**EVALUATION OF DRIVER VISUAL DEMAND AT DIFFERENT DESIGN
SPEEDS ON COMPLEX TWO-DIMENSIONAL RURAL HIGHWAY
ALIGNMENTS**

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By

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**Bachelor of Engineering, University of Engineering & Technology,
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A thesis

Presented to Ryerson University

In partial fulfillment of the requirement of degree of

Master of Applied Science

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Master of Applied Science in Civil Engineering

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Abstract

Road crashes are a major cause of loss of human life, property and money throughout the world. One of the reasons behind these crashes is the interaction between drivers and road alignments. The need to understand the factors that affect drivers has become obvious and is now being addressed by researchers. Moreover, driver workload is gaining attention as a measure of highway-design consistency as it directly reveals design features to the driver. This research focuses on evaluating driver visual demand at different design speeds along with other geometric design features for two-dimensional rural horizontal roadway alignments. Twelve such alignments having simple and complex curves were designed following the standards of the American Association of Highway and Transportation Officials (AASHTO) and the Transportation Association of Canada (TAC). The driver simulator at Ryerson University, Toronto, recently modified after the integration of a car, was used for the simulation of roadway alignments. Scenario Definition Language (SDL) was used to develop Event files for simulation and to save the required data. Twelve drivers drove the simulated alignments. The output data relating to driver visual demand were processed using MS Notepad and MS Excel. The visual demand calculations for full-element length (VDF), half-element length (VDH) and the first 30 m of element length (VD30) for curve and tangent sections of alignments were done using MS Excel. Statistical Analysis Software (SAS) was used to analyze and

develop models for VDF, VDH and VD30 for curve and tangent sections, first considering design speed only as explanatory variable and then considering design speed along with other geometric design characteristics as explanatory variables. It has been observed that visual demand increases with the increase in design speed. Besides, the combined effect of design speed and other geometric design characteristics (e.g., the type of preceding element, the turning direction of a curve) has significant effect on visual demand. It was also found that visual demand followed a Log Normalized distribution which was also observed by previous research. The developed models were used to establish the visual demand profile for highway design consistency evaluation. The comparison of visual demand profile and operating speed profile has shown that the visual demand can be an acceptable measure for evaluating the highway design consistency.

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Chapter 1 INTRODUCTION

1.1 Research Background:

A large number of deaths and injuries take place due to road crashes all over the world, and transportation professionals are trying their utmost to decrease these numbers. In the USA there were an estimated of 6,159,000 police-reported traffic crashes, in which 43,443 people were killed and 2,699,000 people were injured in 2005 (NHTSA 2005). Therefore, on average, 119 people die each day in motor-vehicle crashes. In Canada, there were 12.6 fatalities and 979.8 injuries per 100,000 licensed drivers in 2004 (Transport Canada 2004). In 1995, two million traffic accidents resulted in 120,000 deaths and 2.5 million injured people in the whole European region (WHO 1998). Drivers, highways and vehicles are major components of a road crash. While addressing efforts to reduce the number of road crashes, the interaction between drivers and roads cannot be avoided. Moreover, statistics have demonstrated that most road crashes (approximately 90 %) occur due to driver error.

Highway geometric design is a crucial aspect of highway safety since, during driving, road geometry continuously puts some demand on the driver and therefore affects the driver's performance. A consistent alignment is necessary because there is a relationship between consistency and safety. Safety performance of highway alignments can be significantly improved by the identification of inconsistencies and by suitable subsequent improvements. Driver reactions are estimated by measuring how well drivers' expectations are being met. Highway designers are establishing measures that can reduce uncertainty or unexpected road features for drivers. Among these measures, highway design consistency is one of the concepts gaining wide attention throughout North America. A consistent design puts less demand on the driver as compared to a driving situation that is inconsistent or unexpected by the driver, thus reducing the possibility of a road crash.

In Canada and the USA, the geometric design of highways is based on the American Association of State Highway and Transportation Officials (AASHTO 2004) and the Transportation Association of Canada (TAC 1999) guidelines. The TAC Design Guide

contains a separate chapter on design consistency. Highway design consistency can be evaluated in terms of the following:

- Operating Speed Consistency
- Cross-Section Consistency
- Alignment Indices Consistency
- Driver Workload Consistency

The concept of driver workload consistency, although an old one, has gained recent attention due to new developments in the measurement of driver workload. Driver workload is actually a measure of demands put by the road on the driver. A significant amount of increase or decrease in workload can affect driver performance and can lead to a road crash. The driver workload reflects the effects of a combination of roadway geometric features and the criticality of individual features. Driver workload approach for the measurement of design consistency appears to be more promising because it directly reveals the effects of geometric features on the driver. Research has found several relationships among roadway geometric elements, e.g., curve radii, deflection angle, sequence of curves, etc., and driver workload.

Various methods have been suggested for using driver workload for the evaluation of highway design consistency; the most common being visual demand. Visual demand can be defined as the percentage of time the driver is actually looking at the road while driving. For example, under the same conditions of speed and traffic environment, a driver may need to concentrate more on looking at the road while driving on a curve as compared to driving on a tangent. In this method, the driver wears spectacles with lenses that are opaque in a normal state. As the driver requires, he or she can open the lenses by using an arrangement designed by the experimenter for a period of 0.5 seconds. Thus, the visual-demand calculations can be made by knowing the length of time the driver requests a clear view of the road.

Research has been done to address driver workload as a measure of design consistency. A Federal Highway Administration (FHWA) study report has concluded that driver workload has excellent potential as a design-consistency-rating measure (Fitzpatrick et al. 2000). This report also addresses another vital aspect of road safety research that is the use of a driver simulator in this type of research. This approach is

particularly important since it is often unsafe and unfeasible to carry out road-safety research under real-world driving conditions. After comparing the results of the driver simulator and a real-world driving environment, the FHWA report stated that simulator results can provide reasonable estimates of driver workload and can be used for visual demand studies. The same findings were presented by other researchers by using visual-demand techniques (Easa and Ganguly 2004, Easa and He 2005).

However, the above-mentioned research studies were done by conducting experiments for a specific design speed. In the current research, an attempt was made to evaluate driver workload for different design speeds for complex curves and tangents and to develop visual demand models by considering design speed as an explanatory variable. Moreover, an attempt was made to investigate the effects of other geometric properties (e.g., current curve radius, deflection angle) and the different turning directions of current and previous curve elements on driver workload by conducting experiments at different design speeds in a driver simulator environment. All driver simulator experiments were carried out for two-dimensional rural highways, and the geometric design was performed by following the standards of the AASHTO and the TAC.

1.2 Research Thesis Structure:

The thesis structure consists of the following chapters:

Chapter 1: Introduction

This chapter describes the background for the research work and research motives. A brief concept of highway design consistency and driver workload as a measure of design consistency is provided.

Chapter 2: Literature Review

An in-depth and detailed study of highway design consistency and relevant measures is described in this chapter. A detailed review of different measures of highway design consistency with special emphasis on driver workload as a measure is presented. Different techniques for measuring driver workload and brief comparison are also described. Moreover, a brief review of previous research work regarding the

measurement of workload, the investigations of factors affecting driver mental workload using vision occlusion method along with a few additional methods are given in a tabular form for quick reference. Research Challenge and Hypothesis are described at the end.

Chapter 3: Research Pilot Study

The pilot study was done as a model of a full research study but on a smaller scale. The purpose was to investigate the effects of independent design variables on driver visual demand at different design speeds. The pilot study also intended to evaluate the research design and the research setting, and to test the operation of the new arrangement of the driver simulator at Ryerson University after the integration of a car. It was also desired to test the feasibility of conducting larger-scale experimentation. Three long highway alignments were designed at design speeds of 60 km/hr, 80 km/hr, and 100 km/hr following the AASHTO and the TAC standards, and were simulated using the Scenario Definition Language (SDL) of the simulator. Three drivers drove the alignments by using vision-occlusion spectacles. The pilot study proved that the experimental setting was ideal for conducting large-scale experiments, with the integrated car giving a better real-world driving feeling to the drivers. The explanatory variables were also found to be appropriate for evaluating visual demand by conducting a large-scale investigation. The pilot study statistical models are also presented in this chapter.

Chapter 4: Driving Simulation Arrangement and Experimental Design

This chapter describes the integration of the different components of the driver simulator at Ryerson University, its working principles, its driver training procedure and the detailed methodology of conducting experiments using visual-occlusion spectacles. Geometric design details of the different elements of road alignments are also presented. The details of how to use Scenario Definition Language (SDL) to develop Event files for simulation and the procedure for saving output data are likewise provided.

Chapter 5: Analysis and Results

In chapter 5, first the procedure of extracting simulator output file into MS Excel and the method for visual demand calculations for full-element length (VDF), half-

element length (VDH) and for the first 30 m of element length (VD30) are discussed for both curve and tangent elements of the test alignments. Then the visual demand models for VDF, VDH, and VD30, for both curves and tangents, were developed—first by considering only design speed as an explanatory variable and subsequently by considering other explanatory variables along with design speed.

Chapter 6: Model Validation and Application

In this chapter, one of the developed models was applied to estimate the design consistency of a road alignment. A design consistency evaluation was carried out with respect to driver workload and operating speed measures. A comparison of both these measures is presented for two different highway alignments.

Chapter 7: Conclusions and Recommendations

This chapter describes the findings of the research study. The conclusions and recommendations are discussed, and the areas that require further research are highlighted. In addition, three appendices, A, B and C, are included. These include various tables and photographs.

Chapter 2 LITERATURE REVIEW

2.1 Background

The geometric design of transportation facilities is an important element in planning and developing a facility. The geometric aspects of a highway include features that affect or relate to its operational quality and safety. Investigations show that most road crashes (approximately 90%) in North America occur due to human error (Sabey et al. 1980 and Sayed et al. 1995). One reason behind these errors is the workload imposed on the driver by various highway geometric features. Hence, the design of the geometric alignment and cross-sections of the roadway should be consistent enough to develop a smooth and suitable workload environment for the user. In this regard, organizations like the AASHTO and the TAC furnish the guidelines for designing highway geometric features from time to time.

Recent research has evaluated highway design consistency in terms of operating speed, alignment indices and driver workload. However, very little direct work has been done on the evaluation of driver mental workload. The main cause of the development of mental workload for any driver relates to the visual information conveyed by the roadway characteristics. Although there are many features and factors affecting driver visibility, the most visible and direct features affecting driver performance include elements of the roadway (e.g., horizontal and vertical alignment, intersections and interchanges, cross-sections, medians, etc.), ramps (e.g., freeway, arterial, entrance, exit, speed, change lanes, etc.), and physical features of the roadside (e.g., guard rails, barriers, trees, signs, slopes, etc.).

Compared to other evaluation techniques, the workload approach seems to be the most appealing, for it directly reveals the effects of geometric design on the driver. In order to make the geometric design more consistent for the driver and to provide safe-driving surroundings, driver workload turns out to be a crucial factor that must be taken into account while planning a new roadway and auditing an existing roadway structure. An effort is made in this chapter to reveal the different factors that affect driver workload and the methodologies adapted for its measurement.

2.2 Geometric Design Consistency

Road crashes on the highways can be attributed to the deficiencies in highway operations contributed by the combined effects of driver, vehicle and road—or various combinations thereof. Studies have shown that up to 30% of road crashes are caused by deficiencies in the road component (Navin and Musa 2004). One such deficiency has been identified as the lack of geometric design consistency. The Methodology of Accident Prediction Models was used, and it was demonstrated that when design consistency is considered, the safety performance of an alignment is improved (Joanne and Tarek 2004).

Design consistency implies “the extent to which the road is designed to avoid critical (difficult) driving maneuvers and ensure safe operations.” (Al-Masaeid et al. 1994). Therefore, to ensure consistent design, it is very important to let drivers make fewer errors by designing geometric features that confirm with their expectations. It is evident that a direct relationship exists between consistency and safety. The inconsistencies that exist on a roadway can cause a sudden change in the characteristics of the roadway. Such inconsistencies can suddenly surprise drivers and lead to their making errors, resulting in accident risks. Geometric design consistency has also been defined as the ability of the road’s geometry to conform to driver expectancy, stressing that fewer errors are made in the vicinity of geometric features that conform to driver expectancy (Anderson et al. 1999).

Design consistency refers to the conformance of highway geometry to driver expectancy. Driver expectancy relates to the driver’s readiness to perform the driving task. It is basically referred to as a set of probabilities that a driver expects while driving on a particular section of road based on his or her past experiences. An operational definition of expectancy with regard to transportation is given as follows (Ellis 1972):

“Driver expectancy relates to the observable, measurable features of the driving environment which: (i) increase a driver’s readiness to perform a driving task in a particular manner, and (ii) cause the driver to continue in the task until it is completed or interrupted.” A similar definition is stated as follows: “Expectancy relates to a driver’s readiness to respond to situations, events and information in predictable and successful ways” (Alexander and Lunenfeld 1986).

Two forms of driver expectancy have been defined: *a priori* expectancy and *ad hoc* expectancy (Messer et al. 1981). An *a priori* expectancy is relatively long term and is a widely held expectancy based on collective previous experience that drivers bring to the driving task. Unusual geometric features (e.g., a one-lane bridge) with unusual dimensions (e.g., a very long or very sharp horizontal curve) and features combined in unusual ways (e.g., an intersection hidden beyond a crest vertical curve) may violate *a priori* expectancies. On the other hand, an *ad hoc* expectancy is a short-term expectancy that the driver picks up during a particular trip and is based on site-specific practices and situations encountered in transit.

Geometric features whose dimensions differ significantly from upstream features (e.g., a horizontal curve significantly sharper than upstream curves) may violate *ad hoc* expectancies. Expectancy violations cause the driver to adopt inappropriate speeds, often requiring significant speed reductions or other critical driving maneuvers for safe operations. A geometric inconsistency in rural highway design can be defined as a geometric feature or combination of features that carry such an unexpectedly high driver workload that the driver may be surprised and possibly drive in an unsafe manner (Messer et al. 1981).

Figure 1: Concept of Geometric Inconsistency (Messer et al. 1981)

The concept of geometric inconsistency is shown in Figure 1 above. In this example, a driver unfamiliar with the territory is traveling along a well-designed four-lane divided rural highway. Then, unexpectedly, the median ends and the number of lanes drop to two near the crest of a hill, thus increasing driver workload to a significantly higher level. The driver begins to respond to this new geometric feature. Suddenly an unexpected intersection looms ahead. This may overwhelm the capabilities of the driver to safely deal with the situation.

2.3 Evaluation of Geometric Design Consistency

Geometric design consistency in transportation has been categorized into three main areas for safe and smooth operations (Gibreel et al. 1999). These are as follows: speed consideration, safety consideration and performance consideration.

2.3.1 Speed Consideration

Speed consideration addresses the effects of different design parameters on the prediction of an important component—operating speed along the alignments. Evaluation of geometric design consistency using operating speed is by far the most widely used technique. The actual operating speed is defined as the speed selected by highway users when not restricted by other users (i.e., free-flow conditions) and is normally represented by the 85th percentile speed. Many factors affect the prediction of operating speed, including the radius of the horizontal curve, the length of the horizontal curve, the sight distance, the super-elevation rate, the side-friction factor and pavement conditions (Gibreel et al. 1999). An approach to predict operating speed on the horizontal alignment of two-lane rural highways is given using the curvature change rate (Lamm et al. 1995). The model helps locate the speed inconsistency on horizontal alignments. This philosophy is also termed alignment indices. To evaluate the design consistency based on operating speed, the relationship among accident rate, the geometric characteristics of horizontal curves and the difference between V_d and V_{85} was developed. The criteria for consistency evaluation are illustrated in Table 1 (Lamm et al. 1995).

Table 1: Criteria for Vehicle Stability (using Operating Speed)

Criteria	Evaluation	Remarks
$V_{85} - V_d \leq 10$ km/h	Good	No alignment corrections are necessary
$10 \text{ km/h} < V_{85} - V_d \leq 20$ km/h	Fair	Corrections are required: super-elevation rate and stopping sight distance must be related to the expected V_{85}
$V_{85} - V_d > 20$ km/h	Poor	Redesign is recommended based on V_{85}

Note: V_d = Design Speed V_{85} = 85th percentile operating speed

A linear regression model was developed to predict operating speed considering highway geometry and traffic volume. The model is given as follows:

$$V_{85} = 34.7 - 1.005 * DC + 2.081 * LW + 0.174 * SW + 0.0004 * AADT \quad (1)$$

$$r^2 = 0.842$$

where

V_{85} = 85th percentile operating speed

DC = Degree of curve

LW = Lane width

SW = Shoulder width

AADT = Annual average daily traffic

r^2 = Co-efficient of determination

Operating speed was modeled based upon the observation of a specific highway in Ontario, Canada (Hassan et al. 2000). The 85th percentile speed was used to predict the operating-speed profile. The obtained operating-speed profile was validated by comparison with the results of field measurements. The sight distance was analyzed using a three-dimensional approach for both daytime and nighttime. Models were developed to account for tire friction and vehicle stability.

It has been recommended that the operating speed method be used to evaluate the system consistency of existing or proposed road alignments (Easa 2003). It has been suggested in this method that the speed difference between two consecutive elements of an alignment should be less than 20 km/hr, and, if the difference is more than 20 km/hr, adjustment to the alignment design should be done. For ideal conditions, this difference should be less than 10 km/hr. The new TAC Design Guide recommends a series of regression equations both for two-dimensional (2D) and three-dimensional (3D) highways to predict operating speeds for the evaluation of speed consistency for proposed roads. The relevant regression equations are provided in Section 6.1.

2.3.2 Safety Consideration

Safety consideration addresses the design parameters related to safe traffic operation and efficient driver performance. Traffic and geometric elements like cross section, horizontal alignment, vertical alignment, sight distance and traffic volume are the most crucial factors affecting traffic accidents. When vehicles travel along a circular curve, they are subjected to a lateral acceleration (centrifugal force) and are balanced by the side friction between the vehicle's tires and the pavement, and the super-elevation rate (e). The relation is given as follows (AASHTO 2004):

$$f_R = (V^2 / 127R) - e \quad (2)$$

where

V = Vehicle speed (km/hr)

R = Radius of curve (m)

f_R = Coefficient of side friction

e = Super-elevation rate (%)

This estimated friction is the side friction supply for the geometric design. Inconsistent design would normally mean inconsistent operating speed, and the speed component in the above equation would now be replaced by the operating speed V_{85} to determine the new demand friction f_{RD} .

Table 2: Criteria for Vehicle Stability (using Side Friction)

Criteria	Evaluation	Remarks
$\Delta f_R \geq 0.01$	GOOD	No improvements are required
$+0.02 > \Delta f_R \geq -0.04$	FAIR	Super-elevation rate must be related to operating speed to ensure that the side friction supply will accommodate side friction
$\Delta f_R < -0.01$	POOR	Redesign is recommended

The quantitative approach to evaluate design consistency based on vehicle stability is represented by the difference between side-friction supply and side-friction demand (Lamm et al. 1995). If side-friction demand exceeds side-friction supply, concerns for vehicle stability on the curve will arise. Based on accident experiences, a criterion was developed, using the difference between f_R and f_{Rd} ($\Delta f_R = f_R - f_{Rd}$) and is given in Table 2 above (Lamm et al. 1998).

2.3.3 Performance Consideration

Performance consideration addresses the effects of design parameters on driver workload and driver expectations. This is an important criterion while taking design consistency into account to ensure a better approach for a safe mode of transportation.

2.3.4 Driver Workload Consistency

Driver mental workload may be defined as the load imparted to a driver while he or she is driving on a road. This load on the driver generally relates to the psychological load/stress involved in collecting different information from the roadway, processing and influencing the decisions made while attempting to safely maneuver on the road. The driver workload concept proposes that a consistent design will result in a lower driver workload, thereby promoting a lower collision rate. Moreover, if the workload imposed by the road on the driver rises too high or drops too low, the collision rate can become higher (TAC 2002). If the driver has to drive long straight stretches, the driver may become bored, and the response time to unexpected situations may be slower. At the

other end of the spectrum, a high workload will also cause the driver to make mistakes, e.g., in the case of a sudden sharp curve.

The driver workload method seems to be promising as it can be applied to a whole range of road-design features as long as an appropriate measurement method is available. Driver workload can quantify the criticality of individual features and the interacting effects of a combination of features along the alignment. The driver may face stress during driving due to the information obtained from the road, which can be relevant or irrelevant. As a result, driver workload can be divided into direct and indirect workload (Hicks et al. 1979).

Direct workload is related to the relevant information required to navigate and control the vehicle while in motion, resulting in the workload on the driver. Direct workload is much more vital to driving, and it should lie within a well-defined lower and upper limit to obtain the best possible performance. If the direct workload is below the minimum level, it distracts the driver. For example, on flat stretches of road in rural areas, drivers may become bored, and their responses to unexpected situations may then be inappropriate or slow, as mentioned above. It is also understood that a direct workload beyond a maximum level involves so many possible alternate decisions that driving performance declines significantly. Such direct workload may be due to the presence of a lot of intersections in a stretch, fast-and-heavy traffic in an urban area, a series of signs and numerous construction-work zones.

Indirect workload is imposed by irrelevant information on the roadside. This workload distracts drivers from the main task of driving. Hence, all roadways should be consistent in design so that driver needs to collect and process only relevant information.

2.4 Causes of Workload

Perception of the visual environment is an important aspect while driving. Most of the information, about 90%, is derived from the visual environment. In contrast, 10% is related to the speed estimation monitoring information sources (speedometer). Hence, as the task increases, the demand on the driver to maneuver the vehicle on the roadway increases. The most common examples of dual-natured tasks include maintaining a velocity and headway distance, lane position and movement on curves, monitoring and

operating the vehicle, recognizing and reacting to the hazards, and often, but less importantly, communication on mobile phones, to listening music and changing the radio settings. An excess of directional signboards on highways affects driving behavior profoundly. This may severely affect the performance of the driver.

To keep the workload to a minimum, geometric design is a vital issue and needs to be consistent with the driver's expectation in order to reduce the collision rate. An abrupt increase in the driver workload may increase the collision rate. Geometric elements may cause driver confusion if there are errors while designing and considering the future driver workload. A few basic examples which result in a sudden change in the driver workload are an unexpected lane-drop or an unexpected intersection approach; limited sight distance; dissimilarity of a feature to the previous feature, causing surprise to the driver; and a sharp curve occurring after a long stretch of straight and smooth road.

Road geometry is a crucial factor that affects the visual demand on the driver. However, the landscaping of the area in question may widely affect the driver's visual capacity. Driving through a town instead of on an open road increases workload because it requires that more attention be directed towards hazard detection. A narrower lane increases workload as it increases the amount of attention that is needed for the lateral control of the vehicle. Therefore, in situations like this, less mental capacity is available to the driver and hence the workload increases.

2.5 Measurement of Workload

To date, research has categorized workload measurement techniques as follows:

(1) Primary Task Measurement (2) Secondary Task Measurement (3) Physiological Measurements (4) Subjective Techniques (5) Visual Occlusion Method.

- **Primary Task Measurement**

This technique measures the performance of specific aspects of the primary driving task. This appears to be obvious, for driving is the actual task that the investigator is interested in observing. The measurement is also easy and simple, especially when using a driver simulator. Aspects of measurement include the number of steering wheel reversals, the variation of the angle of the steering wheel, lateral variation and so on. It is

assumed in these measurements that the driver has enough mental capacity available to keep the lateral position of the vehicle fairly steady within a lane of an alignment. Although this technique has many advantages, e.g., it is non-intrusive in nature and it uses multivariate measures, it still presents difficulties in that unique measures should be developed for each experimental situation being examined. It is important to note that primary task measures should always be a part of workload evaluation due to their criticality to operator performance within a system. It has been found that primary task measures are sensitive to variations in workload in a wide range of system-related applications (e.g. Eggemeier and Wilson 1991, Lysaght et al. 1989).

Previous studies have also cautioned that primary task measures can have some important limitations as primary task measures can sometimes prove insensitive to changes in workload in certain cases (e.g. Wierwille & Eggemeier 1993). This situation may occur because sometimes the subject can expand extra processing resources to meet the increased workload demand, thereby maintaining suitable levels of primary task performance over some levels of increased workload. In such cases, the experimenter should be careful while interpreting the findings of primary task measures as indices of workload. This is true particularly at low-to-moderate levels of loading, when the subject can compensate for an increase in workload demand (Wierwille & Eggemeier 1993).

Primary task performance, i.e., driving the vehicle at a controlled level of performance and guidance, can be measured to evaluate driver workload. Driver performance may deteriorate at higher levels of workload. Moreover, the driver adapts and sheds off secondary tasks up to some critical level of workload, and no variations arise though the geometric properties of the alignment are considerably changed (McDonald et al. 1975). Secondary task performance, in such cases, may be a better choice to reveal the shifting of mental resources. Workload is increased when driving in areas of high-traffic density as compared to areas of low-traffic density. Therefore, driving speed in dense traffic areas automatically becomes lower in order to retain the same levels of driving performance. It can be inferred that in high-traffic-density areas, the highway geometric design guidelines need to be somewhat different as compared to those for low-traffic-density areas. It has been shown that operating speed is reduced in narrow-lane widths since much of the driver's attention is required to retain lateral

control of the vehicle (De Waard et al. 1995). As lateral control imposes the primary workload, the other part of the workload needs to be reduced by lowering the driving speed.

- **Secondary Task Measurement**

Secondary task performance is often used to measure mental workload for a primary task. External secondary tasks, utilized by most systems applications of secondary task methodologies, are not a part of normal system functions. In this technique, the driver performs a secondary task by using some spare mental capacity while performing the primary task. Secondary task performance is compared with secondary performance only while performing the primary task. According to this concept, if the driver can perform a secondary task successfully, this means that the primary task is putting little demand on him or her. The difficulty level of the secondary task can be increased gradually. A number of secondary tasks have been used with driving, e.g., doing mental arithmetic, the self-paced generation of random numbers, the delayed recall of random numbers, simple and complex recognition, and digit span. When the driving task is easy, a higher level of attention resource is available to perform the secondary task so that it can be performed with relative ease. However, when the driving task is difficult, relatively fewer resources are available to perform the secondary task while maintaining the same levels of driving performance. In such an instance, therefore, driver performance would deteriorate.

Several studies have concluded that, due to the variable sensitivity associated with secondary tasks, these tasks should be considered diagnostic, keeping in mind that a secondary task is expected to demonstrate the greatest sensitivity when there is considerable overlap in the performance of primary and secondary tasks (e.g. Eggemeier and Wilson 1991, Hart and Wickens 1990).

Driving speed was measured by varying the difficulty of up to three simultaneous secondary tasks while the drivers were asked to drive in a normal way (Harms 1991). The experiments were carried out using a driver simulator. The secondary tasks included two visual tasks originating from the driver simulator screen (a colour-detection task and a naming-detection task) and one auditory task (mental arithmetic). It was found out that driving speed decreased as a result of increasing the secondary task load of name task from one target name with two names presented to two target names with four names

presented simultaneously. It was suggested that driving speed was reduced as fewer attention resources were left available when the secondary task load was higher.

- **Physiological Measurements**

A sudden increase or decrease in the difficulty of the primary task affects the driver's physiology. Mental workload variations create certain changes in some parts of the subject's physiology that can be measured as an index of workload. Examples of these changes include heart rate, eye activity, brain activity, etc. Very few of the available methods of measuring workload through physiological measures are reliable enough to solely measure workload because they are intrusive in nature. As well, the participation of the subject is discouraged in the process for many reasons.

Most criticisms of physiological measurements include the objection that these measures can prove insensitive to variations in the levels of task difficulty. Moreover, these are generally considered to be less precise as compared to secondary-task measurements of workload (Schlegel 1993). It is also difficult to determine what aspect of a task is a cause for increased workload, as all task aspects tend to influence physiological measures. Physiological measures can also be affected by non-mental workload changes. The most prevalent effects are stress from the task, physical activity and the emotional state of the subject. Due to this, the effects of these factors may not be separated from the influence of mental workload (Meshkati et al. 1988).

- **Subjective Techniques**

Rating scales are used in these techniques to collect driver opinion and to ascertain driver mental workload. These scales can be direct, asking for estimates of workload, or indirect, asking for estimates on a number of scales. The best rating techniques include the Cooper-Harper Scale, the NASA Task Load Index (TLX) and the Subjective Work Load Assessment Technique (SWAT). Multidimensional workload is determined by these techniques. Problems associated with these techniques may include the mixing of mental and physical workload by the driver and subjective opinion ratings influenced by experience, emotions and abilities. Subjects need training for these tests, but the training may affect the scale rates. The ratings from these techniques obtain the subjective impact

that the task has put on the driver, and combine the influences of many workload contributors. As these techniques are applied after the task has been completed, these are not intrusive to the primary driving task (Eggemeier 1988).

The pattern of results that has emerged from subjective techniques indicates that these procedures represent globally-sensitive measures of workload, i.e., they have the capability to reflect variations in different types of resource expenditures or factors that affect workload (Wierwille and Eggemeier 1993). However there are considerable individual differences associated with the ways in which ratings are scored. This gives rise to a problem as to how to compare different tasks when these tasks are completed by different subjects. Ratings completed after the task do not always attain all the relative workload information available to subjects and may include contributions of irrelevant demand. This can happen because subjects may not normally quantify and remember experiences of workload. Moreover, the influences and memories of situations at each moment are replaced by those of the following situations (Hart and Stavel 1988). Ongoing ratings can also be used to give more specific information, but these have a major problem of interference with the primary task. Table 3 presents a brief summary of subjective techniques, performance-based assessment techniques and physiological assessment techniques:

Table 3: A Brief Summary of Conventional Workload Measurement Techniques

Method	Highlights
Subjective Techniques	<ul style="list-style-type: none"> ▪ MCH, SWAT and TLX procedures represent globally sensitive measures of workload. Subjective assessment procedures typically require little instrumentation but differ in other implementation requirements. Subjective measures have the tendency to allow prediction of workload associated with proposed systems or design options that have not yet been implemented (Wierwille & Eggemeier 1993).
Primary-Task Measurement:	<ul style="list-style-type: none"> ▪ Primary-task measurement should always be part of the load measurement due to criticality. It can sometimes prove to be insensitive to workload variation due to the subject's ability to utilize extra processing resources to meet increased workload demand. So, extra care should be taken while interpreting the results, particularly at low-to-moderate levels of workload (Wierwille and Eggemeier 1993).

Secondary-Task Measurement:	There is some inconsistency due to the sensitivity and intrusion associated with secondary-task measurement (e.g., Eggemeier and Wilson 1991, Lysaght et al. 1989). The operator may be forced to modify the allocation of processing resources devoted to the primary task due to the intrusive nature of tasks, so the implications of intrusion must be considered (Wierwille and Eggemeier 1993). Secondary tasks should be considered diagnostic in that a secondary task is expected to demonstrate the greatest sensitivity when there is considerable overlap in the resource demands of primary and secondary tasks (Hart and Wickens 1990, Wickens 1984).
Measures of Heart Rate:	<ul style="list-style-type: none"> Simple heart-rate measurement provides an overall effect of workload. The effect of a single factor affecting the workload by using this measure may not be estimated (Hart and Wickens 1990). The measures of heart rate and its variability can generally be considered to be non-intrusive (Wilson et al. 1987).
Measures of Brain Activity:	<ul style="list-style-type: none"> It was concluded that brain-evoked potential techniques showed the potential for application to multitask environments but the use of these measures in such environments has not been yet firmly established (Eggemeier and Wilson 1991).
Measure of Eye Activity:	<ul style="list-style-type: none"> Different aspects of eye activity, including eye-blink latency, eye-blink duration and eye-blink rate have been assessed. It has been suggested that these measures represent somewhat the diagnostic indices of visual workload (Wilson and Eggemeier 1991).

• Vision Occlusion Method

The vision occlusion method is used to measure the ability of the driver to continue driving on the road without being able to see on the road, thus directly revealing the effects of the roadway on the driver. The driver's vision is blocked by occlusion unless he or she presses a switch or a pedal to have the view cleared for a fixed period of time, i.e., 0.5 seconds. The less frequently the driver presses the switch or pedal, the lower the visual-demand need. Visual demand is calculated using following expression:

$$VD = \frac{0.5}{T_{\text{Current request}} - T_{\text{Last request}}} \quad (3)$$

where

0.5 = Time interval during which spectacles are in an open state (s)

VD = Visual demand

$T_{\text{Current request}}$ = Time of recording at current request of opening the spectacles (s)

$T_{\text{Last request}}$ = Time of recording at previous request of opening the spectacles (s)

Since visual tasks such as tracking the lane, selecting the path or preventing conflicts are some of the important factors contributing to the driver's mental workload, the vision occlusion method can accurately determine visual demand so it can be the primary means of determining the workload (Tsimhoni and Green 1999).

Senders et al. (1967) first presented the vision occlusion method as a measure of driver workload. In this research, a vision-interruption apparatus was used to determine the visual demand of the subject drivers. It was found out that more glimpses of view were required by drivers while driving on a complex roadway as compared to the number of glimpses required on a simple roadway. Although a mathematical model was developed to show the moment-to-moment uncertainty of driving, nevertheless, a direct relationship between road curvature and visual demand was not established.

A driver simulator was used to examine the variations among five workload measurement techniques by using a vision occlusion apparatus (Hicks and Wierwille 1979). It was shown that drivers required time to become familiar with the visual occlusion apparatus and that the normal workload might be increased by the extra workload of learning how to use the vision occlusion device. Milgrim and Horst (1984) used special spectacles in place of the vision interruption device by using the characteristics of liquid crystals. The spectacles were opaque in the normal state and could be turned to a transparent state by the driver by pressing a switch whenever the driver required a clear view of the roadway. These crystal visual occlusion spectacles improved the vision occlusion method significantly. The same technique was later used to develop vehicle control models (Godthelp et al. 1984).

The vision occlusion method was later used to study driver attention demand with respect to road design, and, more specifically, with respect to various configurations of delineation on wet roads at night (Blaauw 1985). The vision occlusion was realized by using a pair of spectacles having the characteristics of liquid crystals. It was shown that the vision occlusion method for lateral vehicle control was a sensitive criterion for the various delineation configurations, according to the relation that better delineations led to better observations of driving performance. Drivers required fewer glimpses of a clear view of the roadway for better delineation conditions. In addition, more glimpses were required for deteriorated circumstances due to inclement weather conditions.

2.5.1 Measurement of Driver Workload by Vision Occlusion Method

2.5.1.1 Texas Transportation Institute (TTI) Research

The TTI conducted a number of studies of workload and roadway geometry using the vision occlusion method (Fitzpatrick et al. 2000). The approach varied somewhat among researchers, but the basic principles were same. A pair of goggles or a similar device was equipped by either mechanical or electronic means to block the driver's view of the road. Previously, a study using five drivers found that as the complexity of the road increased, drivers needed more glimpses of the road but did not find a direct relationship between roadway curve characteristics and vision frequency (Senders et al. 1967). At the TTI, driving speed was also examined, and it was found that on complex portions of the road, speed was low, indicating the tradeoff between selected speed and glimpse frequency. The evaluation of driver workload at the TTI was exploratory in nature (Fitzpatrick et al. 2000). Researchers focused on the factors studied in the past to examine the repeatability issues with the addition of a limited number of other factors. Three studies were developed to meet the objectives, with the details as follows.

- **Vision Occlusion Device**

Liquid crystal display (LCD) was used while driving a 1991 Ford Taurus station wagon and was under control of either the driver or the experimenter, depending upon stage of the experiment. The visor blocked the driver's vision until a floor-mounted switch was pressed to have a 0.5 second glimpse of the roadway by clearing the LCD visor.

- **Drivers, Test Courses and Geometric Variables**

The primary criteria used for the selection of drivers were gender and age, with an equal number selected in each of the categories as shown in Table 5. Twenty-one drivers participated in the experiments. Three separated courses having curves in different turning directions were designed to accommodate the various curves as shown in Figures 2 to 4. The geometric variables under study consisted of deflection angle, radius of curvature, direction of travel of next curve with respect to the curve just traversed, and tangents. Average values of VD were determined for the first 30 meters of each curve (VD30) and for the entire length of each curve (VD_L). A limited number of curve

sequences were also studied. The LCD visor worn by the driver was as shown in Figure 5. It was opaque in normal conditions and was changed to a transparent state by the driver as required. During the test, vision requests and the locations of the vehicle were recorded on a personal computer. Visual demand was calculated by using equation (3) as described in section 2.5 of the literature review. The visual demand rating for a given feature of the roadway was simply the sum of the individual observations ($\sum VD_i$) that occurred during a set distance in or before the feature divided by the number of those observations (N) as given by following equation.

$$VD_{avg} = \sum VD_i / N \quad (4)$$

Table 4: Details of TTI Study

Objective	Study	Description
To assess VD	Test-Track-Single curves	Assess VD on isolated curves
	Test-Track-Paired curves	Assess VD on a sequence of two curves
	On-Road-Single curves	Assess VD on isolated curves

Note: VD = Visual Demand

Table 5: Gender and Age (TTI Study)

Gender	Age (years)		
	18-24	35-54	55+
Male	4	4	4
Female	4	4	4

Table 6: Test-Track Curves (TTI Study)

Radius (m)	Deflection angle (Deg.)	Course	Curve
145	20	1	1
145	45	2	1
145	90	3	1
290	20	2	9
290	45	2	5
290	90	3	13

Figure 2: Closed-Loop Test Course 1 (Fitzpatrick et al. 1999)

Figure 3: Closed-Loop Test Course (Fitzpatrick et al. 1999)

Figure 4: Closed-Loop Test Course (Fitzpatrick et al. 1999)

Figure 5: LCD Visor in Clear and Opaque Setting (Fitzpatrick et al. 1999)

The same instrumentation and test vehicle was used in a study conducted on local rural roadways for single curves with different values of deflection angles and radii.

- **Results**

In this study different independent and dependent variables were analyzed to gain a better understanding of the effects of roadway geometry on driver mental workload. VD, as already defined, was the means of examining the driver workload. Visual demand was found to be significantly related to radius or the reciprocal of radius. Contributions of relationships between the deflection angle and the radius were generally quite low. The models developed had relatively high R^2 values, indicating that the models explained much of the variation observed. It was found that curves with sharper radii required significantly higher levels of mental workload.

On-road testing confirmed the relationships found in the test track study. As shown in the test track results, radius was the only significant relationship between curve geometry and visual demand. The examination of paired curves showed that both the type of the curve and the curve pair separation did not affect VD_L significantly. Somewhat contradictory results were found, resulting in different responses, depending upon run. It was anticipated that an S-curve would be more consistent with driver expectations and that more closely spaced curves would impose a greater workload.

Experiments were conducted at the Texas Transportation Institute (TTI) to examine the relationship between collision rates and highway geometric design consistency (Shafer et

al. 1995). The vision through the visual occlusion spectacles was controlled by an onboard microcomputer. It was operated by the driver pressing a foot pedal and provided a viewing of 0.5 seconds for each driver request.

The following relationship was used for calculating workload:

$$WL_i = 0.5 / (t_2 - t_1) \quad (5)$$

where

WL_i = Workload over time interval i from t_1 to t_2

t_2 = Clock reading at current information request (seconds)

t_1 = Clock reading at previous information request (seconds)

0.5 = Time interval of each glimpse of vision (seconds)

A driver workload model was developed as follows:

$$WL = 0.193 + 0.016 * D \quad (6)$$

where

WL = Average workload over the first half of the curve

D = Degree of curvature

The model showed that the workload was significantly affected by the degree of curvature and it increased as the degree of curvature was increased.

2.5.1.2 University of Michigan Transportation Research Institute (UMTRI) Experiments

Simulator-based research has shown the promise of being less costly than on-road experiments in some conditions. Moreover, such research is not affected by weather conditions and is not constrained by the local availability or lack of it of certain road geometries that needed to be tested. Due to these reasons, the driver simulator experiments were conducted at the University of Michigan Transportation Research Institute (UMTRI) to address several issues related to the replicability and generality of

the TTI study (Fitzpatrick et al 2000). Two roads were used in the UMTRI replication experiments, a practice road and a test road, both with 3.7 m-wide lanes as in the prior TTI Research. The test road was composed of 12 curves with different geometric properties, and an operating speed of 72 km/h was used. It was confirmed that visual demand was higher on sharper curves and lower on smoother curves. The simulator arrangement used in the research is shown in Figure 6.

The following findings were presented by the study:

- The simulation study at the UMTRI showed that visual demand for curves proved to be linearly related to curvature. On average, more visual demand was required at sharper curves.
- The degree of curvature was a linear function of the reciprocal of the curve radius. Visual demand was also linearly related to the reciprocal of curve radius, as was expected.
- Visual demand did not vary considerably as a function of deflection angle of the curve. When inspecting the area around the PC (point of curvature), no difference whatsoever was observed.
- It was found that age was slightly significant ($p=0.061$) while gender and the interaction between gender and age were not significant. Older drivers experienced higher workload. This was true for tangents and all curve radii.
- Previous data were successfully replicated in the current UMTRI study. The pattern of results was similar for the occlusion data obtained in a simulator as compared to data collected on a test course or on the road.
- No consistent pattern was found to describe eye-fixation patterns. In general, drivers preferred to look at the imaginary focus of expansion in straight sections.
- In curved sections, there was a tendency to fixate on one of the edges of the road while using backward sequences (saccade forward and several pursuits backwards). Drivers did not show a clear preference for looking at either side of the road. On average, drivers preferred looking inside the curve when the curve radius was large, and, for sharper curves, they preferred looking outside the curve. This preference was more prominent in left curves than in right curves.

Figure 6: Plan view of the Driver Simulator Facility at UMTRI (Fitzpatrick et al. 2000)

2.5.1.3 Visual Demand on 2D Rural Highways involving Complex Curves

Researchers have seen that drivers' surprise increases when they are subjected to unusual visual information provided by the road. This sometimes drastically violates the expectations of the driver. Dissimilarity in geometric features on the same highway may result in higher perception-reaction time on the part of the driver which, in return, increases the overall time needed to implement a judgment to control the vehicle. The more complex the situation on the road, the higher the probability of the driver's making errors imposed due to workload. To evaluate the impact of complex horizontal curves

(reverse and compound curves) on visual demand, a study was done and models were developed to evaluate such visual demand for two-dimensional highway alignments using a driver simulator (Easa and Ganguly 2005). Operating speed was kept at 80 km/hr for all the experiments. The STISIM Model 300 driver simulator was used in the study to simulate highway alignments, and the vision occlusion technique was used for the evaluation of driver workload. The visual occlusion spectacles were used during the experiments. They remained opaque in the normal state while the subject was driving. The spectacles could be made clear when the driver required a clearer view of the road.

Visual demand was evaluated considering the effects of different design features of the preceding and current elements of the alignments. On the curves, VDF (visual demand on full-element length), VDH (visual demand on first half-element length) and VD30 (visual demand on first 30 meters of element length) were used to observe the impacts of various characteristics of complex curves on driver workload. It was shown that all composite curves had a positive impact on visual demand. It was observed that VD had maximum value at the first 30 meters of length on curve (VD30) and decreased for half of the element length (VDH). It had the lowest value for full length of the element (VDF). The characteristics of the preceding element had a significant effect on visual demand. It was observed that the most significant impact occurred when the preceding curve had a direction opposite to the direction of the current curve, i.e., in the case of a reverse curve. Models were developed for VDF, VDH and VD30 for curves and tangents. The best model for VDF for curves is given below:

$$\text{Log VDF} = -0.8096 + 65.9905 \text{ RINVPE} * \text{CC} + 68.0313 \text{ RINVPE} * \text{RC} + \quad (7)$$

$$53.8248 \text{ RINV} - 0.0888 \text{ LW} \quad \text{Pearson chi square} = 6.68$$

where

VDF = Visual demand for full length of curves

PEINVR = Inverse of radius of curvature of the preceding element, where radius is in m

INVR = Inverse of radius of the current element, where radius is in meters

LW = Lane width of the driving lane

DELTA = Angle of deviation for the current curve element (in degree)

CC & RC = Nominal character variables

CC = Preceding curvature, in the same turning direction of the current curve

RC = Preceding curvature, in the opposite direction of the current curve

2.5.1.4 Visual Demand on 3D Highway Alignments

Evaluation of visual demand for 3D alignments was done for a design speed of 80 km/hr by using the STISIM Model 300 driver simulator (Easa and He 2006). The vision occlusion technique was used in this research for estimating driver workload for an operating speed of 80 km/hr. The research showed that for 3D alignments, the effects of radius of horizontal curve and the K parameter of vertical curve on visual demand were statistically significant. The visual demand for 3D alignments was linearly related to the inverse of K and the inverse of R, whereas the preceding grade of the 3D curve did not have a significant effect on visual demand. It was concluded that vertical curves (sag or crest) had a positive effect on visual demand. Models were developed for VDF, VDH and VD30 for curves. The best model for VDF for curves is given below:

$$\begin{aligned} \text{VDF} = & 0.166 + 28.6502 \text{ RINV} + 1.2826 \text{ KINV} * \text{C_type(C)} & (8) \\ & + 0.9592 \text{ KINV} * \text{C_type(S)} + 0.0032 \text{ Age} & (r^2 = 0.8) \end{aligned}$$

where

VDF = Visual demand for full length of curves

RINV = Inverse of radius of curvature

KINV = Inverse of K

C_type(C) = Nominal character variable

C_type(S) = Nominal character variable

2.6 Previous Research on Driver Workload

Table 7 presents an overall brief review of previous research regarding measurement of driver workload and the factors affecting driver workload using the vision occlusion method and a few other methods.

Table 7: Brief Review of Previous Driver Workload Research

Measurement Technique/ Review	Research Topic and Results:
<p>“Vision Occlusion Technique” Senders et al (1967)</p>	<p>Topic: Empirical investigation of relation between amount of interruption of vision and driving speed along with determination of model parameters for various drivers and various roads.</p> <p>Results: It was shown that shorter the observation period, the slower the speed that the driver could maintain. More complicated road results in a lower speed at any constant viewing and occlusion times. For various constant speeds, the driver must look more frequently as he enters and passes through various curves, and this increased frequency of observation is not independent of the nature of the curve itself.</p>
<p>“Subjective Ratings, Expert Opinion and Empirical Evidence” Carroll (1980)</p>	<p>Topic: Evaluation of geometric design consistency based on driver behavior principles.</p> <p>Results: A model for geometric design consistency evaluation using driver workload considering basic feature type, design attribute, sight distance, separation distance, operating speed, and driver familiarity was presented.</p>
<p>“Vision Occlusion Technique” Blaauw (1985)</p>	<p>Topic: Vehicle guidance with respect to road design and specifically with respect to various configurations of delineation on wet roads at night.</p> <p>Results: The study recommended the necessity of using delineation devices at both sides of traffic lanes by providing profiled strips, raised-pavement markers at the location of centre and/or lane boundaries, or post-mounted delineators just beside the boundary. The controlling longitudinal spacing between the raised pavement markers was recommended for curves of 200 m radii and tangents. It was observed that deteriorated conditions due to bad weather resulted in increased vision requests, while the driver’s control strategy was unaffected.</p>
<p>“Subjective Workload Methods” Hancock et al. (1990)</p>	<p>Topic: Motorcycle safety (turning movements as compared to straight driving).</p> <p>Results: Workload values were not significantly different for left or right turns although the consequences of failing to detect an oncoming vehicle were noted to be quite different for the two maneuvers.</p>

<p>“Research Review” Wierwille and Eggemeier(1993)</p>	<p>Topic: Review of mental workload measurement techniques in a test and evaluation environment.</p> <p>Results: Previous research regarding workload measurement techniques was investigated and recommendations for the use of these techniques were given.</p>
<p>“Visual Search Technique” Lee and Fisk(1993)</p>	<p>Topic: Skilled visual search as a function of degree of consistency.</p> <p>Results: Results indicated that performance was disrupted by inconsistency and that disruption increased as consistency decreased. On the return of task consistency, performance improved rapidly to pre-disruption levels, although some performance disruption was evident.</p>
<p>“Time Pool Performance Task” Hancock and Caird (1993)</p>	<p>Topic: To test the mental workload model predictions including the following: (1) Mental workload grows as perceived distance from a task goal increases and the effective time for action decreases. (2) The decrease in workload can be achieved by actions that bring the task goal into the region of acceptable time/distance constraints for successful resolution.</p> <p>Results: The model was confirmed with some differences.</p>
<p>“Visual Occlusion Technique” Shafer et al (1995)</p>	<p>Topic: Relationship between collision rates and highway geometric design consistency.</p> <p>Results: The driver workload model showed that collisions increased as the required speed reduction from an approach tangent to a horizontal curve increased. Driver workload was significantly affected by the inverse of radius of curves.</p>
<p>“Various Workload Measurement Techniques” De Warrd et al (1996)</p>	<p>Topic: Measurement of driver workload and various factors affecting it.</p> <p>Results: Speed reductions on narrower lanes give rise to higher workload and more effortful lane tracking. Global workload measures are low in diagnosticity and provide few clues about the stages in which demand for resources is high.</p>
<p>“Vision Occlusion Technique” Fitzpatrick et al (1999)</p>	<p>Topic: Visual demand on test-track single and paired curves, comparison of road and simulation studies, age and gender effect on workload, and the driver’s viewpoint during occlusion.</p> <p>Results: VD appeared to be highly sensitive to road geometry. It was recommended that driving simulation technique be used for the measurement of driver workload as result patterns were same for the test track and simulation study. Older drivers experienced greater workload. The effects of gender and the interaction of age and gender were not significant. No consistent pattern was found to describe eye-fixation patterns.</p>

<p>“Vision Occlusion Technique” Tsimhoni and Green (2001)</p>	<p>Topic: Effect of display-intensive in-vehicle task.</p> <p>Results: Adding a secondary task significantly degraded the driving performance. Driving performance while not looking at the road for some of the time was similar to that while looking inside the vehicle.</p>
<p>“Auditory Continuous Memory Task” Natasha (2003)</p>	<p>Topic: Effect of increasing secondary task on driving safety.</p> <p>Results: Initial results showed an effect of increase in a secondary task on safety in the conditions that required drivers to interact with other road users. However, increasing the processing demand of a secondary task was not found to influence driving performance in a systematic fashion.</p>
<p>“Physiological , Behavioral and Subjective Indices” Baldwin and Coyne (2003)</p>	<p>Topic: Study of workload as a function of traffic density.</p> <p>Results: Measures of response time (RT) and accuracy were sensitive to the increased workload through moderate versus low-density traffic. No significant difference for RT and accuracy was observed as a function of detection-task modality.</p>
<p>“Vision Occlusion Technique” Richard (2004)</p>	<p>Topic: Investigation of vision as a measure of driver workload.</p> <p>Results: Visual occlusion techniques are effective tools for studying visual sampling behavior, workload in driving, and to access the safety effects of in-vehicle devices.</p>
<p>“Secondary Task Measurement Technique” Navina and Musa (2004)</p>	<p>Topic: Effect of speed and driver-adaptive strategies on workload assessment.</p> <p>Results: Driver workload depended on road complexity, but the driver’s operating speed determined the experienced workload to a great extent. Design should be tailored so that the driver’s speed-adoption strategy would succeed in keeping the workload within limits.</p>
<p>“Vision Occlusion Technique” Easa and Gunguly (2004)</p>	<p>Topic: Effect of complex curves on visual demand.</p> <p>Results: Visual demand was shown to be significantly affected by various geometric characteristics of complex curves. Models were developed for VD estimate.</p>
<p>“Vision Occlusion Technique” Easa and He (2005)</p>	<p>Topic: Effects of 3D (combined horizontal and vertical curves) alignments and age on driver workload.</p> <p>Results: For 3D alignments, the effects of radius of horizontal curve and the K parameter of vertical curves on visual demand were statistically significant. Age had a significant effect on VD.</p>

<p>“Research Review” Tsyganov et al. (2005)</p>	<p>Topic: Review of current techniques of driving behavior estimation.</p> <p>Results: The review shows that there is no single technique that is applicable for all ranges of traffic-safety studies. A real traffic experiment is the best tool for the investigation of the combined effects of roadway, traffic control, traffic flow and the environment. Driver simulator studies are more effective for studying the effects of a single factor.</p>
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2.7 Challenge and Hypothesis

Previous studies for examining visual demand on complex horizontal curves using the vision occlusion method were done for a particular design speed. This research study will examine the effect of design speed on visual demand for two-lane rural highways having 2D complex curves by conducting experiments at design speeds of 60 km/hr, 80 km/hr and 100 km/hr. The combined effect of design speed and other geometric design variables (e.g., design radii, current curve turning direction, type of previous road element) will also be investigated. The hypothesis is that higher design speed will result in increased visual demand and that the combined effect of design speed and other geometric design variables will be significant on the visual demand for the tangent and curve elements of road alignments.

Chapter 3 PILOT STUDY

3.1 Method

A pilot study was carried out to evaluate the research design, the research setting and the use of a new arrangement of driver simulator after the integration of a car and the proposed methodology along with providing information about the feasibility of conducting a larger-scale experimentation, and evaluation.

The pilot study consisted of the following steps:

- Performing geometric design of different alignments following the AASHTO and TAC guide lines for different design speeds.
- Developing roadway scenarios using the Scenario Definition Language (SDL) of the driver simulator, to be run by the subjects.
- Setting the operation of visual occlusion spectacles by using *ToTaLcontrol* software.
- Running the alignment scenarios on the driver simulator and collecting the data, e.g., visual demand data, running time and longitudinal distance traveled by the driver.
- Incorporating the simulator output data to MS EXCEL and calculating the visual demand values for each design element of highway alignments.
- Developing the models for analyzing the effect of design speed on visual demand.

3.2 Road-Design Variables

The focus of the pilot study was mainly to investigate driver visual demand at different design speeds. The design parameters studied in the pilot study included different design radii for horizontal curves turning in right and left directions with different deflection angles at the design speeds of 100 km/hr, 80 km/hr and 60 km/hr.

3.3 Alignments for the Pilot Study

Three highway alignments were designed and simulated in the driver simulator, one for each design speed of 100 km/hr, 80 km/hr and 60 km/hr, following the AASHTO and the TAC design standards. Table 8 shows the curve combinations for a design speed of 100 km/h, and Figure 7 shows a plan view of the designed alignment.

Table 8: Geometry of Horizontal Curves for Alignment 1 used in the Pilot Simulation Study (Design Speed = 100 km/hr)

Element	Element Length (m)	Radius of Curve (m)	PC (m)	PT(m)	Deflection Angle (Degree)
Tangent	400.00	-	-	-	-
Curve	460.95	440	400	860.95	60
Tangent	500.00	-	-	-	-
Curve	654.76	750	1360.95	2015.71	50
Tangent	300.00	-	-	-	-
Curve	1475.40	1300	2315.71	3791.11	65
Tangent	700.00	-	-	-	-
Curve	873.02	1000	4491.11	5364.13	50
Tangent	400.00	-	-	-	-
Curve	353.57	450	5764.13	6117.70	45
Tangent	750.00	-	-	-	-
Curve	768.25	550	6867.70	7635.95	80
Tangent	500.00	-	-	-	-
Curve	916.67	1500	8135.95	9052.62	35
Tangent	400.00	-	-	-	-

Note: PC = Point of curvature

PT = Point of tangency

Figure 7: Alignment 1 for Pilot Study (Design Speed = 100 km/hr)

Each alignment consisted of seven horizontal curves with different design radii turning in right and left directions. Each horizontal curve was preceded and followed by a tangent section. The curve combinations for design speeds of 60 km/hr and 80 km/hr are shown in Tables A1 and A5 in Appendix A respectively. For simulation, each test alignment had a unique ID showing the respective vehicle speed to facilitate data recording and analysis.

3.4 Process and Data Extraction

Three subjects drove the simulation alignments. The drivers were satisfactorily trained to use the driver simulator and visual occlusion device. The drivers had to use visual occlusion spectacles while driving during the simulation. These spectacles lenses were opaque by default. Whenever the driver needed increased visual acuity, these lenses could be changed to a transparent state by the driver by pressing the switch pedal provided under the driver's foot. The opening time of the spectacles was fixed at 0.5 seconds. The spectacles were connected to the simulator through the horn cable of the simulator. Whenever the driver requested a clear glimpse of the roadway by pressing the foot pedal, a signal was also sent to the horn cable through splitter at the same time that it was recorded by the simulator. This recording was later used to calculate the visual demand of each driver on each element of highway alignment being driven.

Throughout the simulation run, the data were recorded for every 0.1 second, meaning that the observer had data about the open or opaque state of the spectacle lenses and other output data for each 0.1 second of the run. The open state of the spectacle lenses was recorded as "0" in one of the columns of the output file while the opaque state of the lenses was recorded as "1" in the same column. Each time the driver opened the spectacles by pressing the foot pedal, five consecutive zeros occurred in the output file as the open time of the spectacles was fixed at 0.5 second. Table 9 shows samples of these recordings, where "0" means the open state and "1" means the opaque state of the spectacle lenses. In this table, five consecutive zeros show the open state of the spectacle lenses. The loop cycle of the spectacle lenses was so designed that between two consecutive openings of the lenses, there was a minimum gap of 0.1 seconds.

Table 9: Sample of Output Data for Open State of Spectacles

Time (s)	Distance (m)	Horn Input
0.1	3.24	1
0.2	6.02	1
0.3	8.8	1
0.4	11.57	1
0.5	14.35	0
0.6	17.13	0
0.7	19.91	0
0.8	22.69	0
0.9	25.46	0
1	28.24	1
1.1	31.02	1
1.2	33.8	1
1.3	36.58	0
1.4	39.35	0
1.5	42.13	0
1.6	44.91	0
1.7	47.69	0
1.8	50.47	1
1.9	53.25	1

In this way, the calculated visual demand was always less than 1. The original output file from the simulator was in *.dat file format and was opened first in MS Notepad. Later, All the *.dat output files were extracted in MS Excel and all the '0' values were separated along with the time of recording. The visual demand was then calculated by the following equation:

$$VD = \frac{0.5}{T_{\text{Current request}} - T_{\text{Last request}}} \quad (9)$$

where

0.5 = Time interval during which the lenses are in the open state (seconds)

VD = Visual demand

$T_{\text{Current request}}$ = Time of recording at current request for opening the lenses (seconds)

$T_{\text{Last request}}$ = Time of recording at previous request for opening the lenses (seconds)

Table 10: Sample of VD Values for Different Curves for a Design Speed of 60 km/hr

VD	Radius (m)	1/Radius (1/m)	Speed (km/hr)
0.48	250	0.00400	60
0.485	140	0.00714	60
0.281	500	0.00200	60
0.614	130	0.00769	60
0.346	900	0.00111	60
0.32	700	0.00143	60
0.586	200	0.00500	60

The time of first request for opening the glasses was used as $T_{\text{Last request}}$ in the above equation for calculating the first VD value. The visual demand value for each curve element of an alignment for each subject was calculated as an average of all values of visual demand for that subject. Table 10 shows a sample of the calculated values of visual demand for each curve of an alignment.

3.5 Data Analysis and Validation

After extracting output data files in MS Excel, VD values for each curve element for each subject were calculated for statistical analysis. The primary object of the statistical analysis was to examine the effect of design speed on visual demand. Linear regression was carried out by using Analyst option in SAS, but it did not give a good model fit. Then SAS INSIGHT was used to try the Generalized Linear Modeling approach. VD was used as response variable with speed being the explanatory variable. SAS INSIGHT gives different options for response distributions and link functions. In the current case, as confirmed previously (Easa and Ganguly 2005), response distribution was assumed as Normal and Log was used as the link function that gave an acceptable model of fit for both curve and tangent sections as described below:

For curve elements:

$$\text{Log (VD)} = -1.0405 + 0.0049 \text{ Speed} \quad (\text{Pearson ChiSq / DF}) = 0.0363) \quad (10)$$

For tangent elements:

$$\text{Log (VD)} = -1.0487 + 0.0044 \text{ Speed} \quad (\text{Pearson ChiSq / DF}) = 0.0318 \quad (11)$$

where

VD = Visual demand on curves

Speed = Design speed in km/hr

The above equation shows that VD increases with increase in the design speed as was anticipated. To check the replicability of previous research and the suitability of the current simulation set-up, the VD model for curves considering inverse of curvature as an explanatory variable was also developed as given below:

$$\text{Log (VD)} = -0.7085 + 25.1882 \text{ INVR} \quad (\text{Pearson ChiSq / DF}) = 0.0374 \quad (12)$$

This model shows that the inverse of radius is a significant variable as was found in the previous research (FHWA 1999, Easa and Ganguly 2004) for the evaluation of driver visual demand. Model outputs for the simulation pilot study are shown in Appendix C (Tables C1, C2 and C3).

3.6 Summary

The new arrangement of the STISIM driver simulator with the integration of a real car body demonstrated that it was an acceptable and reasonable method for accurately obtaining the visual demand load. Drivers had a better real-world driving feeling as compared to the previous arrangement of the driver simulator at Ryerson University that did not have an integrated car and simply had the gas and brake pedals for the driving operation. The developed models showed that the visual demand increases with the increase in design speed. The generalized linear modeling approach was found to be suitable for the analysis of VD as confirmed by the previous researchers (Easa and Ganguly 2005, Easa and He 2006). In summary, it was proved that the pilot study had potential and had the capability of carrying out actual experiments to investigate the effects of design speed and other geometric design variables on driver visual demand for complex 2D rural highways.

Chapter 4 DRIVING SIMULATION ARRANGEMENT AND EXPERIMENTAL DESIGN

4.1 Driver Simulator Apparatus

The driver simulator used in this research study was integrated in the Road Safety Laboratory at the Civil Engineering Department of Ryerson University, Toronto.

The simulator arrangement consisted of the following components:

- STISIM driver simulator (computer and control box)
- Vision occlusion spectacles
- Control box of spectacles with a 9V battery
- Laptop computer with *ToTaLcontrol* software controlling the open and close time of vision occlusion spectacles
- Splitter sending a simultaneous signal to the spectacle lenses and the horn input of the simulator
- A switch pedal provided under the foot of the driver to initiate a request to open the spectacle lenses
- Car integrated with the simulator computer
- Projector projecting the road view directly from the simulator computer to the wall in front of the driver

The simulator used in the study is the STISIM Model 300, an advanced version of simulators developed by STI (Systems Technology Inc). STISIM Drive is a personal-computer-based, interactive driver simulator that allows the driver to control all aspects of driving, including the vehicle's speed and steering. STISIM Drive allows the user to change most aspects of the driving scene with simple text commands. This frees up time for designing and building various roadway situations instead of simply designing and building a roadway. A car that has been integrated to a simulator computer gives a more real-world driving feeling to the driver as compared to a simple arrangement that includes a gas and brake pedal provided under the foot of the driver. The same is true regarding the projector that projects the roadway scene onto the wall in front of the driver as compared to a monitor in front the driver showing a roadway scene used in a

conventional arrangement. Figure B1 in Appendix B shows the driver simulator arrangement and a driver wearing spectacles.

Driving tasks and scenarios can be specified with respective commands listed in an Event file. Scenario definition language (SDL) is used to make Event files to simulate the desired roadway scenery and characteristics. The Scenario Definition Language (SDL) frees the user from having to program visual data bases as is the case with most CGI-based (Common Gateway Interface) simulators. The SDL also simplifies the specification of scenario attributes that relate to driver psychomotor, divided attention and cognitive behavior, and permits the definition of different road parameters, e.g., curvature, elevation, intersections, signal timing, interactive traffic, etc., as desired by the experimenter.

4.1.1 STISIM Simulator Operation

In general, four basic components make up the STISIM Drive simulator operation: the graphics environment, the driver controls, the Scenario Definition Language (SDL) that controls the scenarios, and the STISIM Drive software that ties it all together. STISIM Drive software is installed on a desktop computer. The graphics environment includes the graphics card that generates the images, the display system that displays the images, and the models that are used so that images can be displayed. Driver controls, e.g., maximum speed, lateral position, sound effects, etc., can be set using the Configuration File of the STISIM Drive software. The SDL is used to write the Event file that describes the road features to be displayed for the driver's view.

The individual events are grouped into a scenario file that is specified by the user and then read into the memory by STISIM Drive. As the simulation runs, it uses the various events from the scenario file to generate the roadway environment that the driver navigates. As is the case with the Configuration file, the user can create and save an infinite number of scenario files and can run whichever is required. The scenario files are simple text files that can be created and saved using any text editor, e.g., MS Notepad, called Event files. Each STISIM Drive run is comprised of five components: the simulator configuration, the scenario, the control console, the display devices, and, finally, the simulation kernel that brings all these pieces together in order to create a

realistic driving experience. After the Event file and Configuration are completed, the user can display the roadway scene by simply selecting the desired Event file using the explorer provided on the STISIM window screen. For the current research study, the roadway view was displayed in front of the driver on a wall by using a projector linked to the simulator computer.

4.1.2 Vision Occlusion Spectacles

Vision occlusion spectacles used in the current experiments are operated by software named *ToTaLcontrol* developed by Translucent Technologies Inc., Toronto. The software gives the flexibility of programming the spectacle lenses to open and shut according to particular need. In the current research study, the lenses were programmed to open for 0.5 seconds each time the subject initiated a request, with an interval of 0.1 sec between two consecutive requests. Vision occlusion spectacles apparatus included the following:

- A pair of lenses
- A control box with a 9V battery (replaceable with normal power system) with two switches to control each of right and left lenses
- A laptop computer having *ToTaLcontrol* software installed to control the time that the lenses remained open

All the control data in *ToTaLcontrol* software are stored in an Input Table as shown in Figure B4 in Appendix B. The signal input for opening the spectacle lenses can be given in two ways: External Sync and Internal Sync. External Sync was used in the current experiments as it allows the subject to trigger the spectacles to open by external request by means of a switch mounted on a foot pedal. In the normal condition, both lenses of the spectacles were opaque, i.e., blocking the driver's view of the roadway. When the driver wanted to have a clear glimpse of the view, a request was made by pressing the switch on the foot pedal. The request sent a trigger pulse to a laptop computer that generated a 0.5-second duration signal to open both lenses. This sequence is shown in Figure 8. This process was saved in a *.gl file on the laptop computer. In the Input Table, as shown in Figure B4 in Appendix B, the opening time of the spectacle lenses was set at 500 milliseconds (0.5 seconds), and the duration between the driver's consecutive requests was 100 milliseconds (0.1 seconds), thus making the pulse width equal to 600 milliseconds (0.6 seconds).

Figure 8: Flow Chart for Opening of Spectacle Lenses

When the driver sent a request to open the lenses, at the same time the pulse was recorded by the simulator via the horn cable of the simulator. This recording was later used to calculate visual demand. The following flow chart illustrates this sequence:

4.2 Experimental design

The experiments were designed for two-lane rural highways having simple and complex curves by following the American Association of Highway and Transportation Officials (AASHTO) and Transportation Association of Canada (TAC) standards for design speeds of 60 km/hr, 80 km/hr and 100 km/hr. Four alignments were designed for each speed, and the geometric details are given in Appendix B. Element type detail of alignments for each design speed is as follows:

- The first alignment for each design had seven simple curves with one preceding and one following tangent. The radii and turning directions were varied for different curves to examine the effects of the turning direction.
- The second alignment for each design had two reverse curves and one compound curve with one preceding and one following tangent.
- The third alignment for each design had two compound curves and one reverse curve with one preceding and one following tangent.

- The fourth alignment for each design consisted of a combination of six complex curves, including reverse and compound curves with one preceding and one following tangent.

The length of individual elements was fixed, keeping in mind that while driving on these elements, the subjects would have sufficient time much higher than the perception-reaction time to maneuver on and along each element of each alignment. After the geometric design had been completed for all alignments, the geometric details were used in the SDL (Scenario Definition Language) of the driver simulator to develop Event files to create roadway scenes for simulation. Before running the actual experiments, all alignments were simulated to test their precision and adequacy. A few other long alignments were also developed in the same sequence to give all the subjects test drives in order to familiarize them with the driving simulation environment. Figure 9 shows the sequence of steps of experimentation. The following considerations should be noted regarding the experimental design:

- The design parameters of the alignments used for experiments satisfied the AASHTO and TAC standards for design speeds of 60 km/hr, 80 km/hr and 100 km/hr. For example, the radius of each curve element was kept at more than the minimum radius for a given speed.
- All the alignments were designed for two-lane rural highways. As the purpose of the research was to see the effects of geometric design characteristics and design speed on visual demand, no other elements (e.g., other traffic, intersections and traffic signs) were added that could add the complexity of roadway scenery to the driver workload.
- If the subject ran off the road or drove to the other side of the road, the simulation run had to be stopped and run again.
- Twelve subjects drove the alignments. Each subject was satisfactorily trained before simulating actual test alignments to such a level that the driver felt comfortable with the equipment and the driving environment.
- Initially each subject started driving the test alignments without vision occlusion spectacles. After the subject felt comfortable, the spectacles were introduced. In the normal state, the spectacles remained opaque. In order to have a clearer view

Figure 9: Flow Chart Showing Sequence of Experiments

through the spectacle lenses, the driver had to make a request by pressing a switch provided on a foot pedal under the left foot of the subject. Detailed operation of the vision occlusion apparatus is described above in section 4.1.2.

- Operating speed was the same as the design speed for all experiments.
- Output data for each alignment run for each subject was saved in *.dat file of the simulator computer and then transferred to MS Excel for visual demand calculations. The detailed procedure is described in section 4.4.

4.2.1 Calculation of Geometric Characteristics of Alignment Elements

An MS Excel worksheet was used to do calculations of element geometric details of alignments. A sample is shown in Table 11. The radius of each curve was kept at more than the minimum radius required for each design speed following the TAC (Transportation Association of Canada) and the AASHTO (American Association of State Highway and Transportation Officials) standards. PC represents the start distance of a curve and PT represents the end distance of the curve. Length of curve was calculated using the following relation:

$$\text{Length} = (\pi \times R \times \theta) / 180 \quad (13)$$

where

Length = Length of curve in meters

R = Radius of curve in meters

θ = Deflection angle in degrees

Figure 10 shows Alignment 1 for a design speed of 60 km/hr. Figures A1 to A12 in Appendix A at the end show the complete set of alignments used for the actual experiments.

4.3 Developing Road Scenarios in STISIM

The most important component of the simulation is the roadway scenario that is to be driven by drivers. This defines the simulation experience, dictates what the driver sees at any given time, and specifies what measures are collected during the simulation run. Therefore, the design and implementation of the scenario was carefully planned in order to obtain the out put variables required for the current research work.

Table 11: Worksheet Sample for Calculation of Roadway Design Parameters

Element	Element Length (m)	Turning Direction of Curve	Radius of Curve (m)	1/Radius (1/m)	PC (m)	PT(m)	Deflection Angle (Degree)	Lane Width (m)
Tangent	200	-	-	-	-	-	-	3.7
Curve	576.19	R	1100	0.00091	200	776.19	30	3.7
Curve	680.95	R	1300	0.00077	776.19	1457.14	30	3.7
Tangent	350	-	-	-	-	-	-	3.7
Curve	499.37	L	440	0.00227	1807.14	2306.51	65	3.7
Curve	499.37	R	440	0.00227	2306.51	2805.87	65	3.7

Figure 10: Alignment 1 for Actual Experiments (Design Speed = 60 km/hr)

The basic steps that were followed to storyboard a scenario are as follows:

1. The desired data that is to be collected has to be defined accurately. This determines the “critical events” and driving sequences that have to be incorporated into the scenario. During this step, the experimenter has to make sure that the simulator is capable of recording the desired data. For example, it may be desired to test a driver’s perception to a critical roadway situation. As part of this test, it is desired to look at driver-reaction time and the driver’s behavior (how he solved the problem) during the task. Therefore, an event such as a potential head-on collision may be desired. In such a case, the driver’s reaction time from the time the event begins until the driver reacts with steering or pedal countermeasures may be desired. In addition, the strategy

employed to avert the collision (a combination of steering and braking, just steering or just braking) may also be desired. For this example the scenario must be capable of providing the head on-collision event as well as allowing collection of the steering and pedal inputs, speed and lane-position data.

2. The critical events have to be designed in such a way that they elicit the type of data desired. For example, a merge event requires either a blocked or a dropped lane, and traffic in an adjacent lane with which the driver must merge. The exact timing can be determined later during scenario refinement.
3. The layout of the roadway that is to be used has to be carefully designed. For example, the location of curves and other elements is very important. Figure B3 in Appendix B shows examples of roadway scenes generated by the STISIM drive simulator.

4.3.1 Event File

The Event file actually contains all the features of the roadway to be displayed. The Event file has a floating-file format; this means that each line of the file does not have the same number of parameters. Following is the general format for each line of the file:

ON DISTANCE, EVENT SPECIFIER, PARAMETER 1,..., PARAMETER N,
COMMENTS:

The *ON DISTANCE* parameter is the longitudinal distance down the road (since the start of the simulation run) that the driver has driven when the event will initially appear on the screen. When checking simulation scenarios, at times it might be necessary to delete an event from the display, but not from the Event file. To do this simply the *ON DISTANCE* parameter should be started with a negative sign. This way the event can be deleted from the scene without removing the entire line from the Event file. To put the line back in, the *ON DISTANCE* parameter can be changed back to a positive value again. The total number of events for any simulation run is limited to 10,000 individual events. If one tries to use more than this amount, the program reports an error.

4.3.2 Configuration File

The configuration option allows setting and modifying the global simulation properties, e.g., vehicle properties, maximum speed limit, different sound effects, brake control, the driving side of the road, and the nighttime or daytime driving environment. STISIM Drive has a default configuration file named STISIM.CFG that can be found in the program's root directory. This file contains settings that are typical for using the simulator. However, the user can change the settings as required for a specific research purpose. The same was done in conducting the current research study experiments. The brake setup and steering wheel setup were changed by consulting the subject drivers to have a better real-world driving feeling according to normal driving practices. Figure B2 in Appendix B shows the configuration settings' window used for making the configuration as required for particular driving conditions. This tabbed dialog box basically replaces the GAINS file that was previously used in the DOS-based version of STISIM Drive. At the top of this window are numerous tabs from which to choose. Each of these tabs contains a different group of simulator characteristics that can be modified for the desired set of driving conditions.

The system may be configured with a separate monitor for controlling the simulation and providing a real-time status display for an experimenter. For the current experiments, the roadway view was projected on wall in front of the driver through a projector. STISIM Drive also has an autopilot mode option in which the car is driven without a driver. This option was used for the current experiments to check the designed alignments before the drivers actually drove the scenarios. Different configuration files can be set up and stored for recall when necessary for different vehicles and driving conditions.

4.3.3 Data Output File

At the end of each simulation run, the program creates a data file containing the various data acquired during the simulation run. This file is always created and can be quite lengthy. It also takes up a lot of disk space. The file that is created has the name specified in the Output Data File field from STISIM Drive's main window and is stored in the subdirectory specified in the STISIM Drive configuration. Each STISIM Drive Data File

varies slightly, depending on the scenario that is run. There are eight general sections that may appear in the file. These are as follows:

- General Information
- BSAV/ESAV Block Data
- RMSB/RMSE Data Blocks
- Time To Collision
- Divided Attention Data
- DI Digital Input Data
- Vehicle Following
- Tailgating
- Driver Mistakes

In the current research study, data were saved using the BSAV/ESAV Block Data option. The BSAV option tells the program to begin saving the data. This option was used in conjunction with the ESAV option. The ESAV option tells the simulation program to stop collecting the data. No additional parameters are required. Each of the variables that can be saved in the user defined data block is specified using the BSAV event from the SDL. Following is an example of BSAV/ESAV Block Data option.

```
2000,BSAV,1,.0995,ALIGNMNET1,1,6,4,18,19
3000,ESAV
```

In the above example, the simulator begins collecting a block of data after the driver has traveled 2,000 feet (assuming the system of units used is English) down the road, and the output data block ends after the driver has traveled 3,000 feet down the road. ALIGNMNET1 is the name of the output data block and the numbers 1,6,4,18,19 the various parameters to be saved as selected by the user. When the program saves the data to the data file, it automatically formats the variables so that the resulting file is evenly collimated. In this way, the data can be easy imported into other programs such as MS Excel spreadsheets. The same practice was adopted for the current research experiments. The program automatically assigned the block number as each block was saved. The user-defined block name allows the program to assign each block of data a unique name,

e.g., an alignment name, that can be used later to sort the data. The block name is one of the parameters defined in the BSAV event.

After the user-defined data block has been saved, the program automatically includes some additional information at the bottom of the block before it begins to save a new block of data. These data include the number of off-road accidents occurring when the driver steers the vehicle too far off the road and the number of collisions occurring when the driver runs into another vehicle. This includes vehicles in either lane of traffic, cross-traffic vehicles and vehicles in the rear-view mirror. This is followed by the number of pedestrians that the driver ran over, the number of tickets that were issued because the driver was speeding when a police officer was present, and the number of tickets due to running a red light. The final data field contains the number of times the driver exceeded the posted speed limit if the speed was not fixed by the experimenter.

4.3.4 Recording the Driver's Request for Vision

As described earlier, the spectacle lenses were opaque under normal conditions. Whenever the driver wanted to have a clear view of road, a request was sent by the driver by pressing the switch provided on a foot pedal that sent a smooth pulse to *ToTaLcontrol* software on the laptop computer. The switch was linked to *ToTaLcontrol* software through a wire and a splitter. The software immediately generated a signal to the spectacle lenses to open for the duration of 0.5 seconds (500 milliseconds). One of the outputs of the software was connected to the horn cable of the simulator through the splitter. As soon as the spectacle lenses were opened by the software for the given time period, this signal was sent to the horn cable input being recorded by the simulator computer in output file. This data was later used for calculating the visual demand by using VD calculation equation (3) as described in Section 2.5.

4.4 The Experimental Process

Actual experiments were conducted after completing the experimental design, the synchronization of the driver simulator components and the training of the drivers. To simulate the alignments, all the Event files developed by using Scenario Definition Language (SDL) were copied into one folder on the simulator computer to be run one

after the other. Four alignments were designed for design speeds of 60 km/hr, 80 km/hr and 100 km/hr, and had different combinations of roadway elements. The geometric details of all the alignments are provided in Appendix A. No traffic, traffic signs, intersections or lateral obstructions were introduced into any scenario as this was not part of the current study. The driving speed was kept constant by the experimenter at 60 km/hr, 80 km/hr and 100 km/hr for each respective set of alignments. The alignments were named as AL1 1 to AL4 for each design speed, e.g., 60AL1 means alignment number one for a design speed of 60 km/hr, and so on. All alignments were tested by using the pilot-mode option available in STISIM drive.

Pilot mode gives the experimenter the option of running the alignments without the driver to see the correctness of the simulation of road features as designed. As the car is running in the Pilot mode, the experimenter can see the value of distance being run by the car on the simulator computer monitor and thus can verify the length with the start-and-end distances of different elements of the roadway. Special emphasis was given to driving training. The drivers were asked to drive practice alignments first at lower speeds and then, gradually, at higher speeds. Once each driver was at ease and confident, the visual occlusion spectacles were introduced. The purpose and working principle of the spectacles had already been explained to the drivers before the experiments began. It was simple to open the spectacle lenses by pressing the foot switch, but the task of controlling the opening time was performed by using the *ToTaLcontrol* software installed in the laptop computer. The software was designed in such a way that each time a request was made to open the spectacles, the spectacles opened with a preset pulse width. The pulse width in current experiments was kept equal to 0.6 seconds, i.e., the glasses opened for 0.5 seconds and then closed for 0.1 seconds before opening the next time at the next request. In this way, the value of visual demand was always less than one.

Initially, the opening of the visual occlusion spectacles was controlled by the experimenter based on the lateral position of the driver. Later the drivers were told to open the visual occlusion spectacles as and when they desired. The drivers were told how to open the spectacles by pressing a switch provided under their left foot. The drivers could open the spectacles as many times as necessary to remain in their driving lane and

drive comfortably as in the case of normal, everyday driving. The experiment had to be repeated if the driver ran off the road or went onto the opposite lane of the road.

After each run by each driver, the output data file was saved in a separate folder for each driver. Each data output file was named as, e.g., AG60AL1, with AG as the initials of the driver and 60AL1 showing the alignment for the design speed of 60 km/hr. The total number of output files was 144. All these files were saved in MS Notepad to be later transferred to MS Excel for visual-demand calculations. Each visual demand request during the experiment was recorded by the simulator through the horn input cable initiated by driver by pressing the foot switch. This input was saved in the last column of the output data file in the form of five consecutive zeros. Each zero represented the opening of the spectacles for 0.1 seconds, implying that each request by the driver opened the spectacles for a total duration of 0.5 seconds. A sample of the output table with variables and the further calculation of visual demand is described in the Analysis and Results chapter.

Chapter 5 ANALYSIS AND RESULTS

5.1 Analysis Procedure

As soon as a driver completed driving a roadway alignment, an individual output file was saved by the driver simulator computer. Each of these files had *.dat extension and could be saved initially in the MS Notepad. Twelve folders were created, one for each driver, and an output file for all the alignments run by each driver was saved in the respective folder. In this way, a total of 144 files were saved for twelve alignments run by the drivers. After the completion of the experiments, these files were opened in MS Excel for visual-demand calculations for analysis. The detailed procedure is as follows:

- The *.dat file was opened using MS Excel.
- As the data file had output variables in columns without separation lines, the “delimited” option was used in MS Excel to separate data in individual columns.
- The description of each output column was put in place for proper identification.
- Visual demand calculations had to be done using the horn input data which gave the time when the driver made a request for vision. The output column had a binary number format. Whenever the driver requested a glimpse of view by pressing the foot pedal, the spectacle lenses were opened for 0.5 seconds, and this was recorded in the form of five consecutive zeros in the horn input column. Otherwise, the horn input column showed value as “1”, meaning that the spectacle lenses were closed. The horn input table was selected and the filter option of MS Excel was used to separate all the zeros, i.e., all the entries during which the spectacle lenses were in an open state to have a clear view of the roadway.
- All this filtered data showing zeros and the other columns showing other relevant information (e.g., the time since the start of the run, the distance traveled since the start of the run, and acceleration) were copied onto another MS Excel sheet. The data were saved for each 0.1 seconds of run. The visual demand was calculated for each fifth row using the equation (3) given in section 2.5.
- After calculating the visual demand for each driver request, the calculations for VDF (visual demand for full-element length), VDH (visual demand for the element’s first

half length and VD30 (visual demand for the first 30 m of element length) were done for tangents and curves. For ease of calculation, the tangent sections of the alignments were highlighted in green for quick reference.

- VDF was calculated by averaging the visual demand values obtained on the entire length of each element (curve and tangent) of the alignments.
- VDH was obtained by averaging the visual demand values obtained on the first half of the total length of each element (curve and tangent) of the road alignments.
- VD30 was obtained by averaging the visual demand values on the first 30 meters of each element (curve and tangent) of the alignments. Where such values were not found, the method of proportioning was used, i.e., by adding all the VD values on that element, dividing this value by the length of the element, and then multiplying by 30.
- After completing the above-mentioned measures for all the data files, all values of VD for curves and tangents were copied onto separate sheets for curves and tangents. Other variables were also copied onto these sheets, e.g., design speed, the inverse of radius and the turning direction of curves.
- Considering VD as a response variable and using all the explanatory variables, a modeling process was carried out to develop models for VDF, VDH and VD30 by assuming different probability distributions. Models were also developed by considering only design speed as an explanatory variable. MS Excel and Statistical Analysis Software (SAS) were used in the modeling process.
- The different models developed from the experimental work were investigated and the best models for VDF, VDH and VD30 for curve and tangent sections were selected.

5.2 Development of Visual Demand Models

The response and explanatory variables data for tangent and curve sections were saved in separate MS Excel files and imported into SAS for the development of models. The INSIGHT option in SAS was used for the final modeling. The generalized linear modeling approach gave the best results. VDF, VDH, and VD30 were considered as the dependent variables. First, design speed was considered as the only explanatory variable

for developing the models. Then, different variables were crossed with each other using the INSIGHT option in SAS to evaluate the combined effect of the explanatory variables. The link function was given as “Log” in the modeling process. The explanatory variables that have non-numerical values were defined as Nominal variables. The details are as follows.

5.2.1 Visual Demand Models for Curves

The objective of this research study was to examine the effect of design speed on visual demand and also the combined effects of design speed and other design variables. By examining the visual demands at different design speeds, it was observed that visual demand varied for different design speeds. By using MS Excel, the trend line was plotted to see the effect of design speed on visual demand as shown in Figure 11. It was observed that visual demand increased with increasing the design speed. Statistical analysis software (SAS) was used to model the effect of design speed for confirmation.

Figure 11: Trend Line for VD at Different Design Speeds for Continuous Alignments

The following models were obtained for VDF, VDH and VD30:

$$\text{Log (VDF)} = - 0.7048 + 0.0011 S \quad (\text{Pearson ChiSq} / \text{DF} = 0.0259) \quad (14)$$

$$\text{Log (VDH)} = - 0.7010 + 0.0014 S \quad (\text{Pearson ChiSq} / \text{DF} = 0.0290) \quad (15)$$

$$\text{Log (VD30)} = - 0.6251 + 0.0007 S \quad (\text{Pearson ChiSq} / \text{DF} = 0.0464) \quad (16)$$

where

VDF, VDH, VD30 = Visual demand for full, half and the first 30 meters of length of curves

S = Design speed (km/hr)

The model output details are given in Appendix C in Tables C4, C5 and C6. To oversee the effect of other design variables on visual demand, the variation of visual demand was plotted as shown in Figure 12. By examining the plot, it was observed that visual demand changed at the junction of any change of curvature and also varied as the direction or type of the previous element varied. The variability of visual demand also reflected that the current element was not the only factor affecting visual demand, but that the characteristics of the preceding element might also influence it.

For this reason, the characteristics of individual elements were carefully studied and were categorized into three types, depending upon their combination with the preceding element. These three types of preceding-element characteristics were then considered as three Nominal Variables for statistical modeling in SAS and are described below:

- CC: It occurs when the turning direction of the preceding curve element is the same as that of the current curve element, i.e., a compound curve case.
- RC: It occurs when the turning direction of the preceding curve element is opposite to that of the current curve element, i.e., a reverse curve case.
- T: It occurs when the preceding element is a tangent.

Figure 12: Graph Showing Variability of VD on a Continuous Alignment

PE=CC: Adjacent Curves Having Different Turning Directions

PE=CC: Adjacent Curves Having the Same Turning Directions

PE=T: Preceding Element to the Current Curve is a Tangent

Figure 13: Types of Preceding Elements Considered as Nominal Variables

Moreover, turning directions of the current curve element, i.e., left or right-turning direction, were also considered as a Nominal Variable represented by L or R respectively. Finally, models were developed for visual demand by considering design speed along with other design variables as described above. The summary outputs for the selected models of VDF, VDH and VD30 for curves are given in Appendix C in Tables C7, C8 and C9 respectively. The best models are as follows:

$$\begin{aligned} \text{Log (VDF)} = & -1.1591 + 55.1923 \text{ INVR} * \text{L} + 53.8424 \text{ INVR} * \text{R} + 0.0043 \text{ S} * \text{CC} + \\ & 0.0046 \text{ S} * \text{RC} + 0.0051 \text{ S} * \text{T} + 17.2821 \text{ PEINVR} \end{aligned} \quad (17)$$

(Pearson ChiSq / DF = 0.0233)

$$\begin{aligned} \text{Log (VDH)} = & -1.2444 + 63.5760 \text{ INVR} * \text{L} + 61.0929 \text{ INVR} * \text{R} + 0.0050 \text{ S} * \text{CC} + \\ & 0.0057 \text{ S} * \text{RC} + 0.0062 \text{ S} * \text{T} + 25.0161 \text{ PEINVR} \end{aligned} \quad (18)$$

(Pearson ChiSq / DF = 0.0253)

$$\begin{aligned} \text{Log (VD30)} = & -1.2267 + 69.5885 \text{ INVR} * \text{L} + 66.1259 \text{ INVR} * \text{R} + 0.0048 \text{ S} * \text{CC} + \\ & 0.0062 \text{ S} * \text{RC} + 0.0059 \text{ S} * \text{T} + 27.6674 \text{ PEINVR} \end{aligned} \quad (19)$$

(Pearson ChiSq / DF = 0.0413)

where

INVR = Inverse of radius of curvature of the current element, where radius is in meters

R and L = Nominal character variables representing the turning direction of the current curve as described above. When the turning direction of the current curve element is right, R takes a value of 1 and L takes a value of 0. When the turning direction of the current element is left, the opposite happens.

CC, RC, T = Nominal character variables as described above. When any one of these variables occurs, it takes a value of 1 and the other two variables take a value of 0.

S = Design speed in km/hr

PEINVR = Inverse of radius of curve of the preceding curve element where the radius is in meters takes a value of 0 if the preceding element is a tangent.

All statistical analysis was carried out at the 0.05 significance level (α). The response distribution was used as Normal and Log was used as a link function. The inverse of radius of curvature crossed with the turning direction of the current element was observed as the most significant variable for all types of visual demand models. Table 12 shows the parameter estimates for VDF on curves. The analysis result shows that all variables have reliability greater than 99.99% for curves. The same is true for VDH and VD30, with estimates given in Appendix C.

Table 12: Parameter Estimates of VDF on Curves

Parameter Estimates							
Variable	CETD	PE	DF	Estimate	Std Error	ChiSq	Pr > ChiSq
Intercept			1	-1.1591	0.0673	296.4230	<.0001
INVR*CETD	L		1	55.1923	6.5045	71.9999	<.0001
	R		1	53.8424	5.5615	93.7268	<.0001
S*PE		CC	1	0.0043	0.0007	35.4001	<.0001
		RC	1	0.0046	0.0007	46.7781	<.0001
		T	1	0.0051	0.0007	53.9659	<.0001
PEINVR			1	17.2821	6.1154	7.9863	0.0047

5.2.2 Visual Demand Models for Tangents

Visual demand models for tangents were also developed. First, only design speed was considered as an explanatory variable for developing models. Following are the models:

$$\text{Log (VDF)} = - 0.9196 + 0.0027 S \quad (\text{Pearson ChiSq / DF} = 0.0244) \quad (20)$$

$$\text{Log (VDH)} = - 0.9860 + 0.0038 S \quad (\text{Pearson ChiSq / DF} = 0.0273) \quad (21)$$

$$\text{Log (VD30)} = - 0.8791 + 0.0029 S \quad (\text{Pearson ChiSq / DF} = 0.0490) \quad (22)$$

where

VDF, VDH, VD30 = Visual demand for full, half and the first 30 meters length of tangents

S = Design speed in km/hr

Summary outputs for developed models are given in Appendix C at the end in Tables C10, C11 and C12. Observed VD values showed that VD varied with the variations in other design variables. Therefore, other variables were also used to develop VD models. The best models are as follows (summary outputs for developed models are given in Appendix C in Tables C13, C14 and C15):

$$\text{Log (VDF)} = -1.0181 + 0.3571 \text{ PEINVR} * \text{PEDEL} + 0.0035 S * L + 0.0034 S * R \quad (23)$$

(Pearson ChiSq / DF = 0.0242)

$$\text{Log (VDH)} = -1.1685 + 0.6517 \text{ PEINVR} * \text{PEDEL} + 0.0052 S * L + 0.0051 S * R \quad (24)$$

(Pearson ChiSq / DF = 0.0268)

$$\text{Log (VD30)} = -1.1978 + 1.1064 \text{ PEINVR} * \text{PEDEL} + 0.0051 S * L + 0.0055 S * R \quad (25)$$

(Pearson ChiSq / DF = 0.0466)

where

PEINVR = Inverse of radius of curvature of the preceding curve, where
radius is in meters

PEDEL = Deflection angle of the preceding curve element in degrees

S = Design speed in km/hr

R and L = Nominal character variables representing the turning direction of the preceding curve. When the turning direction of the preceding curve element is right, R takes a value of 1 and L takes a value of 0. When the turning direction of the preceding curve current element is left, the opposite takes place.

Table 13 shows the statistical significance of the explanatory variables considered for evaluation VDF on tangents. All the variables are well within the 95% confidence interval. The tangent models clearly showed that PEINVR crossed with the PEDEL affected the visual demand most significantly. Moreover, the design speed variable crossed with the turning direction of the preceding curve element was also another significant variable affecting visual demand. The reliability of all the explanatory variables considered for evaluation of VDH and VD30 for tangent sections, as obtained from the analysis, is given in Appendix C in Tables C14 and C15 respectively. All of these explanatory variables have reliability greater than 99.99%.

Table 13: Parameter Estimates of VDF on Tangents

Parameter Estimates						
Variable	PETD	DF	Estimate	Std Error	ChiSq	Pr > ChiSq
Intercept		1	-1.0181	0.0767	176.2640	<.0001
PEINVR*PEDEL		1	0.3571	0.1606	4.9399	0.0262
S*PETD	L	1	0.0035	0.0008	16.6841	<.0001
	R	1	0.0034	0.0008	17.3000	<.0001

5.3 Discussion

The basic objective of the current research study was achieved by developing models for visual demand in terms of VDF, VDH and VD30 for curves and tangents. The variability of visual demand was established using the developed models. Different design speeds were used to see the effect of design speed on visual demand for curves and tangents for full-element length (VDF), half-element length (VDH) and for the first 30 meters of the roadway element (VD30). The other design variables, e.g., the radius of curvature of the current element, were also varied for visual demand measures for curve elements along with the type of preceding element (tangent, curve turning in the same direction, and curve turning in the opposite direction). Similarly, for tangents, the effect of inverse of radius of the preceding curve and its turning direction (right or left) for different design speeds was examined.

5.3.1 Visual Demand on Curves

For the evaluation of visual demand for curves, a number of explanatory variables were considered in the course of research with special emphasis on design speed, for previous research was carried out for one particular speed. The design speed showed a statistically significant relationship with visual demand when considered alone as an explanatory variable and also when considered with other design variables. Figure 14 shows the variation of VD with respect to design speed. It clearly shows that visual demand in terms of VDF, VDH, and VD30 increases with the increase in design speed. Moreover, VD30 is higher than VDF and VDH, indicating that as the driver travels a curve, visual demand is higher at the start of the curve and then gradually decreases as the driver travels along the curve. It is also clear from the figure that as the design speed increases, the difference between VDH and VDF also increases for curve sections of the roadway.

The INVR (inverse of radius of curve) crossed with the turning direction was shown to be the statistically most significant explanatory variable for visual demand as reflected in Figure 15. This figure clearly shows that visual demand increases as the inverse of radius of curve increases for different design speeds, having higher value at a higher design speed.

Figure 14: Sensitivity of VDF, VDH and VD30 with Varying Design Speed (For Curve Sections)

This is true for all three measures of visual demand, i.e., VDF (visual demand for full-element length), VDH (visual demand for half-element length) and VD30 (visual demand for the first 30 meters of element length). Figure 16 shows the effect of turning direction of a curve on its visual demand. It clearly shows that visual demand value is always greater for a left-turning curve as compared to a right-turning curve although the difference is small. The effect of the preceding element type (tangent, curve turning in the same direction, curve turning in the opposite direction) also proved to be statistically significant when crossed with design speed as shown in Figure 17. This figure shows that when a driver travels from a tangent section to a curve section, visual demand is higher as compared to a situation when traveling from one curve to another curve. Secondly, if a driver travels from one curve to a curve having the same turning direction as the previous curve (i.e., the case of a circular curve), visual demand is less as compared to the visual demand on a curve turning in a direction opposite to the previous curve (i.e., the case of a reverse curve). It reflects the concept of *ad hoc* expectancy, for when the driver travels from a tangent to a curve, he or she has to face a shift over in VD due to the type of element being traveled, i.e., from a tangent to a curve as compared to a curve-to-curve situation.

Figure 15: Sensitivity of VDF, VDH and VD30 with Varying Inverse of Radius (For Curve Sections)

Figure 16: Sensitivity of VDF for Left and Right Turning Directions of Current Curve (For Curve Sections)

Figure 17: Sensitivity of VDF to Type of Preceding Element
(For Curve Sections)

The same concept is further shown when the two types of curve-to-curve situations (compound curve and reverse curve) are compared. Moreover, it is clear from Figure 17 that as the design speed increases, the difference among VDF, VDH and VD30 measures also increases for the same design speed. PEINVR (inverse of radius of preceding curve element) has also been found to be statistically significant. Visual demand increases as PEINVR (inverse of radius of preceding curve element) increases. It is important to specify that the same set of explanatory variables were statistically significant for all the measures of visual demand, i.e., for VDF (visual demand for full-curve length), VDH (half-curve length) and VD30 (visual demand for the first 30 meters of curve length) with different coefficients as given in the model equations.

5.3.2 Visual Demand on Tangents

As for curves, design speed, when considered alone as an explanatory variable, shows that visual demand is directly proportional to design speed for tangents. Figure 18 clearly demonstrates that as the design speed increases, visual demand also increases on tangent sections. Moreover, at lower speeds, the difference between VDF (visual demand for full-element length) and VDH (visual demand for half-element length) is small, but it

increases as the design speed increases. It is also clear that VD30 (visual demand for the first 30 meters of element length) is always higher as compared to VDF and VDH, indicating that as the driver travels a tangent section of an alignment, visual demand is higher at the start and then gradually decreases as the driver covers more distance. At higher values of design speed, the difference between VDH and VD30 decreases as reflected in Figure 18.

In the second step of model development for the tangent sections, design speed was considered along with other design variables, mainly the characteristics of the preceding curve element. The developed model indicated that PEINVR (inverse of radius of preceding curve element), when crossed with PEDEL (deflection angle of preceding curve), was statistically significant. This significance was higher at higher design speeds. Figure 19 shows that visual demand increases as PEINVR increases and has higher value for a higher design speed. This is true for all three measures of visual demand, i.e., VDF (visual demand for full-element length), VDH (visual demand for half-element length) and VD30 (visual demand for the first 30 meters of element length).

Design speed, when crossed with the turning direction of the preceding curve, was also statistically significant. The turning direction of the preceding curve element was divided into two categories, PETD (R) and PETD (L), which indicate the directions of the preceding curve as right and left respectively. These two variables were considered as Nominal Variables in SAS for the purpose of analysis. Figure 20 clearly shows the impact of this variable on visual demand for different speeds in terms of VDF. It shows that visual demand has higher value on the current tangent element when coming from a left-turning curve as compared to visual demand value when coming from a right-turning curve. This finding is the same for VDF and VDH. However, in case of VD30 (visual demand for the first 30 meters of element length), this effect is opposite, as shown in Figure 21. It is likely that in the case of VD30, this is due to the sight-distance issue as available sight distance for a given right-turning curve always becomes less than that for a left-turning curve. Moreover, in case of VD30, it has been observed that the difference between VD values for the two variables (preceding curve turning in a right direction and preceding curve turning in a left direction) is higher compared with VD values for VDF and VDH.

Figure 18: Sensitivity of VDF, VDH and VD30 to Design Speed
(For Tangent Sections)

Figure 19: Sensitivity of VDF, VDH and VD30 to PEINVR
(For Tangent Sections)

Figure 20: Sensitivity of VDF with varying Preceding Element Turning Direction (For Tangent Sections)

Figure 21: Sensitivity of VD30 with Varying Preceding Element Turning Direction (For Tangent Sections)

This implies that while traveling the first 30 meters of the tangent section, different turning directions of the preceding curve may have more impact on a driver's visual demand, and this impact decreases as a driver travels additional distance along the tangent section.

5.4 Model Verification and Comparison with FHWA Models

A comparative study was carried out to compare the results of the current research with those predicted by previous FHWA models for VDF (visual demand for full-element length) and VD30 (visual demand for the first 30 meters of element) for curves. The FHWA models are given below (Fitzpatrick et al. 2000):

$$\text{VDF} = 0.202 + 19.0 \, 1/R \quad (26)$$

$$\text{VD30} = 0.195 + 27.1 \, 1/R \quad (27)$$

where

$1/R$ = Inverse of radius of curve (1/m)

A continuous 2D horizontal alignment having various curves preceded and followed by a tangent was designed following the AASHTO and TAC standards. All the individual curve elements had radius values greater than the minimum radius required for the given design speed. The information pertaining to individual observation elements and geometric details are provided in Table 12 for this alignment. It is important to note that the FHWA models were developed at 72 km/hr speed value whereas models developed by the current research consider speed as an explanatory variable. In designing the alignment and calculating the visual demand values using the current models, the same value as that used by the FHWA was applied. A series of visual demand values for the individual curve elements was calculated using the models developed in the current research, called Current Model VD. Another series of visual demand values was calculated for each curve element using the models developed by the FHWA called FHWA Model VD. The objective of this comparative study was to verify the effectiveness of applying the current developed models in evaluating visual demand on two-dimensional highway alignments. The comparison graph for VDF is presented in Figure 22. The graph indicates that the current model of VDF shows a trend similar to that of the FHWA study.

Table 14: Information of Individual Observation Elements (Horizontal Curves)
For 72 km/hr

Element	Element Length (m)	1/Radius (1/m)	PC (m)	PT(m)	Deflection Angle (Degree)	Lane Width (m)
Tangent	200.00	-	-	-	-	3.7
Curve	235.71	0.0044	200	435.71	60	3.7
Tangent	300.00	-	-	-	-	3.7
Curve	218.25	0.004	735.71	953.97	50	3.7
Tangent	300.00	-	-	-	-	3.7
Curve	453.97	0.0025	1253.97	1707.94	65	3.7
Tangent	250.00	-	-	-	-	3.7
Curve	261.90	0.00333	1957.94	2219.84	50	3.7
Tangent	300.00	-	-	-	-	3.7
Curve	180.71	0.00435	2519.84	2700.56	45	3.7
Tangent	200.00	-	-	-	-	3.7
Curve	488.89	0.002857	2900.56	3389.44	80	3.7
Tangent	400.00	-	-	-	-	3.7
Curve	275.00	0.00222	3789.44	4064.44	35	3.7
Tangent	300.00	-	-	-	-	3.7

Moreover, the absolute values of the developed model are also close to those calculated by the FHWA model. Secondly, VD30 (visual demand for the first 30 meters of element length) data were compared using the current model and the FHWA Model. The same alignment details were used as described for VDF. The comparison graph is presented in Figure 23. The graph indicates that the VD30 models of the current research and those of the FHWA showed a similar trend. Moreover, the absolute values were also close, thus verifying the current models.

In the second step of model comparison and verification, visual demand values were compared using the current developed model and the FHWA model for a design speed of 100 km/hr. The FHWA model for visual demand was developed by using only one design speed. A limitation may arise here to use it only for the experimental speed. The visual demand model developed from the current research considered design speed as an explanatory variable, so it was expected that the current model would give better results for evaluating visual demand for any given design speed value. For this comparison, a second continuous 2D horizontal alignment was designed for 100 km/hr following the steps as described above for the first alignment.

Figure 22: Comparative Study for VDF at 72 km/hr

Figure 23: Comparative Study for VD30 at 72 km/hr

The information of individual observation elements and geometric details are provided in Table 15 for this alignment. The comparison graph for VDF values calculated by using the current model and the FHWA model is presented in Figure 24. The graph clearly shows that the VDF values given by both models show a similar trend, but while comparing absolute values, it shows that the FHWA model underestimates the visual demand. It can be stated that the FHWA model was developed by using a lower speed value and it does not consider the effect of the higher speed value used in this comparison. The graph shows that the values given by the current model are higher as they take care of the higher design speed value used in this comparison.

The same comparison result was observed in the case of VD30, as shown in Figure 25. According to the results of the comparative study, it is evident that the models developed by the current research study not only give acceptable results but also seem to have higher accuracy than the previous FHWA model that was developed without considering design speed as an explanatory variable.

Table 15: Information of Individual Observation Elements (Horizontal Curves) For 100 km/hr

Element	Element Length (m)	Radius of Curve(m)	1/Radius (1/m)	PC (m)	PT(m)	Deflection Angle (Degree)	Lane Width (m)
Tangent	200.00	-	-	-	-	-	3.7
Curve	460.95	440	0.0023	200	660.95	60	3.7
Tangent	300.00	-	-	-	-	-	3.7
Curve	436.51	500	0.002	960.95	1397.46	50	3.7
Tangent	300.00	-	-	-	-	-	3.7
Curve	680.95	600	0.0017	1697.46	2378.41	65	3.7
Tangent	250.00	-	-	-	-	-	3.7
Curve	392.86	450	0.00222	2628.41	3021.27	50	3.7
Tangent	300.00	-	-	-	-	-	3.7
Curve	589.29	750	0.00133	3321.27	3910.56	45	3.7
Tangent	200.00	-	-	-	-	-	3.7
Curve	768.25	550	0.0018	4110.56	4878.81	80	3.7
Tangent	400.00	-	-	-	-	-	3.7
Curve	550.00	900	0.0011	5278.81	5828.81	35	3.7
Tangent	300.00	-	-	-	-	-	3.7

Figure 24: Comparative Study for VDF at 100 km/hr

Figure 25: Comparative Study for VD30 at 100 km/hr

Thus, the main objectives of this research work have been successfully accomplished. All the independent variables were considered for developing the models for different visual-demand measures, and statistically insignificant variables were not included in the developed models. A total of twelve models were developed for tangent and curve sections. A null hypothesis was carried out for the development of the models and a confidence interval of 99 % was generally achieved for the explanatory variables. It is important to note that the same set of explanatory variables was found to be significant for VDF, VDH and VD30 for curve and tangent sections of the highway alignments. Design speed was the main explanatory variable considered as previous research studies had evaluated visual demand for one specific speed value. The current research study showed that design speed is a significant variable while developing visual demand models both for curve and tangent sections of the alignments. The developed models clearly indicated that visual demand increases with an increase in design speed, and thus models developed by using only one design speed may not be applied for other speed values. The currently developed models can be used to evaluate visual demand for 2D rural highways for any given design speed while considering the other design variables as indicated by the developed models. More research is required to identify threshold values of visual demand at different design speeds in order to identify desired safety levels.

Chapter 6 APPLICATION AND IMPLEMENTATION

6.1 Background

Highway geometric design inconsistencies cause the potential threat of traffic collisions. Researchers have been trying to develop ideas to minimize drivers' surprise or uncertainty regarding highway geometric design elements. The TAC (Transportation Association of Canada) Design Guide has a revised chapter on design consistency assessment methodologies (Easa 2002). Three major categories of highway design consistency are described in that chapter as follows:

- System Consistency
- Local Consistency
- Safety and Consistency

The visual demand method for the evaluation of design consistency falls in the area of system consistency. Therefore, system consistency has been considered for the application of visual demand criteria. The models developed for visual demand reflect their acceptability and promising application for evaluating design consistency. Visual demand can be evaluated by using these models for individual elements as well as for roadway stretches that comprise a composite curve with preceding and following tangents. The applicability of the currently developed models was tested by applying these models to a continuous 2D alignment with elements having different highway geometric properties. Comparison was made with other widely accepted speed profile methods for the evaluation of design consistency. A speed profile is developed in this method by using the predicted 85th percentile operating speeds for new roads or the measured 85th percentile speeds for existing roads.

It is necessary to predict operating speeds for the evaluation of speed consistency for a proposed new road. A series of regression equations has been recommended by the new TAC Design Guide for 2D and 3D highway alignment conditions. Table 16 shows the regression equations for 2D curves (Fitzpatrick 1999). The TAC Design Guide has suggested that, for long tangents of two-lane rural highways, the observed 85th percentile speed has a range from 94 km/hr to 104 km/hr, implying that a rounded value of 100

km/hr is a good estimate for the desired speed. A tangent section of an alignment may be considered a long tangent that has sufficient length so that the driver can accelerate to a desired speed for some distance. This can be checked by calculating TL_c . The critical length for speed changes between speed-limiting curves, TL_c , is the distance required for a vehicle to accelerate from one curve speed to the desired speed and then decelerate to the next curve speed. It is given by the following equations:

$$TL_c = X_{1a} + X_{1b} \quad (30)$$

$$X_{1a} = \frac{V_f^2 - V_n^2}{25.92 a}$$

(31)

$$X_{1d} = \frac{V_f^2 - V_{n+1}^2}{25.92 d} \quad (32)$$

where

X_{1a} = Length of road for acceleration from curve n speed to desired speed

X_{1d} = Length of road for deceleration from desired speed to curve n+1 speed

V_f = Desired speed

V_n and V_{n+1} = 85th percentile speeds for curve n and n+1 (using equations in Table 14)

If TL_c is less than 100 m, then it is a long tangent.

Table 16: Equations for Estimating Operating Speed (2D Horizontal Curves only)

Type	2D Alignment Conditions	Corresponding Equation
1	Horizontal curve on grade: $-9\% \leq G \leq -4\%$	$V_{85} = 102.10 - 3077.13/R$
2	Horizontal curve on grade: $-4\% \leq G \leq 0\%$	$V_{85} = 105.98 - 3709.90/R$
3	Horizontal curve on grade: $0\% \leq G \leq 4\%$	$V_{85} = 104.82 - 3574.51/R$
4	Horizontal curve on grade: $4\% \leq G \leq 9\%$	$V_{85} = 96.91 - 2752.19/R$
<p>V_{85} = 85th percentile speed of passenger cars (km/hr)</p> <p>G = Grade (%)</p> <p>1) Lowest speed among predicted speeds is to be used from Type 1 or 2 (for downgrade) and Type 3 or 4 (for upgrade)</p>		

6.2 Description of Test Alignments

In order to evaluate highway design consistency for both simple and complex 2D horizontal highway alignments, two different alignments were established as described below:

- The first alignment is a continuous simple 2D horizontal alignment having various simple horizontal curves with different turning directions and curve radii. Each curve is preceded and followed by a tangent. This alignment has total of ten elements that include five tangents and five simple horizontal curves.
- The second alignment is a complex 2D horizontal alignment having a combination of reverse curve, compound curve, simple horizontal curve and tangent sections. The horizontal curves have different values of radius. The alignment has a total of nine elements that include four tangents and five individual curve elements.

Figures 26 and 27 show the plan views of the test alignments having a design speed of 80 km/hr. The detailed geometric properties of the two highway alignments under consideration are presented in Table 17 and Table 18.

Figure 26: Test Alignment 1 for Consistency Evaluation

Figure 27: Test Alignment 2 for Consistency Evaluation

Table 17: Detailed Geometric Properties of Test Alignment 1 (Simple 2D Horizontal Alignment)

Element No.	Element Type	Turning Direction of Curve	Element Length (m)	1/Radius (1/m)	Def. Angle (Degree)	Start Distance (m)	End Distance (m)
1	Curve	R	314.29	0.00333	60	200.00	514.29
2	Tangent	-	200.00	-	-	514.29	714.29
3	Curve	R	576.19	0.00182	60	714.29	1290.48
4	Tangent	-	200.00	-	-	1290.48	1490.48
5	Curve	R	419.05	0.00250	60	1490.48	1909.52
6	Tangent	-	200.00	-	-	1909.52	2109.52
7	Curve	L	314.29	0.00333	60	2109.52	2423.81
8	Tangent	-	200.00	-	-	2423.81	2623.81
9	Curve	L	628.57	0.00167	60	2623.81	3252.38

Table 18: Detailed Geometric Properties of Test Alignment 2 (Complex 2D Horizontal Alignment)

Element No.	Element Type	Turning Direction of Curve	Element Length (m)	1/Radius (1/m)	Def. Angle (Degree)	Start Distance (m)	End Distance (m)
1	Curve	L	628.6	0.00167	60	200.0	828.6
2	Curve	R	314.3	0.00333	60	828.6	1142.9
3	Tangent	-	200.00	-	-	1142.9	1342.9
4	Curve	L	314.3	0.00333	60	1342.9	1657.1
5	Curve	L	471.4	0.00222	60	1657.1	2128.6
6	Tangent	-	200.00	-	-	2128.6	2328.6
7	Curve	R	419.00	0.00250	60	2328.6	2747.6
8	Tangent	-	200.00	-	-	2747.6	2947.6

The desired speed on the tangents was taken equal to 100 km/hr as recommended by the TAC (Transportation Association of Canada). After checking TL_c by using the equations provided above in section 6.1, all tangent sections of alignments were found to be long tangents, so the operating speed was 100 km/hr. The operating speeds on all the horizontal curve elements were calculated using the Type 3 equation provided in Table 16 in section 6.1 above. The visual demand for the curve and tangent sections of the alignments were calculated by using the VDF (visual demand on full element) models developed by this study. The VDF models for tangent and curve sections are provided in sections 5.2.1 and 5.2.2 respectively.

6.2.1 Results for Simple Horizontal Alignment

After calculating visual demand and operating speeds for each element of Test Alignment 1, the differences between these two measures were calculated for adjacent elements. The summary results are presented in Table 19. The proposed alignment was considered to be consistent in terms of operating speed consistency criteria as the maximum difference among operating speeds was 7.1 km/hr, being within the limit of 10 km/hr. Design consistency in terms of visual demand can be evaluated if critical threshold limits for visual demand difference become available. However, the visual demand profile and the operating speed profile as shown in Figure 28 are quite similar and well comparable.

Table 19: Visual Demand and Operating Speed for Test Alignment 1
(Simple Horizontal Alignment)

Element No.	Element Type	Element Length (m)	1/R (1/m)	Chainage (m)	Visual Demand		Operating Speed (km/hr)	
					VDF	VD Absolute Difference (x100)	V ₈₅	Speed Absolute Difference
1	Curve	314.29	0.00333	200.0	0.26	-	92.9	-
2	Tangent	200.00	-	514.3	0.21	5.7	100.0	7.1
3	Curve	576.19	0.00182	714.3	0.22	1.1	98.3	1.7
4	Tangent	200.00	-	1290.5	0.19	2.6	100.0	1.7
5	Curve	419.05	0.00250	1490.5	0.24	4.6	95.9	4.1
6	Tangent	200.00	-	1909.5	0.20	3.9	100.0	4.1
7	Curve	314.29	0.00333	2109.5	0.27	6.8	92.9	7.1
8	Tangent	200.00	-	2423.8	0.21	5.6	100.0	7.1
9	Curve	628.57	0.00167	2623.8	0.21	0.4	98.9	1.1

Figure 28: Comparison of VD Profile Vs Speed Profile for Simple Horizontal Alignment

6.2.2 Results for Complex Horizontal Alignment

The complex 2D horizontal alignment was also analyzed using the methods based upon operating speed consistency and the visual demand estimate consistency. The purpose was to investigate visual demand measure as a design consistency measure as compared to operating speed measure being an accepted measure of design consistency. The difference for operating speed and visual demand values for adjacent elements were calculated for comparison. The summary results are presented in Table 20. The maximum difference among operating speeds was 7.1 km/hr and was within the limit of 10 km/hr. Thus the complex horizontal alignment was considered a consistent alignment. The visual demand profile and the operating speed profile for this alignment are presented in Figure 29 and are quite similar and well comparable.

6.3 Discussion

The consistency evaluation of the above-described highway alignments was carried out with the results obtained from the operating-speed consistency method and the visual demand method using the VD models developed by the current research. The objective was to determine whether the two methods produce comparable results and thus the application of the currently developed visual demand models.

For the simple 2D horizontal alignment, the results in Table 19 show that visual demand increases as the radius of curvature decreases or the visual demand increases with the increase of the inverse of radius. Moreover, the visual demand decreases from the curve section to the following tangent and increases from the preceding tangent to the curve. Compared to this, the table also shows that the operating speed increases from the curve to the following tangent and decreases from the preceding tangent to the curve. Based upon the operating speed difference values, this alignment is considered a consistent alignment as the difference is within the limit of 10 km/hr. Since the threshold values for visual demand have not yet been developed, it is possible to comment on the workload design consistency based only on the strict engineering sense of the matter. The two profiles, one for visual demand and the other for operating speed, are shown in Figure 28. The profiles are quite similar and well matched for the simple horizontal alignment. The comparison of the two profiles clearly suggests that the visual demand measure has very good potential.

Table 20: Visual Demand and Operating Speed for Test Alignment 2
(Complex Alignment)

Element No.	Element Type	Element Length (m)	1/Radius (1/m)	Chainage (m)	Visual Demand		Operating Speed (km/hr)	
					VDF	VD Absolute Difference (x100)	V85	Speed Absolute Difference
1	Curve	628.57	0.00167	400.0	0.22	-	98.9	-
2	Curve	314.29	0.00333	1028.6	0.26	4.2	92.9	6.0
3	Tangent	200.00	-	1342.9	0.21	5.0	100.0	7.1
4	Curve	314.29	0.00333	1542.9	0.27	5.9	92.9	7.1
5	Curve	471.43	0.00222	1857.1	0.23	3.9	96.9	4.0
6	Tangent	200.00	-	2328.6	0.20	2.8	100.0	3.1
7	Curve	419.05	0.00250	2528.6	0.24	3.8	95.9	4.1
8	Tangent	200.00	-	2947.6	0.20	3.9	100.0	4.1

Figure 29: Comparison of VD Profile Vs Speed Profile for Complex Horizontal Alignment

to be a design consistency rating measure if threshold limit values for visual demand are developed. For the 2D complex horizontal alignment, the visual demand and operating speed difference values are provided in Table 20. The complex alignment analysis shows that the visual demand produces more sensitive results as it considers the direct effects of element characteristics and turning directions. Based upon the operating speed difference values, this alignment is considered a consistent alignment as the difference is within the limit of 10 km/hr. The visual demand and operating speed profiles were developed for the complex horizontal alignment as shown in Figure 29. It is clear from the figure that both the profiles are quite similar and well matched. The following important points are highlighted from the above discussion:

- The visual demand and speed difference are useful tools for evaluating the consistency of highway design, and the profiles for both of these measures match very well. The workload consistency results can be supported by comparing the difference in operating speeds and the difference in visual demand values.
- The critical threshold values for visual demand consistency need to be developed for the evaluation of highway-design consistency.

Chapter 7 CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

Driver visual demand is gaining attention as a measure of highway design consistency among highway geometric design researchers. Various research studies have been conducted and models have been developed to evaluate the visual demand on highway alignments. The available models for the evaluation of driver visual demand have not considered design speed as an explanatory variable. The purpose of the current research work was to investigate the effect of design speed on a driver's visual demand for 2D rural highways—first by considering only design speed as an explanatory variable, and, secondly, by considering the combined effects of design speed and other highway design variables. The experimental design and evaluation procedures adopted in this research were developed by synchronized steps throughout the course of this study. The models developed by the current research study clearly show that design speed has a significant effect on driver visual demand.

The simulation scenarios used in the current research study were developed for different design speeds. The visual demand models were developed for tangent and curve sections—first by considering only design speed as an explanatory variable, and, secondly, by considering design speed along with other highway design variables. The following findings are highlighted:

- Conventional models for the estimation of driver visual demand are applicable to a specific design speed. The design speed has a significant effect on visual demand. The visual demand increases as the design speed increases, and log-normalized distribution shows a suitable matching and goodness of fit. This finding is the same for visual demand for full-element length (VDF), visual demand for half-element length (VDH) and visual demand for the first 30 meters of element length (VD30) both for curve and tangent sections of highway alignments.

- The difference between visual demand values in terms of VDF, VDH and VD30 for curve and tangent sections decreases with an increase in design speed with visual demand values for curve sections always remaining high.
- For curve sections of highway alignments, the type of preceding element (tangent, curve turning in same direction, curve turning in opposite direction) is statistically significant when crossed with design speed. When a driver travels from a tangent section to a curve section, visual demand is higher as compared to the situation when traveling from one curve section to another curve. Secondly, if a driver travels from one curve to a curve having the same turning direction as the previous curve (the case of a circular curve), visual demand is less as compared to visual demand on a curve turning in a direction opposite to the previous curve (the case of a reverse curve). This finding supports the concept of *ad hoc* expectancy by comparing visual demand for tangent-to-curve shift over case, and, secondly, comparing visual demand for curve-to-curve shift over (for compound curve and reverse curve).
- For curve sections of highway alignment, visual demand is higher for a left-turning curve as compared to that for a right-turning curve, and the difference increases with an increase in design speed.
- For tangent sections of highway alignment, the turning direction of the previous curve element (right or left) affects visual demand. Visual demand value is higher on tangents having a left-turning curve as the preceding curve as compared to tangents having a right-turning curve as the preceding element, and the difference between these two values increases with an increase in design speed.
- The comparison of visual demand profile and operating speed profile for design consistency showed that visual demand is a promising measure for evaluating design consistency if threshold values are developed.

7.2 Recommendations

Based on this research, the following recommendations are made:

- The developed visual demand models consider design speed as an explanatory variable and thus should be verified by using rural two-lane highways for different design speeds.
- The current research was focused on the evaluation of visual demand for 2D horizontal highway alignments at different design speeds. Models for three-dimensional highway alignments, consisting of combined horizontal and vertical curves, should likewise be developed. Moreover, the effect of transition curves on visual demand should also be investigated.
- Threshold values of driver visual demand for different design speeds should be established for desired safety levels.
- While developing models for visual demand by this research, traffic parameters such as traffic volume, traffic signals, signs and pavement markings were not considered as explanatory variables. It is expected that traffic parameters may have considerable effect on driver visual demand, so future research should focus on these parameters.
- Two-lane rural highways were used to evaluate visual demand in the current research. Further research is required to investigate the effect of an urban environment on visual demand.
- The experiments were conducted in this study using a daytime environment only. Previous research has shown that driver performance in a nighttime environment varies as compared to that of a daytime environment, so visual demand experiments should be conducted for a nighttime environment as well.
- Road safety audits as a pro-active measure are gaining significant interest among highway safety professionals. Threshold values of visual demand should be established so that these can be used in road safety audits to prioritize the improvement of specific highway locations in an effort to improve safety.

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Appendix A

Design Characteristics of tested Alignments for Pilot Study and Actual Experiments

Table A1: Geometric Design Characteristics of Test Alignment 1
(Design Speed of 60 km/hr)

Element	Element Length (m)	Turning Direction of Curve	Radius of Curve (m)	1/Radius (1/m)	PC (m)	PT(m)	Deflection Angle (Degree)	Lane Width (m)
Tangent	300.00	-	-	-	-	-	-	3.7
Curve	261.90	R	250	0.004	300	561.90	60	3.7
Tangent	400.00	-	-	-	-	-	-	3.7
Curve	122.22	L	140	0.00714	961.90	1084.13	50	3.7
Tangent	250.00	-	-	-	-	-	-	3.7
Curve	567.46	L	500	0.002	1334.13	1901.59	65	3.7
Tangent	500.00	-	-	-	-	-	-	3.7
Curve	113.49	R	130	0.00769	2401.59	2515.08	50	3.7
Tangent	300.00	-	-	-	-	-	-	3.7
Curve	707.14	L	900	0.00111	2815.08	3522.22	45	3.7
Tangent	500.00	-	-	-	-	-	-	3.7
Curve	977.78	R	700	0.00143	4022.22	5000.00	80	3.7
Tangent	400.00	-	-	-	-	-	-	3.7
Curve	122.22	R	200	0.005	5400.00	5522.22	35	3.7
Tangent	300.00	-	-	-	-	-	-	3.7

Figure A1: Test Alignment 1 (Design Speed =60 km/hr)

Table A2: Geometric Design Characteristics of Test Alignment 2
(Design Speed of 60 km/hr)

Element	Element Length (m)	Turning Direction of Curve	Radius of Curve (m)	1/Radius (1/m)	PC (m)	PT(m)	Deflection Angle (Degree)	Lane Width (m)
Tangent	200	-	-	-	-	-	-	3.7
Curve	181.59	L	130	0.00769	200	381.59	80	3.7
Curve	261.90	R	250	0.004	381.59	643.49	60	3.7
Tangent	400	-	-	-	-	-	-	3.7
Curve	550.00	R	900	0.00111	1043.49	1593.49	35	3.7
Curve	488.89	L	700	0.00143	1593.49	2082.38	40	3.7
Tangent	200	-	-	-	-	-	-	3.7
Curve	220.00	R	140	0.00714	2282.38	2502.38	90	3.7
Curve	672.22	R	550	0.00182	2502.38	3174.60	70	3.7
Tangent	300	-	-	-	-	-	-	3.7

Figure A2: Test Alignment 2 (Design Speed =60 km/hr)

Table A3: Geometric Design Characteristics of Test Alignment 3
(Design Speed of 60 km/hr)

Element	Element Length (m)	Turning Direction of Curve	Radius of Curve (m)	1/Radius (1/m)	PC (m)	PT(m)	Deflection Angle (Degree)	Lane Width (m)
Tangent	200	-	-	-	-	-	-	3.7
Curve	181.59	R	130	0.00769	200	381.59	80	3.7
Curve	261.90	L	250	0.004	381.59	643.49	60	3.7
Tangent	350	-	-	-	-	-	-	3.7
Curve	220.00	R	140	0.00714	993.49	1213.49	90	3.7
Curve	550.00	R	450	0.00222	1213.49	1763.49	70	3.7
Tangent	200	-	-	-	-	-	-	3.7
Curve	366.67	L	700	0.00143	1963.49	2330.16	30	3.7
Curve	471.43	L	900	0.00111	2330.16	2801.59	30	3.7
Tangent	300	-	-	-	-	-	-	3.7

Figure A3: Test Alignment 3 (Design Speed =60 km/hr)

Table A4: Geometric Design Characteristics of Test Alignment 4
(Design Speed of 60 km/hr)

Element	Element Length (m)	Turning Direction of Curve	Radius of Curve (m)	1/Radius (1/m)	PC (m)	PT(m)	Deflection Angle (Degree)	Lane Width (m)
Tangent	200	-	-	-	-	-	-	3.7
Curve	384.13	R	550	0.00182	200	584.13	40	3.7
Curve	488.89	R	700	0.00143	584.13	1073.02	40	3.7
Tangent	350	-	-	-	-	-	-	3.7
Curve	181.59	L	130	0.00769	1423.02	1604.60	80	3.7
Curve	261.90	R	250	0.004	1604.60	1866.51	60	3.7
Tangent	400	-	-	-	-	-	-	3.7
Curve	288.10	L	550	0.00182	2266.51	2554.60	30	3.7
Curve	471.43	L	900	0.00111	2554.60	3026.03	30	3.7
Tangent	300	-	-	-	-	-	-	3.7
Curve	171.11	R	140	0.00714	3326.03	3497.14	70	3.7
Curve	392.86	L	450	0.00222	3497.14	3890.00	50	3.7
Tangent	350	-	-	-	-	-	-	3.7
Curve	471.43	R	900	0.00111	4240.00	4711.43	30	3.7
Curve	611.11	R	700	0.00143	4711.43	5322.54	50	3.7
Tangent	400	-	-	-	-	-	-	3.7
Curve	218.25	L	250	0.004	5722.54	5940.79	50	3.7
Curve	384.13	L	550	0.00182	5940.79	6324.92	40	3.7
Tangent	200	-	-	-	-	-	-	3.7

Figure A4: Test Alignment 4 (Design Speed =60 km/hr)

Table A5: Geometric Design Characteristics of Test Alignment 5
(Design Speed of 80 km/hr)

Element	Element Length (m)	Turning Direction of Curve	Radius of Curve (m)	1/Radius (1/m)	PC (m)	PT(m)	Deflection Angle (Degree)	Lane Width (m)
Tangent	300.00	-	-	-	-	-	-	3.7
Curve	377.14	L	360	0.00278	300	677.14	60	3.7
Tangent	400.00	-	-	-	-	-	-	3.7
Curve	523.81	L	600	0.00167	1077.14	1600.95	50	3.7
Tangent	700.00	-	-	-	-	-	-	3.7
Curve	283.73	R	250	0.004	2300.95	2584.68	65	3.7
Tangent	500.00	-	-	-	-	-	-	3.7
Curve	916.67	L	1050	0.00095	3084.68	4001.35	50	3.7
Tangent	300.00	-	-	-	-	-	-	3.7
Curve	204.29	R	260	0.00385	4301.35	4505.63	45	3.7
Tangent	600.00	-	-	-	-	-	-	3.7
Curve	1117.46	R	800	0.00125	5105.63	6223.10	80	3.7
Tangent	300.00	-	-	-	-	-	-	3.7
Curve	763.89	L	1250	0.0008	6523.10	7286.98	35	3.7
Tangent	400.00	-	-	-	-	-	-	3.7

Figure A5: Test Alignment 5 (Design Speed =80 km/hr)

Table A6: Geometric Design Characteristics of Test Alignment 6
(Design Speed of 80 km/hr)

Element	Element Length (m)	Turning Direction of Curve	Radius of Curve (m)	1/Radius (1/m)	PC (m)	PT(m)	Deflection Angle (Degree)	Lane Width (m)
Tangent	200	-	-	-	-	-	-	3.7
Curve	458.33	L	375	0.00267	200	658.33	70	3.7
Curve	349.21	R	250	0.004	658.33	1007.54	80	3.7
Tangent	350	-	-	-	-	-	-	3.7
Curve	611.11	R	700	0.00143	1357.54	1968.65	50	3.7
Curve	523.81	L	1000	0.001	1968.65	2492.46	30	3.7
Tangent	200	-	-	-	-	-	-	3.7
Curve	317.78	R	260	0.00385	2692.46	3010.24	70	3.7
Curve	436.51	R	500	0.002	3010.24	3446.75	50	3.7
Tangent	400	-	-	-	-	-	-	3.7

Figure A6: Test Alignment 6 (Design Speed =80 km/hr)

Table A7: Geometric Design Characteristics of Test Alignment 7
(Design Speed of 80 km/hr)

Element	Element Length (m)	Turning Direction of Curve	Radius of Curve (m)	1/Radius (1/m)	PC (m)	PT(m)	Deflection Angle (Degree)	Lane Width (m)
Tangent	200	-	-	-	-	-	-	3.7
Curve	305.56	R	250	0.004	200	505.56	70	3.7
Curve	392.86	L	450	0.00222	505.56	898.41	50	3.7
Tangent	350	-	-	-	-	-	-	3.7
Curve	471.43	R	900	0.00111	1248.41	1719.84	30	3.7
Curve	576.19	R	1100	0.00091	1719.84	2296.03	30	3.7
Tangent	200	-	-	-	-	-	-	3.7
Curve	363.17	L	260	0.00385	2496.03	2859.21	80	3.7
Curve	733.33	L	700	0.00143	2859.21	3592.54	60	3.7
Tangent	400	-	-	-	-	-	-	3.7

Figure A7: Test Alignment 7 (Design Speed =80 km/hr)

Table A8: Geometric Design Characteristics of Test Alignment 8
(Design Speed of 80 km/hr)

Element	Element Length (m)	Turning Direction of Curve	Radius of Curve (m)	1/Radius (1/m)	PC (m)	PT(m)	Deflection Angle (Degree)	Lane Width (m)
Tangent	200	-	-	-	-	-	-	3.7
Curve	305.56	R	250	0.004	200	505.56	70	3.7
Curve	436.51	R	500	0.002	505.56	942.06	50	3.7
Tangent	350	-	-	-	-	-	-	3.7
Curve	327.38	L	375	0.00267	1292.06	1619.44	50	3.7
Curve	488.89	R	700	0.00143	1619.44	2108.33	40	3.7
Tangent	400	-	-	-	-	-	-	3.7
Curve	550.00	L	900	0.00111	2508.33	3058.33	35	3.7
Curve	611.11	L	700	0.00143	3058.33	3669.44	50	3.7
Tangent	300	-	-	-	-	-	-	3.7
Curve	363.17	R	260	0.00385	3969.44	4332.62	80	3.7
Curve	523.81	L	500	0.002	4332.62	4856.43	60	3.7
Tangent	350	-	-	-	-	-	-	3.7
Curve	523.81	R	600	0.00167	5206.43	5730.24	50	3.7
Curve	628.57	R	1200	0.00083	5730.24	6358.81	30	3.7
Tangent	400	-	-	-	-	-	-	3.7
Curve	261.90	L	375	0.00267	6758.81	7020.71	40	3.7
Curve	510.71	L	650	0.00154	7020.71	7531.43	45	3.7
Tangent	200	-	-	-	-	-	-	3.7

Figure A8: Test Alignment 8 (Design Speed = 80 km/hr)

Table A9: Geometric Design Characteristics of Test Alignment 9
(Design Speed of 100 km/hr)

Element	Element Length (m)	Turning Direction of Curve	Radius of Curve (m)	1/Radius (1/m)	PC (m)	PT(m)	Deflection Angle (Degree)	Lane Width (m)
Tangent	400.00	-	-	-	-	-	-	3.7
Curve	460.95	R	440	0.00227	400	860.95	60	3.7
Tangent	500.00	-	-	-	-	-	-	3.7
Curve	654.76	L	750	0.00133	1360.95	2015.71	50	3.7
Tangent	300.00	-	-	-	-	-	-	3.7
Curve	1475.40	L	1300	0.00077	2315.71	3791.11	65	3.7
Tangent	700.00	-	-	-	-	-	-	3.7
Curve	873.02	R	1000	0.00100	4491.11	5364.13	50	3.7
Tangent	400.00	-	-	-	-	-	-	3.7
Curve	353.57	R	450	0.00222	5764.13	6117.70	45	3.7
Tangent	750.00	-	-	-	-	-	-	3.7
Curve	768.25	R	550	0.00182	6867.70	7635.95	80	3.7
Tangent	500.00	-	-	-	-	-	-	3.7
Curve	916.67	L	1500	0.00067	8135.95	9052.62	35	3.7
Tangent	400.00	-	-	-	-	-	-	3.7

Figure A9: Test Alignment 9 (Design Speed =100 km/hr)

Table A10: Geometric Design Characteristics of Test Alignment 10
(Design Speed of 100 km/hr)

Element	Element Length (m)	Turning Direction of Curve	Radius of Curve (m)	1/Radius (1/m)	PC (m)	PT(m)	Deflection Angle (Degree)	Lane Width (m)
Tangent	200	-	-	-	-	-	-	3.7
Curve	268.89	L	440	0.00227	200	468.89	35	3.7
Curve	737.70	R	650	0.00154	468.89	1206.59	65	3.7
Tangent	400	-	-	-	-	-	-	3.7
Curve	353.57	R	450	0.00222	1606.59	1960.16	45	3.7
Curve	654.76	L	750	0.00133	1960.16	2614.92	50	3.7
Tangent	450	-	-	-	-	-	-	3.7
Curve	576.19	R	1100	0.00091	3064.92	3641.11	30	3.7
Curve	550.00	R	900	0.00111	3641.11	4191.11	35	3.7
Tangent	300	-	-	-	-	-	-	3.7

Figure A10: Test Alignment 10 (Design Speed =100 km/hr)

Table A11: Geometric Design Characteristics of Test Alignment 11
(Design Speed of 100 km/hr)

Element	Element Length (m)	Turning Direction of Curve	Radius of Curve (m)	1/Radius (1/m)	PC (m)	PT(m)	Deflection Angle (Degree)	Lane Width (m)
Tangent	200	-	-	-	-	-	-	3.7
Curve	499.37	R	440	0.00227	200	699.37	65	3.7
Curve	567.46	L	650	0.00154	699.37	1266.83	50	3.7
Tangent	400	-	-	-	-	-	-	3.7
Curve	680.95	R	1300	0.00077	1666.83	2347.78	30	3.7
Curve	785.71	R	900	0.00111	2347.78	3133.49	50	3.7
Tangent	350	-	-	-	-	-	-	3.7
Curve	611.11	L	500	0.002	3483.49	4094.60	70	3.7
Curve	654.76	L	750	0.00133	4094.60	4749.37	50	3.7
Tangent	300	-	-	-	-	-	-	3.7

Figure A11: Test Alignment 11 (Design Speed =100 km/hr)

Table A12: Geometric Design Characteristics of Test Alignment 12
(Design Speed of 100 km/hr)

Element	Element Length (m)	Turning Direction of Curve	Radius of Curve (m)	1/Radius (1/m)	PC (m)	PT(m)	Deflection Angle (Degree)	Lane Width (m)
Tangent	200	-	-	-	-	-	-	3.7
Curve	576.19	R	1100	0.00091	200	776.19	30	3.7
Curve	680.95	R	1300	0.00077	776.19	1457.14	30	3.7
Tangent	350	-	-	-	-	-	-	3.7
Curve	499.37	L	440	0.00227	1807.14	2306.51	65	3.7
Curve	499.37	R	440	0.00227	2306.51	2805.87	65	3.7
Tangent	400	-	-	-	-	-	-	3.7
Curve	907.94	L	1300	0.00077	3205.87	4113.81	40	3.7
Curve	785.71	L	1500	0.00067	4113.81	4899.52	30	3.7
Tangent	300	-	-	-	-	-	-	3.7
Curve	550.00	R	450	0.00222	5199.52	5749.52	70	3.7
Curve	654.76	L	750	0.00133	5749.52	6404.29	50	3.7
Tangent	350	-	-	-	-	-	-	3.7
Curve	576.19	R	1100	0.00091	6754.29	7330.48	30	3.7
Curve	1222.22	R	1400	0.00071	7330.48	8552.70	50	3.7
Tangent	400	-	-	-	-	-	-	3.7
Curve	628.57	L	900	0.00111	8952.70	9581.27	40	3.7
Curve	567.46	L	650	0.00154	9581.27	10148.73	50	3.7
Tangent	200	-	-	-	-	-	-	3.7

Figure A12: Test Alignment 12 (Design Speed = 100 km/hr)

Appendix B

Driver Simulator Arrangement Details

Figure B1: Driver Simulator Arrangement

Post Run	Roadway Scenery	Sound	Vehicle	Views and Playback
Dynamics	Graphics	Initialize	I/O Control	Other

☐ Use advanced dynamics

Simple Dynamics

Yaw rate scale factor:	<input type="text" value="0.0008"/>	Rad/Sec/Deg
Oversteer coefficient:	<input type="text" value="0.002"/>	
Acceleration limit:	<input type="text" value="0.25"/>	gs
Deceleration limit:	<input type="text" value="0.6"/>	gs
Coefficient of drag:	<input type="text" value="0.0001"/>	
Yaw instability:	<input type="text" value="0"/>	
Speed instability:	<input type="text" value="0"/>	
Steering deadband:	<input type="text" value="0"/>	Degrees
Yaw instability lag:	<input type="text" value="0"/>	Seconds
Idle throttle setting:	<input type="text" value="0"/>	

Dynamics Output Parameters

Powertrain Parameters

Advanced Dynamics Command File:

Figure B2: Configuration Settings Window for Simulation

Figure B3: Examples of STISIM Drive Roadway Scenes

Control

Options

Left

#	Delay	Open	Close	Period	Number
1	0	0	0	0	0
2					
3					
4					
5					

Right

#	Delay	Open	Close	Period	Number
1	0		0	0	0
2					
3					
4					
5					

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☒ Loop (Internal Mode Only)

☐ L-R Complement

Figure B4: Input Table of *ToTaLcontrol* Software for Open and Close Time of Spectacle Lenses

Appendix C

Graphs, Summary Output and Results

Table C1: Model Developed on VD for Curves by Pilot Study
Considering Design Speed Only as Explanatory Variable

VD	=	Speed
Response Distribution: Normal		
Link Function: Log

Model Equation					
Log (VD)	=	-	1.0405	+	0.0049 Speed

Summary of Fit					
Mean of Response	0.5258	Deviance	2.2159	Pearson ChiSq	2.2159
SCALE (MLE)	0.1875	Deviance / DF	0.0363	Pearson ChiSq / DF	0.0363

Analysis of Deviance			
Source	DF	Deviance	Deviance / DF
Model	1	0.1109	0.1109
Error	61	2.2159	0.0363
C Total	62	2.3268

Type III (Wald) Tests			
Source	DF	ChiSq	Pr > ChiSq
Speed	1	3.1691	0.0750

Parameter Estimates					
Variable	DF	Estimate	Std Error	ChiSq	Pr > ChiSq
Intercept	1	-1.0405	0.2332	19.9163	<.0001
Speed	1	0.0049	0.0028	3.1691	0.0750

Table C2: Model Developed on VD for Tangents by Pilot Study
Considering Design Speed Only as Explanatory Variable

VD	=	Speed
Response Distribution: Normal		
Link Function: Log

Model Equation		
Log (VD)	=	- 1.0487 + 0.0044 Speed

Summary of Fit					
Mean of Response	0.5005	Deviance	1.9368	Pearson ChiSq	1.9368
SCALE (MLE)	0.1753	Deviance / DF	0.0318	Pearson ChiSq / DF	0.0318

Analysis of Deviance			
Source	DF	Deviance	Deviance / DF
Model	1	0.0803	0.0803
Error	61	1.9368	0.0318
C Total	62	2.0172

Type III (Wald) Tests			
Source	DF	ChiSq	Pr > ChiSq
Speed	1	2.6501	0.1035

Parameter Estimates					
Variable	DF	Estimate	Std Error	ChiSq	Pr > ChiSq
Intercept	1	-1.0487	0.2280	21.1486	<.0001
Speed	1	0.0044	0.0027	2.6501	0.1035

Table C3: Model Developed on VD for Curves by Pilot Study
Considering 1/Radius Only as Explanatory Variable

VD	=	INVR
Response Distribution: Normal		
Link Function: Log		

Model Equation					
Log	(	VD	)	=	- 0.7085 + 25.1882 INVR

Summary of Fit					
Mean of Response	0.5258	Deviance	2.2793	Pearson ChiSq	2.2793
SCALE (MLE)	0.1902	Deviance / DF	0.0374	Pearson ChiSq / DF	0.0374

Analysis of Deviance			
Source	DF	Deviance	Deviance / DF
Model	1	0.0475	0.0475
Error	61	2.2793	0.0374
C Total	62	2.3268	

Type III (Wald) Tests			
Source	DF	ChiSq	Pr > ChiSq
INVR	1	1.3678	0.2422

Parameter Estimates					
Variable	DF	Estimate	Std Error	ChiSq	Pr > ChiSq
Intercept	1	-0.7085	0.0751	89.1172	<.0001
INVR	1	25.1882	21.5372	1.3678	0.2422

Table C4: Model Developed on VDF for Curves by Actual Experiments
Considering Design Speed Only as Explanatory Variable

☒ VDF	=	S
Response Distribution: Normal		
Link Function: Log		

☒	Model Equation				
Log	(	VDF	)	=	- 0.7048 + 0.0011 S

☒	Summary of Fit				
Mean of Response	0.5409	Deviance	28.8330	Pearson ChiSq	28.8330
SCALE (MLE)	0.1607	Deviance / DF	0.0259	Pearson ChiSq / DF	0.0259

☒	Analysis of Deviance			
Source	DF	Deviance	Deviance / DF	
Model	1	0.1090	0.1090	
Error	1114	28.8330	0.0259	
C Total	1115	28.9421		

☒	Type III (Wald) Tests			
Source	DF	ChiSq	Pr > ChiSq	
S	1	4.2713	0.0388	

☒	Parameter Estimates					
Variable	DF	Estimate	Std Error	ChiSq	Pr > ChiSq	
Intercept	1	-0.7048	0.0448	247.3648	<.0001	
S	1	0.0011	0.0005	4.2713	0.0388	

Table C5: Model Developed on VDH for Curves by Actual Experiments
Considering Design Speed Only as Explanatory Variable

☒ VDH	=	S
Response Distribution: Normal		
Link Function: Log		

☒	Model Equation				
Log	(	VDH	)	=	- 0.7010 + 0.0014 S

☒	Summary of Fit				
Mean of Response	0.5534	Deviance	32.3448	Pearson ChiSq	32.3448
SCALE (MLE)	0.1702	Deviance / DF	0.0290	Pearson ChiSq / DF	0.0290

Analysis of Deviance			
Source	DF	Deviance	Deviance / DF
Model	1	0.1679	0.1679
Error	1114	32.3448	0.0290
C Total	1115	32.5127	

☒	Type III (Wald) Tests		
Source	DF	ChiSq	Pr > ChiSq
S	1	5.8399	0.0157

☒	Parameter Estimates				
Variable	DF	Estimate	Std Error	ChiSq	Pr > ChiSq
Intercept	1	-0.7010	0.0465	227.5749	<.0001
S	1	0.0014	0.0006	5.8399	0.0157

Table C6: Model Developed on VD30 for Curves by Actual Experiments
Considering Design Speed Only as Explanatory Variable

☒ VD30	=	S
Response Distribution: Normal		
Link Function: Log		

☒	Model Equation				
Log	(	VD30	)	=	- 0.6251 + 0.0007 S

☒	Summary of Fit				
Mean of Response	0.5665	Deviance	51.6940	Pearson ChiSq	51.6940
SCALE (MLE)	0.2152	Deviance / DF	0.0464	Pearson ChiSq / DF	0.0464

☒	Analysis of Deviance			
Source	DF	Deviance	Deviance / DF	
Model	1	0.0472	0.0472	
Error	1114	51.6940	0.0464	
C Total	1115	51.7412		

☒	Type III (Wald) Tests			
Source	DF	ChiSq	Pr > ChiSq	
S	1	1.0387	0.3081	

☒	Parameter Estimates					
Variable	DF	Estimate	Std Error	ChiSq	Pr > ChiSq	
Intercept	1	-0.6251	0.0571	119.7365	<.0001	
S	1	0.0007	0.0007	1.0387	0.3081	

Table C7: Model Developed on VDF for Curves by Actual Experiments
Considering Design Speed with Other Explanatory Variables

VDF = INVR*CETD S*PE PEINVR
Response Distribution: Normal
Link Function: Log

Nominal Variable Information		
Level	CETD	PE
1	L	CC
2	R	RC
3		T

Parameter Information			
Parameter	Variable	CETD	PE
1	Intercept		
2	INVR*CETD	L	
3		R	
4	S*PE		CC
5			RC
6			T
7	PEINVR		

		Model Equation			
Log (VDF)	=	-	1.1591	+	55.1923 P_2
				+	53.8424 P_3
				+	0.0043 P_4
				+	0.0046 P_5
				+	0.0051 P_6
				+	17.2821 PEINVR

Summary of Fit					
Mean of Response	0.5409	Deviance	25.8700	Pearson ChiSq	25.8700
SCALE (MLE)	0.1523	Deviance / DF	0.0233	Pearson ChiSq / DF	0.0233

Analysis of Deviance			
Source	DF	Deviance	Deviance / DF
Model	6	3.0720	0.5120
Error	1109	25.8700	0.0233
C Total	1115	28.9421	

Type III (Wald) Tests			
Source	DF	ChiSq	Pr > ChiSq
INVR*CETD	2	102.5971	<.0001
S*PE	3	60.6719	<.0001
PEINVR	1	7.9863	0.0047

Parameter Estimates							
Variable	CETD	PE	DF	Estimate	Std Error	ChiSq	Pr > ChiSq
Intercept			1	-1.1591	0.0673	296.4230	<.0001
INVR*CETD	L		1	55.1923	6.5045	71.9999	<.0001
	R		1	53.8424	5.5615	93.7268	<.0001
S*PE		CC	1	0.0043	0.0007	35.4001	<.0001
		RC	1	0.0046	0.0007	46.7781	<.0001
		T	1	0.0051	0.0007	53.9659	<.0001
PEINVR			1	17.2821	6.1154	7.9863	0.0047

Table C8: Model Developed on VDH for Curves by Actual Experiments
Considering Design Speed with Other Explanatory Variables

VDH	=	INVR*CETD	S*PE	PE INVR
Response Distribution: Normal				
Link Function: Log				

Nominal Variable Information			
Level	CETD	PE	
1	L	CC	
2	R	RC	
3		T	

Parameter Information			
Parameter	Variable	CETD	PE
1	Intercept		
2	INVR*CETD	L	
3		R	
4	S*PE		CC
5			RC
6			T
7	PE INVR		

Model Equation				
Log (VDH)	=	-	1.2444	+ 63.5760 P_2 + 61.0929 P_3 + 0.0050 P_4
			+ 0.0057 P_5	+ 0.0062 P_6 + 25.0161 PE INVR

Summary of Fit					
Mean of Response	0.5534	Deviance	28.0738	Pearson ChiSq	28.0738
SCALE (MLE)	0.1586	Deviance / DF	0.0253	Pearson ChiSq / DF	0.0253

Analysis of Deviance			
Source	DF	Deviance	Deviance / DF
Model	6	4.4390	0.7398
Error	1109	28.0738	0.0253
C Total	1115	32.5127	

Type III (Wald) Tests			
Source	DF	ChiSq	Pr > ChiSq
INVR*CETD	2	126.9605	<.0001
S*PE	3	88.1893	<.0001
PE INVR	1	16.6208	<.0001

Parameter Estimates							
Variable	CETD	PE	DF	Estimate	Std Error	ChiSq	Pr > ChiSq
Intercept			1	-1.2444	0.0700	316.3113	<.0001
INVR*CETD	L		1	63.5760	6.6181	92.2834	<.0001
	R		1	61.0929	5.6985	114.9376	<.0001
S*PE		CC	1	0.0050	0.0007	45.2156	<.0001
		RC	1	0.0057	0.0007	66.9670	<.0001
		T	1	0.0062	0.0007	73.4748	<.0001
PE INVR			1	25.0161	6.1361	16.6208	<.0001

Table C9: Model Developed on VD30 for Curves by Actual Experiments
Considering Design Speed with Other Explanatory Variables

VD30	=	INVR*CETD	S*PE	PEINVR
Response Distribution: Normal				
Link Function: Log				

Nominal Variable Information			
Level	CETD	PE	
1	L	CC	
2	R	RC	
3		T	

Parameter Information			
Parameter	Variable	CETD	PE
1	Intercept		
2	INVR*CETD	L	
3		R	
4	S*PE		CC
5			RC
6			T
7	PEINVR		

Model Equation				
Log (VD30)	=	-	1.2267 + 69.5885 P_2 + 66.1259 P_3 + 0.0048 P_4	
		+	0.0062 P_5 + 0.0059 P_6 + 27.6674 PEINVR	

Summary of Fit					
Mean of Response	0.5665	Deviance	45.7915	Pearson ChiSq	45.7915
SCALE (MLE)	0.2026	Deviance / DF	0.0413	Pearson ChiSq / DF	0.0413

Analysis of Deviance			
Source	DF	Deviance	Deviance / DF
Model	6	5.9497	0.9916
Error	1109	45.7915	0.0413
C Total	1115	51.7412	

Type III (Wald) Tests			
Source	DF	ChiSq	Pr > ChiSq
INVR*CETD	2	96.9204	<.0001
S*PE	3	65.3588	<.0001
PEINVR	1	13.8714	0.0002

Parameter Estimates							
Variable	CETD	PE	DF	Estimate	Std Error	ChiSq	Pr > ChiSq
Intercept			1	-1.2267	0.0880	194.5138	<.0001
INVR*CETD	L		1	69.5885	8.1902	72.1906	<.0001
	R		1	66.1259	7.0857	87.0921	<.0001
S*PE		CC	1	0.0048	0.0009	25.5172	<.0001
		RC	1	0.0062	0.0009	51.3404	<.0001
		T	1	0.0059	0.0009	42.2608	<.0001
PEINVR			1	27.6674	7.4286	13.8714	0.0002

Table C10: Model Developed on VDF for Tangents by Actual Experiments
Considering Design Speed Only as Explanatory Variable

VDF	=	S
Response Distribution: Normal		
Link Function: Log

Model Equation
Log (VDF) = - 0.9196 + 0.0027 S

Summary of Fit					
Mean of Response	0.4944	Deviance	16.6085	Pearson ChiSq	16.6085
SCALE (MLE)	0.1558	Deviance / DF	0.0244	Pearson ChiSq / DF	0.0244

Analysis of Deviance			
Source	DF	Deviance	Deviance / DF
Model	1	0.3159	0.3159
Error	682	16.6085	0.0244
C Total	683	16.9245	

Type III (Wald) Tests			
Source	DF	ChiSq	Pr > ChiSq
S	1	13.1259	0.0003

Parameter Estimates					
Variable	DF	Estimate	Std Error	ChiSq	Pr > ChiSq
Intercept	1	-0.9196	0.0614	224.3629	<.0001
S	1	0.0027	0.0007	13.1259	0.0003

Table C11: Model Developed on VDH for Tangents by Actual Experiments
Considering Design Speed Only as Explanatory Variable

☒ VDH	=	S
Response Distribution: Normal		
Link Function: Log		

☒	Model Equation				
Log	(	VDH	)	=	- 0.9860 + 0.0038 S

☒	Summary of Fit				
Mean of Response	0.5054	Deviance	18.6184	Pearson ChiSq	18.6184
SCALE (MLE)	0.1650	Deviance / DF	0.0273	Pearson ChiSq / DF	0.0273

Analysis of Deviance			
Source	DF	Deviance	Deviance / DF
Model	1	0.6592	0.6592
Error	682	18.6184	0.0273
C Total	683	19.2776	

Type III (Wald) Tests			
Source	DF	ChiSq	Pr > ChiSq
S	1	24.1607	<.0001

☒	Parameter Estimates				
Variable	DF	Estimate	Std Error	ChiSq	Pr > ChiSq
Intercept	1	-0.9860	0.0641	236.3280	<.0001
S	1	0.0038	0.0008	24.1607	<.0001

Table C12: Model Developed on VD30 for Tangents by Actual Experiments
Considering Design Speed Only as Explanatory Variable

VD30	=	S
Response Distribution: Normal		
Link Function: Log

Model Equation				
Log	(	VD30	)	=	- 0.8791 + 0.0029 S

Summary of Fit				
Mean of Response	0.5234	Deviance	33.3546	Pearson ChiSq	33.3546
SCALE (MLE)	0.2210	Deviance / DF	0.0490	Pearson ChiSq / DF	0.0490

Analysis of Deviance			
Source	DF	Deviance	Deviance / DF	
Model	1	0.4118	0.4118	
Error	681	33.3546	0.0490	
C Total	682	33.7664

Type III (Wald) Tests			
Source	DF	ChiSq	Pr > ChiSq	
S	1	8.4656	0.0036

Parameter Estimates				
Variable	DF	Estimate	Std Error	ChiSq	Pr > ChiSq
Intercept	1	-0.8791	0.0824	113.8747	<.0001
S	1	0.0029	0.0010	8.4656	0.0036

Table C13: Model Developed on VDF for Tangents by Actual Experiments
Considering Design Speed with Other Explanatory Variables

☒	VDF = PE INVR*PEDEL S*PETD
	Response Distribution: Normal
	Link Function: Log

☒	Parameter Information		
Parameter	Variable	PETD	
1	Intercept		
2	PE INVR*PEDEL		
3	S*PETD	L	
4		R	

☒	Model Equation				
Log (VDF)	=	-	1.0181	+	0.3571 P_2 + 0.0035 P_3 + 0.0034 P_4

☒	Summary of Fit				
Mean of Response	0.4944	Deviance	16.4893	Pearson ChiSq	16.4893
SCALE (MLE)	0.1553	Deviance / DF	0.0242	Pearson ChiSq / DF	0.0242

☒	Analysis of Deviance			
Source	DF	Deviance	Deviance / DF	
Model	3	0.4352	0.1451	
Error	680	16.4893	0.0242	
C Total	683	16.9245		

☒	Type III (Wald) Tests			
Source	DF	ChiSq	Pr > ChiSq	
PE INVR*PEDEL	1	4.9399	0.0262	
S*PETD	2	17.6003	0.0002	

☒	Parameter Estimates					
Variable	PETD	DF	Estimate	Std Error	ChiSq	Pr > ChiSq
Intercept		1	-1.0181	0.0767	176.2640	<.0001
PE INVR*PEDEL		1	0.3571	0.1606	4.9399	0.0262
S*PETD	L	1	0.0035	0.0008	16.6841	<.0001
	R	1	0.0034	0.0008	17.3000	<.0001

Table C14: Model Developed on VDH for Tangents by Actual Experiments
Considering Design Speed with Other Explanatory Variables

VDH = PEINVR*PEDEL S*PETD
Response Distribution: Normal
Link Function: Log

Parameter Information		
Parameter	Variable	PETD
1	Intercept	
2	PEINVR*PEDEL	
3	S*PETD	L
4		R

Model Equation					
Log (VDH)	=	-	1.1685	+	0.6517 P_2 + 0.0052 P_3 + 0.0051 P_4

Summary of Fit					
Mean of Response	0.5054	Deviance	18.2016	Pearson ChiSq	18.2016
SCALE (MLE)	0.1631	Deviance / DF	0.0268	Pearson ChiSq / DF	0.0268

Analysis of Deviance			
Source	DF	Deviance	Deviance / DF
Model	3	1.0760	0.3587
Error	680	18.2016	0.0268
C Total	683	19.2776	

Type III (Wald) Tests			
Source	DF	ChiSq	Pr > ChiSq
PEINVR*PEDEL	1	15.9425	<.0001
S*PETD	2	37.0410	<.0001

Parameter Estimates						
Variable	PETD	DF	Estimate	Std Error	ChiSq	Pr > ChiSq
Intercept		1	-1.1685	0.0803	211.8651	<.0001
PEINVR*PEDEL		1	0.6517	0.1632	15.9425	<.0001
S*PETD	L	1	0.0052	0.0009	35.2984	<.0001
	R	1	0.0051	0.0008	36.3549	<.0001

Table C15: Model Developed on VD30 for Tangents by Actual Experiments Considering Design Speed with Other Explanatory Variables

VD30 = PEINVR*PEDEL S*PETD
Response Distribution: Normal
Link Function: Log

Parameter Information		
Parameter	Variable	PETD
1	Intercept	
2	PEINVR*PEDEL	
3	S*PETD	L
4		R

Model Equation									
Log (VD30)	=	-	1.1978	+	1.1064 P 2	+	0.0051 P 3	+	0.0055 P 4

Summary of Fit					
Mean of Response	0.5234	Deviance	31.6535	Pearson ChiSq	31.6535
SCALE (MLE)	0.2153	Deviance / DF	0.0466	Pearson ChiSq / DF	0.0466

Analysis of Deviance			
Source	DF	Deviance	Deviance / DF
Model	3	2.1128	0.7043
Error	679	31.6535	0.0466
C Total	682	33.7664	

Type III (Wald) Tests			
Source	DF	ChiSq	Pr > ChiSq
PEINVR*PEDEL	1	31.2530	<.0001
S*PETD	2	27.5810	<.0001

Parameter Estimates						
Variable	PETD	DF	Estimate	Std Error	ChiSq	Pr > ChiSq
Intercept		1	-1.1978	0.1030	135.1690	<.0001
PEINVR*PEDEL		1	1.1064	0.1979	31.2530	<.0001
S*PETD	L	1	0.0051	0.0011	19.9010	<.0001
	R	1	0.0055	0.0011	26.4812	<.0001