson, J.A. Side Friction and Speed as Controls for horizontal Curve Design. 1999 *Journal of Transportation Engineering*, Vol. 125, No. 6, pp. 473-480.

Bonneson, J.A. *Superelevation Distribution Methods and Transition Designs*. 2000 National Cooperative Highway Research Program NCHRP Report 439, Washington, D.C.

Chowdhury, M., D., Warren, and H. Bissell. Analysis of Advisory Speed Setting Criteria. 1991. *Public Roads*, Vol. 55, No. 3, pp. 65-71.

Dimitropoulos, I. and G. Kanellaidis. 1995. Highway Geometric Design: The Issue of Driving Behaviour Variability. International Symposium on Highway Geometric Design Practices.

Glennon, J.G. and G.D. Weaver. 1971. The relationship of vehicle paths to highway curve design. (TTI Report 134-5). Texas A&M University, Texas Transportation Institute, College Station, Texas. (cited in Tom (1995)).

Johnston, I.R. 1983. The effects of roadway delineation on curve negotiation by both sober and drinking drivers. Australian Road Research Board, ARR No 128. Victoria. Australia. (cited in Tom (1995)).

Kanellaidis, G., 1996. Human Factors in Highway Geometric Design. Journal of Transportation Engineering, ASCE, Vol. 122 (1), pp. 59-66.

Messer, C.J. 1980. Methodology for Evaluating Geometric Design Consistency. *Transportation Research Record 757*, Transportation Research Board, Washington, DC, pp. 7-14.

Said, D., Hassan, Y., and Abd El Halim, A., 2006 Methodology for Analysing Vehicle Trajectory and Relation to Geometric Design of Highways, *Advances in Transportation Studies: An International Journal*, Issue (X), pp. 55-71.

Said, D., Hassan, Y., and Abd El Halim, A., 2007. Quantification and Utilization of Driver Path in Improving the Design of Highway Horizontal Curves, presented in *86th Annual Meeting* and published in the Conference Proceedings, Transportation Research Board, January 21, 2007, Paper No. 07-2037.

Said, D., Hassan, Y., and Abd El Halim, A. 2008. Driver Comfort Thresholds for Horizontal Curve Design. Submitted to the Canadian Journal of Civil Engineering, Paper No. 08140.

Said, D., Abd El Halim, A. and Hassan, Y. 2009. Desirable Spiral Length Based on Driver Steering Behavior. Paper submitted for publication in Transportation Research Record: Journal of the Transportation Research Board and presentation in the 88th Annual Meeting, TRB, National Research Council, Washington, D.C., January 2009.

Shinar, D., E.D. McDowell, E.D., and J.H. Rockwell. 1974. Improving driver performance on curves in rural highways through perceptual changes. (Report EES 423). The Ohio State University, Department of Industrial Engineering, Columbia, Ohio. (cited in Tom (1995).

Syed, L. and Y. Hassan. 2005. Role of Uneven Vehicle Weight Distribution in Curve Driving. Proceedings, *6th Transportation Specialty Conference, Canadian Society for Civil Engineering*, CSCE, Toronto, Ontario, June 2-4, Paper TR-162.

The Math Forum Drexel University. 2000. Finding the Center of a Circle Given 3 Points. <http: //mathforum.org /library /drmath /view /55239.html> (January 18, 2005)

Tom, G. 1995. Accidents on Spiral Transition Curves. *ITE Journal*. pp. 49-53. September.

Transportation Association of Canada. 1999. Geometric Design Guide for Canadian Roads. Ottawa, Ontario.

Figure 1. Relationship between Driver Behaviour and Highway Design.

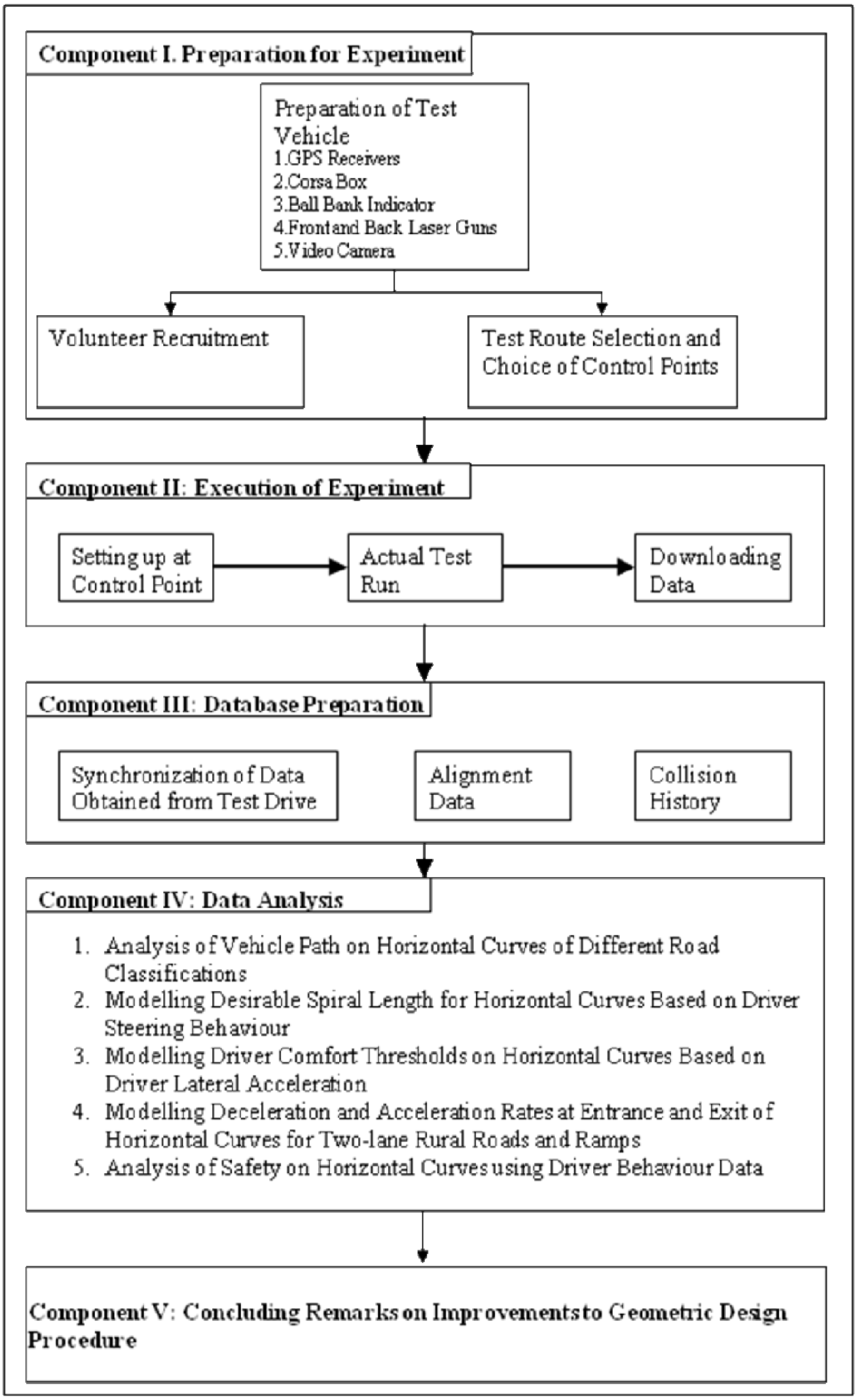


Figure 2. Research Methodology

Figure 3. Test Vehicle.

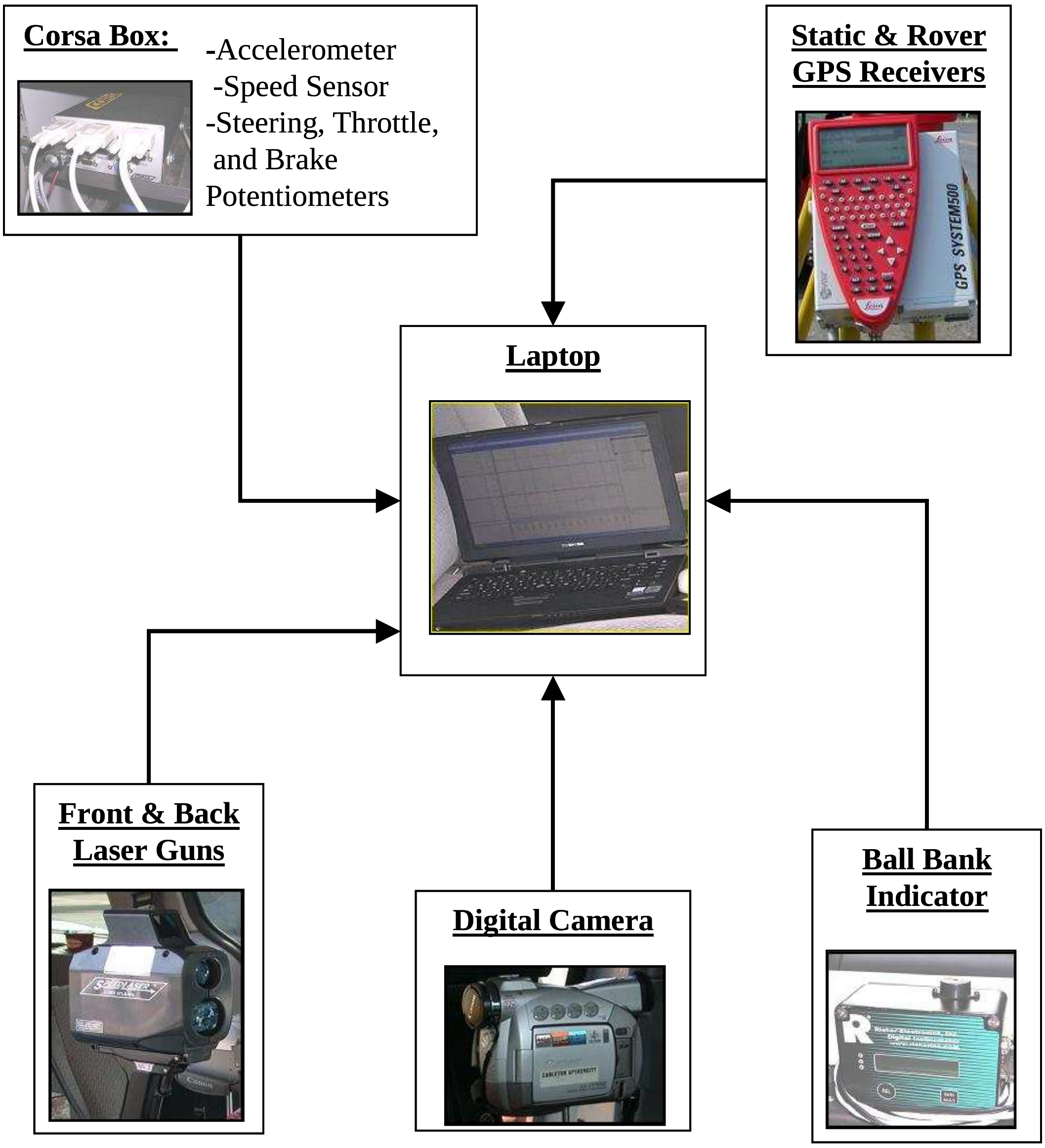


Figure 4. Data Collected Synchronized in Database

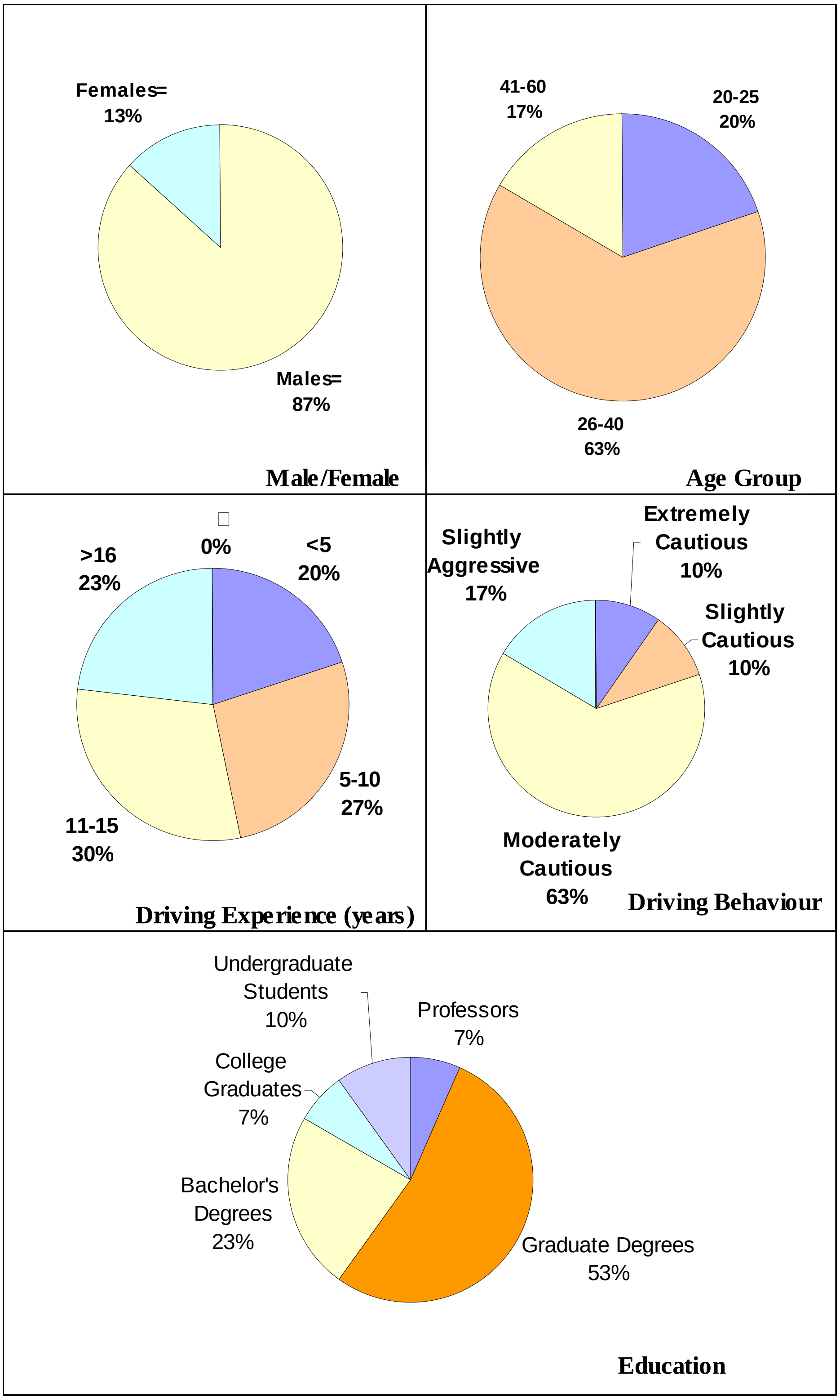


Figure 5. Different Characteristics of Driver Sample

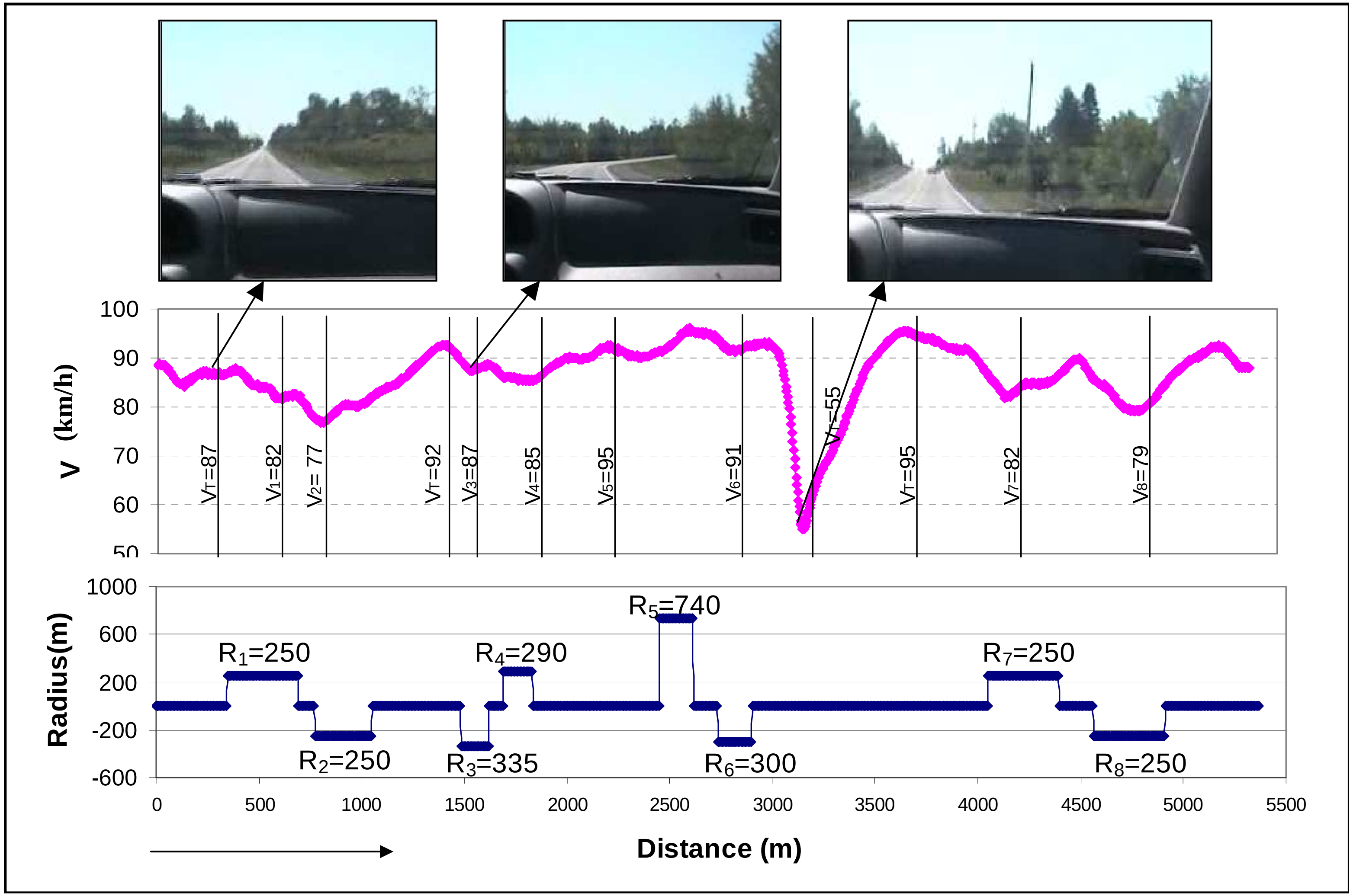


Figure 6. Alignment, Speed and Driver's View for Part of RR3

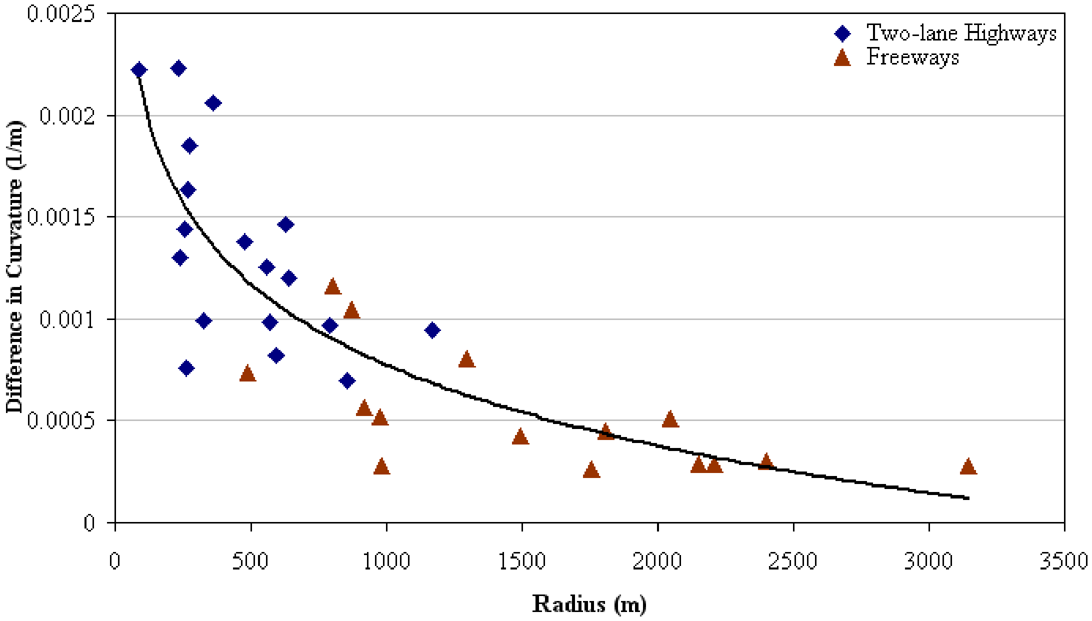
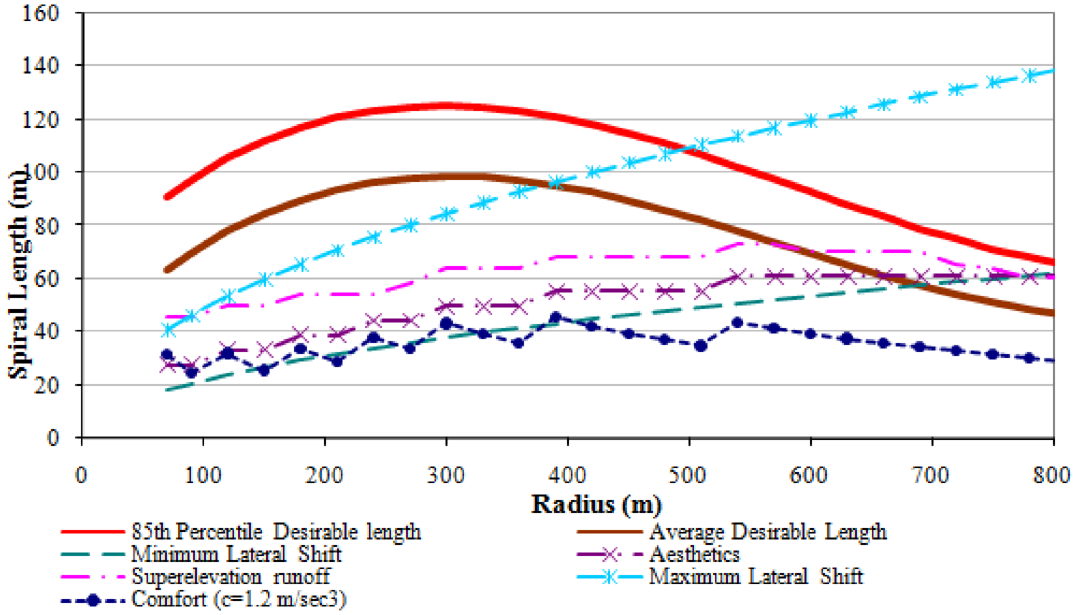
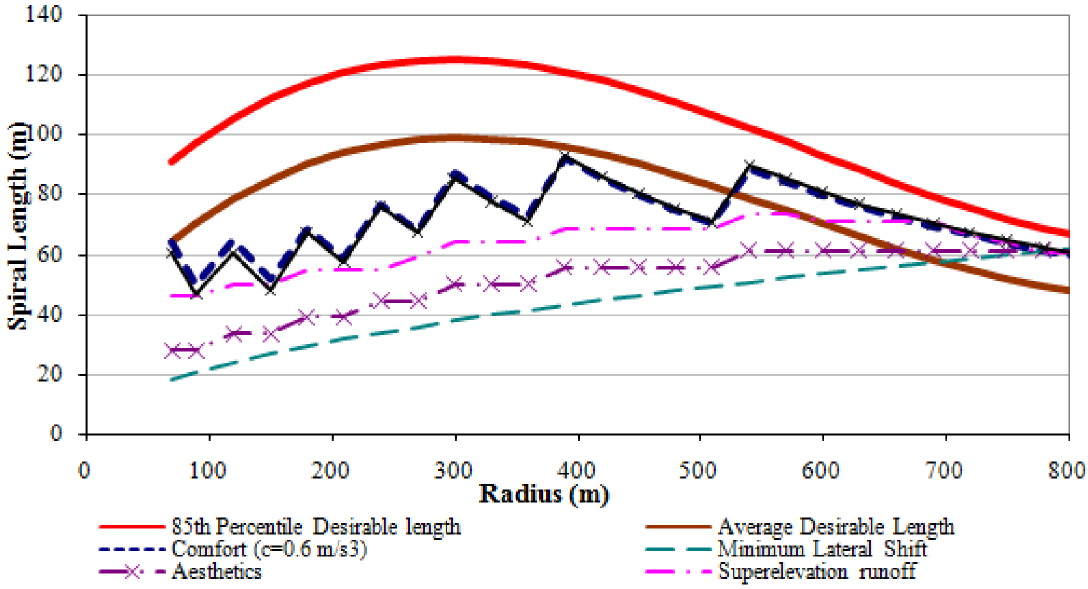


Figure 7. Relationship between *R* and *ΔCurve*.



(a) The Green Book Control Criteria



(b) The Canadian Design Guide Control Criteria.

Figure 8. Desirable Spiral Length Compared to Current North American Control Criteria.