Potential of Driver Physiological Measures for Assessing Non-Urban Highway Geometry

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ABSTRACT

Life is a complex phenomenon, mostly controlled by sympathetic and parasympathetic systems. And it is quite dynamic in response to numerous stimulations getting from a system called, human-vehicle-environmental ensemble. Geometry is one of the fundamental stimulus for a driver driving on a highway. His/her mental workload will be based on the input he/she gets from the above system. A system that provides an optimum workload will be the most efficient one. This study explored the capability of different physiological measures to assess the quality of geometric design of non-urban highways. Heart rate, galvanic skin resistance and rate of eye blinking and their variance from base condition were the candidate measures under consideration. Radius of curve, length of curve, length of tangent section, superelevation at curves, degree of curvature, deflection angle and minimum available sight distance at curves were the geometric variables considered. The study included driving experiments done on 114 horizontal curves of gradient less than 2 percentage, each curve being driven over by 30 car drivers. The subjects were equipped with sensors for collecting physiological measures and continuous logging of the data along with geometric coordinates made the database for study. The study revealed the relationship between significant geometric variables and workload measures. The study will be a contribution in the field of road safety auditing, planning and designing of non-urban highways.

Keywords: Geometric design consistency, heart rate, galvanic skin resistance, rate of eye blinking, driver workload.

1 Introduction

Life is a complex phenomenon, mostly controlled by sympathetic and parasympathetic nervous systems. And it is quite dynamic in response to numerous stimulations getting from a system called, human-vehicle-environmental ensemble. Geometry of the road is one of the fundamental stimulus for a driver who drives along a highway. Along with the above factor, the conditions of vehicle and driver himself will be controlling the driver expectations of the roadway ahead. His/her mental workload will be based on the input he/she gets from the above system. Workload will be an optimum as and when the variations between what a driver observes in the field and what he expects is less. When an inconsistency exists, which violates driver's expectation, driver may adopt erroneous driving manoeuvre and this may result in road crashes (Messer et al. 1981, Kannellaidis 1996). Many studies have reported that accident rate is more on sections where geometry

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deviates from the straight alignment. For example, horizontal curvature is mostly identified as location of high crash potential (Glennon 1987, Zegeer et al. 1992, KTC 2005).

To eliminate these inconsistencies researchers have been working on developing several tools and strategies. Different methods have been developed to measure and evaluate the consistency of highway alignment (Fitzpatrick et al. 2000) viz., operating speed based evaluation, vehicle stability based evaluation, alignment index method and driver workload method. Among these methods, Driver workload based method is the one which directly takes into account the effect of geometry and its consistency on drivers.

The objective of this paper is to understand the effect of two-lane non-urban highway geometry on driver workload under Indian scenario. Specific objectives can be listed as given below:

- To determine whether physical characteristics of a driver influences workload
- To identify the variables that influences workload on two lane non-urban highway
- To quantify the effect of the identified variables on workload and
- To check if driver physiological measures are potential candidates to assess geometry of non-urban highway

Scope of this work is limited to workload of car drivers.

2 Literature Review on driver workload

A driver driving through a highway is more or less continuously processing visual and kinaesthetic information, making decisions, and carrying out control movements. This forms the basis for driver workload method of evaluating highway geometry. Driver workload method of rating consistency is based on driver performance on highway alignment. It also considers other aspects that affect driver anticipations such as highway aesthetics and interchange design. Workload has been defined as "a measure of the 'effort' expended by a human operator while performing a task, independently of the performance of the task itself" (Senders 1970). It is the time rate at which drivers must perform a given amount of driving tasks that increases with the increase of the complexity in highway geometric features (Messer 1980). Locations with high workload or large positive change in workload were found to be associated with high accident rates (Wooldridge 1994). But it is found difficult to capture or observe the change in driver mental workload. Moreover, compared to other consistency measures, this measure is much more complex. Thus, it is generally recommended to avoid highway sections that have very low or very high driver workload to avoid drivers becoming bored or tired and to avoid conditions causing driver confusion, misinterpretation of an unexpected development, or inappropriate response.

A methodology for evaluating and improving design consistency of two-lane rural highways, based on driver workload, has been established by Messer (Messer et al. 1979; Messer 1980). A subjective rating scale (from 1 to 6) was suggested to estimate an average workload value (Rf) on general individual geometric features by a group of highway experts. The features include presence of bridges and intersections, changes in lane and shoulder width and type of alignment. A level tangent section is taken as the control feature. Then, a regression model was established to estimate the expected workload value (measured on the same scale) on a specific feature on a road section as follows:

$$\mathrm{WL_n} = (\mathrm{U} \times \mathrm{E} \times \mathrm{S} \times \mathrm{R_f}) + (\mathrm{C} \times \mathrm{WL_l}) \qquad \text{Eqn. 1}$$

Where: $\mathrm{WL_n}$ = expected workload value for the specific feature;

U = driver unfamiliarity factor (depends on highway classification and location);

E = feature expectancy factor (E = C - 1 if the feature is similar to the previous one, otherwise E = 1);

S = sight distance factor (which depends on the available sight distance to the feature);

R_f = average workload potential value for the general feature;

C = carryover factor (which depends on the separation distance between features); and WL_l = workload value of the previous feature.

The model is based on the presumption that the roadway itself provides most of the information that the driver uses to control the vehicle and hence, the roadway imposes a workload on the driver.

Wooldridge et al. (2000) applied visual occlusion technique for measuring driver workload. Generally, little visual information processing capacity is required for an experienced driver to perform the driving task. Consistent roadway geometry allows a driver to accurately predict the correct path while using minimal visual information processing capacity, thus allowing attention or capacity to be dedicated to obstacle avoidance and navigation. Wooldridge et al. (2000) measured a driver's visual demand on horizontal curves as a percentage of time a driver observes the roadway. Analytical models that relate visual demand to the inverse of the horizontal curve radius, R were developed using data collected from a test track, local road and simulator. Models were developed for unfamiliar and familiar drivers.

$$VDLU = 0.173 + 43.0/R \qquad \text{Eqn. 2}$$

$$VDLF = 0.198 + 29.2/R \qquad \text{Eqn. 3}$$

Where, VDLU = visual demand of unfamiliar drivers (first run)

VDLF = visual demand of familiar drivers (later runs)

A review of literature showed that driver workload is an important parameter in evaluating design consistency. Many researchers have identified several critical factors that influence the workload of the drivers in a highway. Interestingly, no uniformity has been found in the variables used, model form and model parameters. This may be due to the differences in driver, vehicle, road, culture and socio-environmental characteristics which are mostly location specific. This warrants the development of consistency models that are specifically suitable for Indian conditions.

3 Methodology

Driver expectancy is the "driver's readiness to respond to situations, events, and information in predictable and successful ways". Among the two forms of expectancy – priori and ad hoc expectancies, priori expectancies are formed based on the driver's long term exposure to driving task. This research focuses on ad hoc expectancies which are short term in nature. These are formed during a particular trip at a particular section. To eliminate the effect of long term expectancies, a base line data is collected. Variation of the driver workload from the base line data is what the subject point of analysis. Abrupt increase in driver workload increases the probability of crash. A successful highway design would make a driver's mental workload level to an optimum so that neither he/she becomes drowsy nor he would not exceed his processing capacities.

3.1 Study stretches

Study stretches were selected from two lane non-urban state highways of Kerala with low to medium traffic volume condition (SH 39, SH 50 and SH 74). Other criteria are listed below:

- No stop-controlled or signalized intersections nearby.
- No influence of other adjacent sections.

- No physical features or activities adjacent to, or in the course of the roadway that may create an abnormal hazard such as narrow bridges, schools, factories, or recreational parks.
- Not located close to towns or built up areas that may significantly affect the driver travel patterns on the curves
- Presence of adequate tangent length on a flat terrain prior to the section of horizontal curve.
- Condition of pavement has to be good. As the driver data collection could be completed after the repair work on road sections were over, this criterion could be ensured.

Sites with these characteristics were selected to identify the curves and to ensure that only the geometric characteristics of the curves influence the driver workload.

3.2 Sample size

The sample size of horizontal curves with adequate preceding tangent length is 114. A total of 93 drives were done ensuring a minimum of 30 drives in each curve. Drivers were so selected that they are not familiar with the selected study stretches.

3.3 Geometric Data

Details of curve geometry retrieved through geometric data collection are radius of curvature (R), length of horizontal curve (LH), degree of curvature (DC), deflection angle (DA), superelevation (e), sight distance (SD) and length of preceding tangent (PTL). Summary statistics of the geometric data is given in Table 1.

Table 1. Summary statistics of geometric data

Geometric Feature	**Min**	**Max**	**Mean**	**Std. Dev.**	**Skewness**	**Kurtosis**
Radius of curvature (m)	18.33	899.66	219.83	173.49	2.05	4.92
Length of horizontal curve (m)	15.39	109.68	52.56	20.46	0.59	-0.20
Deflection angle (deg)	5.00	63.00	18.88	11.70	1.59	2.68
Width of road (m)	4.93	13.90	6.82	1.01	3.10	20.10
Superelevation (%)	-0.93	8.10	2.90	2.13	0.37	-0.48
Preceding tangent length (m)	50	684	165.91	87.54	2.36	10.09
Shoulder width (m)	0	8.30	2.33	1.58	1.39	3.07
Sight distance (m)	10.80	57.50	30.45	12.57	0.18	-1.16

3.4 Driver Physical Characteristic Data

Physical characteristics of drivers like reaction time, peripheral vision, depth perception, and vision acuity were determined for all drivers by conducting laboratory experiments. Reaction time is measured using experimental set up of signal detection theory. Peripheral vision is measured in degrees based on recognition of any well-defined object in the field of vision without the need for focusing. Depth perception experiment was done using a depth scale, and vision acuity is measured using Snellen standardized chart. These are used to determine if any significant correlation exist between driver physical characteristics and their workload. Summary statistics of the physical characteristics is given in Table 2.

Table 2. Summary statistics of driver characteristics

Statistic	Age	Experience	Vision acuity	Reaction time (milli seconds)	Depth perception (cm)	Peripheral vision (deg)
Min	21	2	0.8	468	-5.6	164
Max	61	41	1.54	870.5	5	201
Average	34.54	11.89	1.28	610	-0.18	182
Std. dev	10.98	9.02	0.26	91.05	1.39	7.76

3.5 Fabrication of Road Driver Data Acquisition System

`A system for acquiring driver workload was fabricated in-house. Both the hardware and software components were designed and integrated to form a handy module as shown in Figure 2.

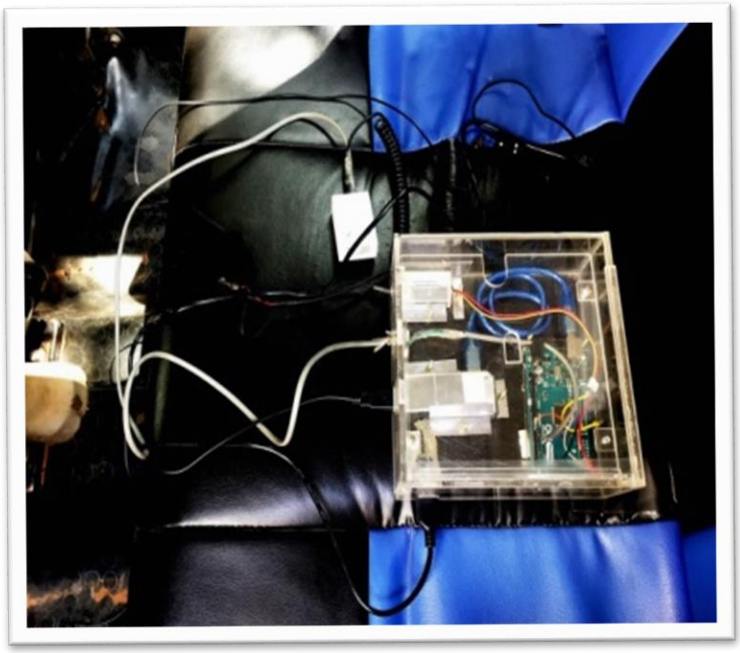
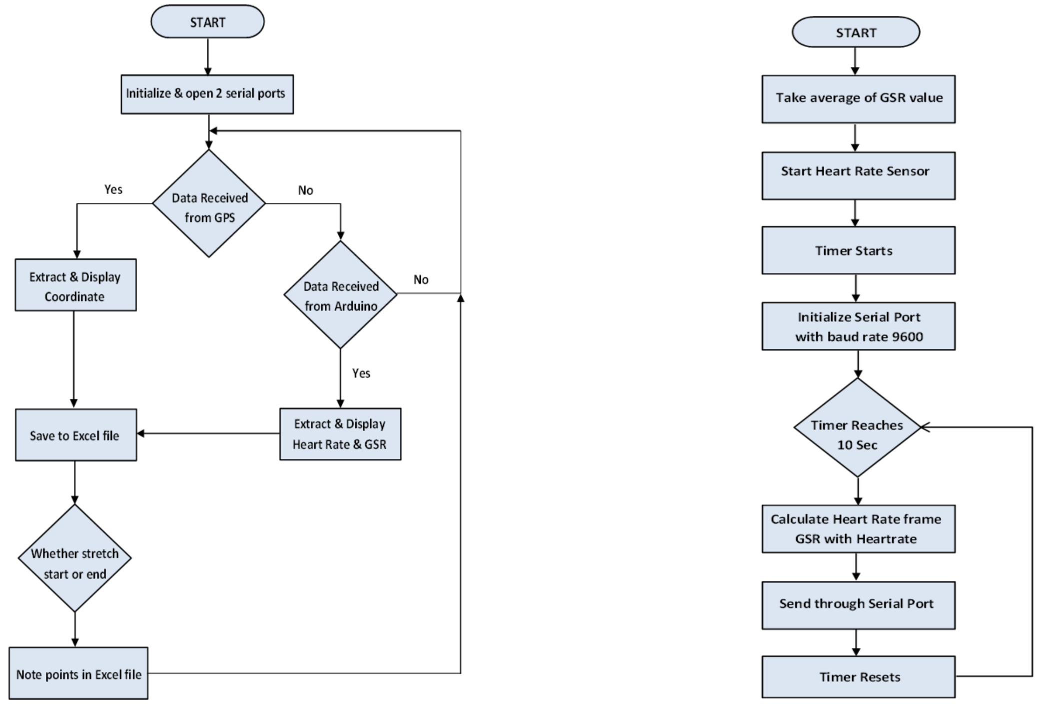


Figure 2. Road Driver Data Acquisition System (RDDAS)

The hardware of the module consists of GPS unit, two web camera – one for collecting driver eye blinking and another for collecting the road environment, a galvanic skin response (GSR) sensor for sensing the skin resistance and heart rate (HR) sensor for sensing the heart rate of driver. GPS unit is provided with a patch antenna mounted on the top of vehicle, Camera mounted to wind shield of the car, GSR sensor attached to fingers of the driver and HR sensor attached to the ear lobe of driver.

The main processor for the RDDS hardware is Arduino Mega Board which contains an ATmega2560 microcontroller. GSR connected to its analog input and Heart rate is connected to its hardware interrupt. GSR sensor takes reading and set a threshold value. A timer is to be started to calculate the heart rate. Heart rate sensor will provide the pulses to interrupt pin. A counter will increment with the pulse and when the timer reaches 10 seconds it will take current reading and calculate heart rate. Arduino mega will send these values by combining with necessary delimiter to the computing system. The algorithms for RDDAS software and hardware are given in Figure 3.



(a) (b)

Figure 3. Algorithms for (a) RDDAS software and (b) hardware

3.6 Driver Workload Data Collection

Each driver wearing RDDAS sensors was asked to drive along the stretch in a GPS mounted car. After the setup is done on the vehicle and driver, the driver is given a rest period of about ten minutes in order to record his/her normal workload. Subsequently, he/she will be driving along a ten kilometer stretch from the origin to the reach the study stretch. Even though the driver is unaware of the study locations, this drive will help him or her to get familiarize with the vehicle and the RDDAS. During the drive, workload data is collected continuously along with GPS coordinates. The program developed in the study makes it possible to tag the information regarding start and end of each isolated horizontal curve along the route. This helps to quantify the workload data corresponding to each curve. The output data include, an excel sheet showing GPS and workload data and the video footage of driver and road are saved into the laptop with the date and name of the driver.

3.6.1 Candidate Workload Measures

Following are the candidate measures for workload selected in the study.

1. Absolute HR (HR)
2. Deviation of HR (DHR)
3. Absolute GSR (GSR)
4. Deviation of GSR (DGSR)
5. Absolute rate of eye blinking (EB)
6. Deviation of rate of eye blinking (DEB)

Two types of measures were considered for the study – one is absolute value of workload (HR, GSR, EB) and the other is the deviation of the workload measure from the control workload value (DHR, DGSR, DEB).

For each of the above measures, average value, 50th percentile value and 85th percentile value were considered for analysis making altogether 18 candidate measures for study.

4 Data Analysis

4.1 ANOVA test on driver characteristics

One way ANOVA was done to test whether workload measures significantly varies with changes in the driver characteristics. Table 3 shows the results.

Table 3. Results of ANOVA done on car driver characteristics

Driver Characteristics	**HR**			**DHR**		
Hypothesis	**H_0**	**H_1**	**Accepted**	**H_0**	**H_1**	**Accepted**
Age	90	10	H_0	100	0	H_0
Experience	88	12	H_0	90	10	H_0
Occupation	88	12	H_0	100	0	H_0
Reaction Time	93	7	H_0	91	9	H_0
	GSR			**DGSR**		
Hypothesis	**H_0**	**H_1**	**Accepted**	**H_0**	**H_1**	**Accepted**
Age	60	40	H_0	82	18	H_0
Experience	85	15	H_0	90	10	H_0
Occupation	80	20	H_0	85	15	H_0
Reaction Time	100	0	H_0	90	10	H_0
	EB			**DEB**		
Hypothesis	**H_0**	**H_1**	**Accepted**	**H_0**	**H_1**	**Accepted**
Age	93	7	H_0	92	8	H_0
Experience	95	5	H_0	100	0	H_0
Occupation	100	0	H_0	98	2	H_0
Reaction Time	100	0	H_0	94	6	H_0

Results show that workload measures such as heart rate, skin resistance and eye blinking rate are not significantly varying with respect to age of driver, experience, occupation and reaction time. Hence, no segmentation of data based on driver characteristics is needed in further analysis.

4.2 Correlation Analysis

For each of the above workload measures, average, 85th and 50th percentile values were calculated for each curve. A correlation study was then conducted against traffic volume and the geometric variables viz., radius of curvature, curve length, deflection angle, width of the road, superelevation, tangent length, shoulder width and absolute minimum sight distance available at site to explore the existence of any linear correlation between variables. Results of correlation study are presented in Table 4.

Table 4. Summary of Correlation study for different workload variables

Dependent Variable	Traffic Volume (ADT)	Radius of curve (m)	Curve length (m)	Deflection angle (deg)	Width of road (m)	Superelevation (m)	Tangent length (m)	Shoulder width (m)	Sight distance (m)
AVG HR	-0.13	0.12	0.12	0.08	0.01	0.06	0.09	0.31	0.49
85th HR	-0.07	0.13	0.16	0.12	0.02	0.09	0.10	0.27	0.61
50th HR	-0.08	0.14	0.14	0.05	-0.01	0.05	0.10	0.21	0.46
AVG DHR	-0.19	0.04	0.09	0.13	0.10	0.05	0.04	0.20	0.34
85th DHR	-0.11	0.09	0.10	0.14	0.18	0.12	0.05	0.25	0.38
50th DHR	-0.20	-0.01	0.05	0.18	0.09	0.07	-0.02	0.22	0.37
AVG GSR	0.11	-0.08	-0.27	-0.07	0.18	-0.10	-0.14	-0.30	-0.71
85th GSR	0.19	-0.07	-0.23	0.01	0.20	0.04	-0.27	-0.21	-0.56
50th GSR	0.03	-0.06	-0.20	-0.02	0.18	-0.05	-0.09	-0.24	-0.46
AVG DGSR	0.14	-0.09	-0.32	0.01	0.31	-0.07	-0.10	-0.27	-0.54
85th DGSR	0.09	-0.05	-0.01	0.11	0.17	0.04	0.11	0.17	0.02
50th DGSR	0.16	-0.03	-0.27	-0.04	0.23	-0.10	-0.08	-0.24	-0.52
AVG EB	-0.05	0.06	-0.21	-0.28	-0.14	-0.15	-0.02	0.03	-0.05
85th EB	-0.01	0.06	-0.11	-0.18	-0.09	-0.11	0.01	-0.02	-0.06
50th EB	-0.03	0.04	-0.02	-0.09	0.00	-0.14	0.02	-0.06	-0.02
AVG DEB	0.04	0.27	0.04	-0.21	0.06	-0.18	-0.06	-0.12	-0.12
85th DEB	-0.01	0.18	-0.07	-0.22	-0.07	-0.12	0.02	0.00	0.00
50th DEB	0.09	0.22	0.00	-0.20	0.07	-0.13	-0.09	-0.11	-0.17

The correlation coefficients show that shoulder width and sight distance are the two variables which have linear correlation with HR, DHR, GSR and DGSR of car drives. EB and DEB do not show any significant correlation with traffic volume or geometry.

4.3 Scatter plot analysis

Scatter plot study was done for each of the candidate measure with respect to traffic volume and geometric variables. Figure 4 to 6 show typical plots for heart rate and GSR with sight distance and shoulder width respectively.

Figure 4 shows the trend of absolute heart rate as well as deviation of heart rate with respect to sight distance. The trend shows an increase in heart rate/deviation of heart rate with increase in sight distance. This is as per the expectation that with more visual input, heart rate increases as proven by medical records (Darrow 1929, Lacey 1959 and Obrits1963). Figure 5 shows the trend of variation of heart rate/deviation of heart rate with shoulder width.

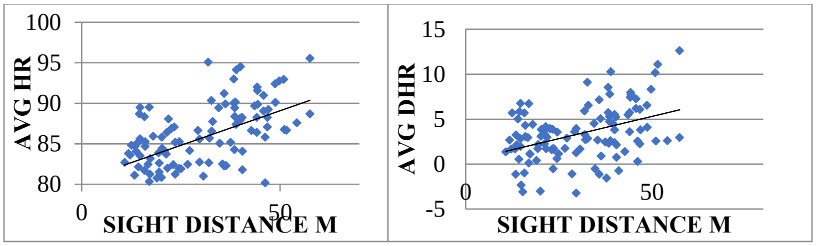


Figure 4 HR vs. Sight Distance

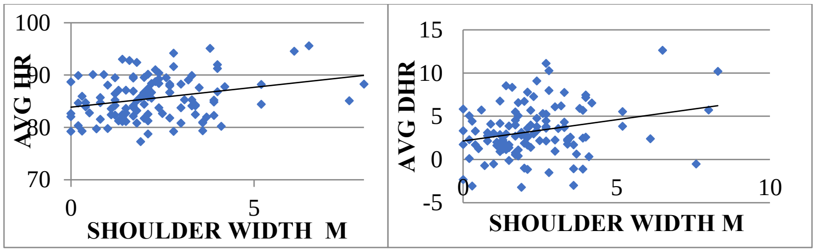


Figure 5 HR vs. Shoulder Width

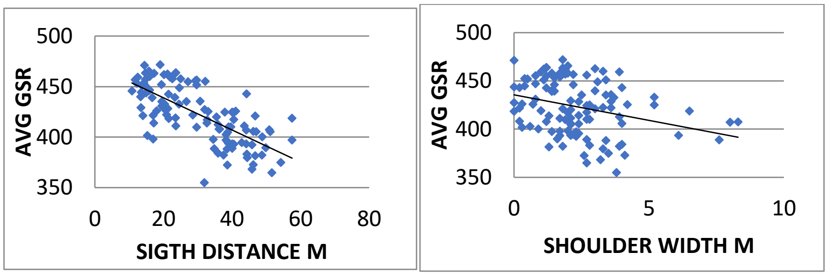


Figure 6 GSR variation with Sight distance and Shoulder Width

Figure 6 shows the variation of GSR with sight distance and shoulder width. With increase in sensory input, workload increases which increases the sweating of body and thereby decreases the skin resistance.

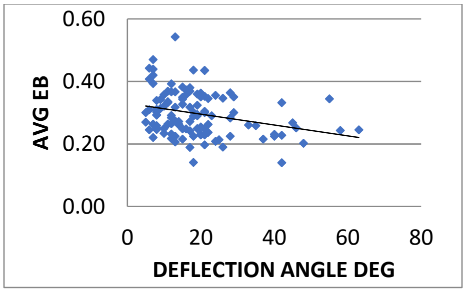


Figure 7. Variation of eye blinking rate with Deflection angle

Figure 7 shows how the rate of blinking of eye decreases with increase in deflection angle. As the deflection angle increases, the curve becomes sharper and driver is more likely to stare on to the curve section to gather minimum input required for safe maneuver.

A few of the major observations based on scatter plot study are listed below:

1. Heteroscadasticity of workload measures decreases or stabilises when radius of curve becomes flatter.

2. Radius, curve length, deflection angle, shoulder width and minimum sight distance available at curves are found to be correlated to heart rate, galvanic skin resistance or rate of eye blinking either directly or based on their deviation from normal values.
3. The average GSR increases with increase in curve length and shoulder width, reaches a maximum and then decreases. It shows that workload decreases, reaches a minimum and then increases.
4. With increase in traffic volume, average GSR is found to decrease showing an increase in driver workload.

4.4 Model Development

The scatter plot analysis underline the fact that there is good correlation between workload and geometry, but, in many cases, there is a lot of dispersion in the workload data. To better understand the effect of geometry on workload, it was decided to go for an interval estimate of workload data. Such a study is found to be more reasonable than a point estimate output. The best models are given in Table 5. Graphical representations of the models are given in Figure 8.

Table 5. Regression models for workload measures

Workload measure	Model	Value of X	R^2	RMSE	Skewness of residuals	Kurtosis of residuals
HR	81.34+1.612X	X=1 for SD<20 X=2 for 20<SD<30 X=3 for 30<SD<40 X=4 for 40<SD<50	0.83	3.64	-0.05	0.78
GSR	464.7-16.9X	X=1 for SD<20 X=2 for 20<SD<30 X=3 for 30<SD<40 X=4 for 40<SD<50	0.87	19.99	0.20	0.06
DGSR	-37.69-7.526X	X=1 for SD<20 X=2 for 20<SD<30 X=3 for 30<SD<40 X=4 for 40<SD<50	0.85	13.07	0.38	0.59

4.4.1 Check for the normality of residuals to appreciate the regression analysis

Table 5 summarises the skewness and kurtosis of the geometric data. They are the measures for checking the normality of distribution. Skewness is a measure of the asymmetry of the probability distribution of a random variable about its mean.

- If skewness is less than -1 or greater than 1, the distribution is highly skewed.
- If skewness is between -1 and -0.5 or between 0.5 and 1, the distribution is moderately skewed.
- If skewness is between -0.5 and 0.5, the distribution is approximately symmetric or normal.

Kurtosis gives an idea of the height and sharpness of the central peak, relative to that of a standard normal curve. A value of 3 is the perfect normal curve. A range of + or – 2 is accepted as approximately normal (Gravetter & Wallnau, 2014). Hence, the regression analysis that was conducted holds good.

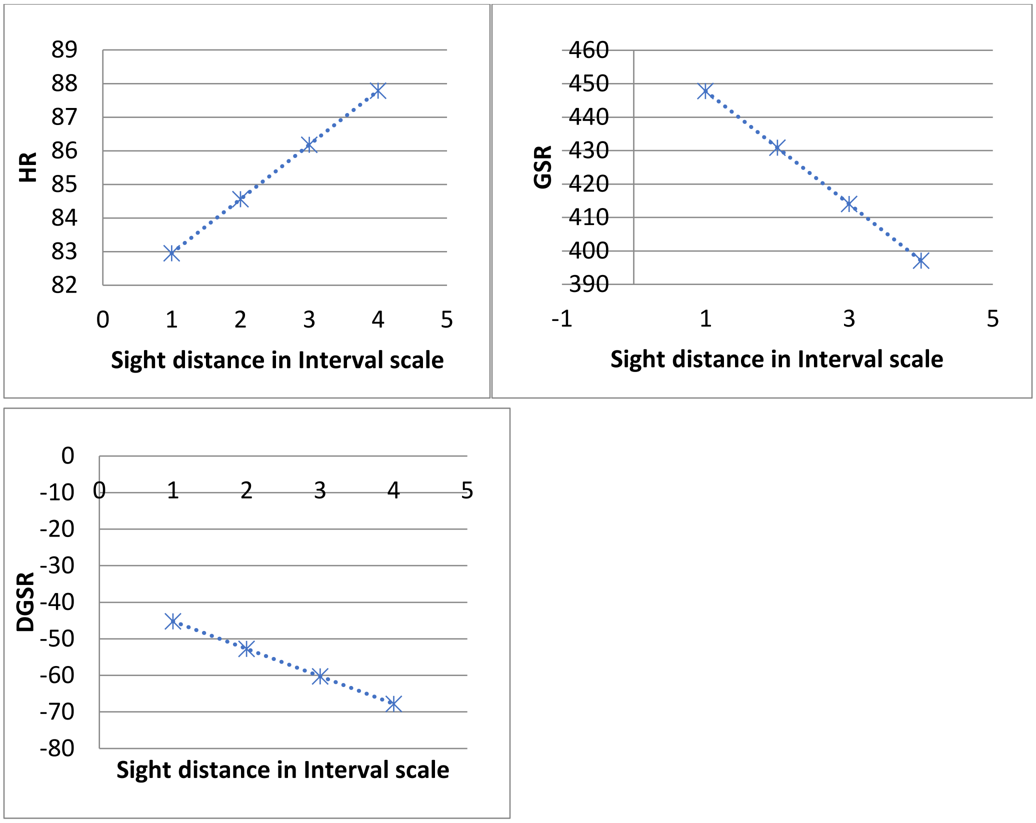


Figure 8. Graphical representations of workload models

5 Conclusion and Scope for Future Work

The preliminary studies like correlation and scatterplot analysis revealed that geometric variables definitely have significant influence on driver physiological measures. Potential of these measures can be utilized to evaluate consistency of geometric design in two lane non-urban highways. Sight distance is found to be one of the most significant variable that influences driver workload and hence, regression models were developed to predict HR, GSR and DGSR based on sight distance. The study gives promising results regarding the potential of driver physiological measures on workload measurements. It is found worth to explore further on workload based method of design consistency to develop criteria for evaluating the highways which is the scope for future work in this field of study.

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