Effect of Two Lane Non-Urban Highway Geometry on Workload Profile of Drivers

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ABSTRACT

Transportation engineers play an important role to achieve zero- crash vision of the Government. The onus for occurrence of road crashes at under-designed and poorly constructed roads lies on the shoulders of transportation engineers. To ensure safe and comfortable driving, it is essential and necessary to evaluate the geometric design of roads, especially highways, from the perspective of the vehicle drivers. If the road is of consistent design, the driver can achieve smooth and safe driving. Inconsistent design of roads can confuse a driver and it may lead to unnecessary speed changes and even may result in unfavourable level of crashes. This paper attempts to study how the highway geometry affects the driver workload at horizontal curves and curves with gradient on two lane non-urban highways. The driver workload is assessed by measuring variations in physiological conditions of subject driver while driving in a test car under real field conditions. Heart rate (HR) and galvanic skin response (GSR) of drivers are continuously recorded using sensors attached to the driver's ear and fingers respectively to develop a continuous profile of driver workload at varying highway geometry. The variations in heart rate from tangent sections to succeeding curve sections are determined to understand the effect of curve geometry on heart rate. The geometrical data such as radius of curvature, superelevation, sight distance, gradient and tangent length are collected from the selected study stretches. The study revealed that the inconsistent design of roads leads to large variations in heart rate and galvanic skin response. Consequently, crash frequency is found to be higher at such locations. The outcome of the study will help highway designers to design safer roads. The outcome of the study throws light on safety evaluation of highway geometry and will be helpful in developing tools and guidelines for designing safer roads.

Keywords: - Heart rate, Galvanic skin response, Design consistency, Workload profile, Crash frequency

1 INTRODUCTION

Safety on roads is a growing concern as road crashes cause social and economic losses to the society. The number of fatal crashes and injuries relative to population goes on increasing in India, even if there is a declination in total number of crashes (based on data 1970 to 2016). As per National data, average length of Indian highways is only 4.88% of total road network, still highways contribute 53.16% of total road crashes (based on data 2013-14,2014-15,2015-16). Moreover, the report on Road Crashes in India-2017shows that 57.9% of crashes occur on rural areas which includes most of the National and State Highways. The data for 2017 has shown that 54077 crashes (11.6%) occurred on curved roads (2505 curve crashes in Kerala).It is also

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reported that young adults in the age group of 25-45 accounted for 48.9% of total road crash fatalities. Traffic safety on highways underlines the need for maintaining consistency in the geometric design of highways. The probability occurrence of driving perception errors increases as the complexity of the road alignment increases. It is therefore important to study how the curve geometry affects the driver behavior. The geometry of the curve is defined by many factors like super elevation, grade, length of curve, radius of curve, width of road, deflection angle, tangent length, curvature etc. Other than the geometry of curve, crashes are also influenced by traffic volume, friction and other psychological characteristics of the driver. Objective of this paper is to illustrate how the driver workload variables (HR and GSR) varies with variation in highway geometry.

2 LITERATURE REVIEW

The measures for evaluating Geometric consistency of highway are based on: operating speed, alignment indices, vehicle stability and driver workload (Gibreel, et al., 1999). Among the measures, driver workload evaluate safety from the viewpoint of driver's performance. Workload measurement techniques can be classified into three (Moray 1979, Green P. et al. 1993, Miller 2001) - Physiological measures, Self-evaluated subjective measures (Hart and Staveland, 1988) and Performance or behavioural measures.

Hicks and Wierwille (1979) performed a study to compare five methods of empirically measuring the mental workload of driving. Five methods of assessing workload were primary task performance, secondary task performance, visual occlusion, cardiac arrhythmia, and subjective opinion rating scales. Each was used to categorize among low, medium, and high levels of workload defined in terms of the geometric point of application of crosswind gusts in a driving task. The visual occlusion device which was developed by Senders replaced with the spectacle of liquid crystal display to determine visual demand. Study results showed that the techniques primary task performance and subjective opinion rating scale yielded a significant difference among workload levels. Authors recommended that occlusion, heart rate variability, and secondary task performance might have shown a significant workload effect if a real-car-roadway situation had been used.

A study by Messer et al. (1980) presented a methodology for evaluating and improving design consistency of proposed or existing two-lane and four-lane rural highways in flat or rolling terrain based on workload. He defined workload as the time rate at which drivers must perform a given amount of work or driving tasks. He also explained the geometrical inconsistency in the rural highway as a geometric feature or combination of adjacent features that have such unexpectedly high driver workload that motorists may be surprised and possibly drive in an unsafe manner. Seven point rating scale was developed to (no problem-0 to big problem-6) to identify hazardous locations based on driver expectancy considerations.

In 1989, Hulse et al. proposed an overall objective rating model to quantify driver workload. His model takes into account the sight distance, degree of curvature, road width and lane restriction. Overall objective regressions models were developed and results showed that sight distance was the most significant parameter, followed by road width and distance to the closest obstruction. Green et al. (1994) assessed driver performance as a function of road geometry and found that standard deviation of the lateral position increases with road width. The study suggested that the lateral variance could not be used to assess workload across road widths. Studies also proposed that the greater sight distance results in less lateral variation since drivers have more time to plan manoeuvres. Heger (1998) conducted the study under real field conditions on existing road and traffic conditions to measure the mental workload associated with opposing travel, curvature change rate of the single curve and crash data. Speeds, driving dynamic characteristics such as lateral acceleration, and psychophysiological data such as cardiac, electrodermal and electromyographic responses were jointly assessed using a computerized measurement system in an instrumented car. Video techniques were used to analyze roadway and roadside environment. The test results indicated that the mental workload demand of the drivers was 20% of available mental workload capacity on the tangents. Driver workload was increased on curves with high curvature change rate and decreased with road width. The study revealed that the most psychophysiological parameters reached their maximum value after passing the inconsistent design feature. Subjective ratings of inconsistent features validated the psychophysiological data. He suggested that the study can be extended to evaluate critical sight distance of vertical curves.

Cafiso et al. (2005) used a Driver Instrumented Vehicle Acquisition System for collecting data under real traffic conditions on the existing two-lane rural roads. It consisted of Global Positioning System (GPS), optical odometer, inertial gyroscope, triaxial accelerometer, web camera and a Varioport system that permitted the collection of many psychophysiological measures such as an electrocardiogram (ECG), electrooculogram (EOG), electrodermal activity (EDA), and electromyography (EMG). The study confirmed that an isolated curve following a long tangent caused higher workload than a coordinated sequence of curves. Similarly, it was observed that the lack of transition curves is a cause of inconsistency. Inconsistent designs were compared and evaluated as good, fair and poor based on operating speed and lateral friction. Kang et al. (2018) conducted Structural Equation Modelling (SEM) to examine the influence of road geometry on driving behaviour and vehicle manoeuvrability. Driving workload was recorded by EEG for four areas of the brain; the frontal lobe (self-awareness and judgment center), temporal lobe (auditory center), parietal lobe(somatosensory center), and occipital lobe (visual center).It was observed that four lobes had the same trend of workload. The result showed that the workload on the curve was higher than that on straight sections.

Anitha et al. (2018) conducted a study to find the influence of geometry on driver workload on two-lane rural highway. Galvanic skin response, heart rate, and eye blink rate were recorded using Road Driver Data Acquisition System. (RDDAS).This equipment consisted of ear attached heart rate sensor, galvanic skin sensor attached to the palm of the hand, GPS, two video cameras to record road environment and driver movements. Correlation study showed that the effect of the radius was negatively correlated with heart rate. Deflection angle was negatively correlated with Galvanic skin response and eye blink. An increase in workload was found on horizontal alignments with a small radius and higher deflection.

3 data collection

18 km stretch of two-lane non-urban State Highway (Vazhakode - Pazhayannur route - SH 74) of Kerala was selected for this study. This stretch is of rolling terrain which consists of 20 horizontal curves and 15 combined curves. There were 9 positive gradient and 6 negative gradient curves. The curves were selected in such a way that the driver workload was not influenced by external factors other than highway geometry. The curves nearer to the intersections, towns etc. were avoided for this purpose. The following data was collected to study the effect of geometry on driver's physiological condition.

3.1 Geometrical data

The geometrical data of the curves such as radius of curve, curve length, deflection angle, width of road and superelevation were collected using Total Station survey and tangent length was measured using rodometer. The gradient of combined curve was also calculated using Total station data. Table 1 gives the descriptive statistics of horizontal curves.

Table 1. Descriptive statistics of horizontal curves

Curve Geometry /Statistics	Radius of Curve (m)	Curve length (m)	Deflection Angle (Deg)	Width of the road (m)	Superelevation (%)	Tangent Length(m)
Mean	241.11	47.37	15.59	7.03	2.46	137.91
Standard Deviation	34.24	3.15	1.46	0.06	0.34	9.23
Kurtosis	2.71	-0.72	4.10	-0.14	0.18	-0.95
Skewness	1.72	0.57	1.83	0.30	0.66	0.46
Minimum	29.21	18.38	5.00	6.47	0.09	50.00
Maximum	829.45	84.57	42.00	7.80	8.10	240.00

It is clear from the Table 1 that except for deflection angle, all other variables are platykurtic. Sample distributions of tangent length and width are fairly symmetrical and that of radius of curve and deflection angle are highly skewed. All other variables are moderately skewed. It is also clear that all the variables are positively skewed. That means most of the curve data is less than the mean value. Large variation between the minimum and the maximum values show the range of geometry within 20 km distance.

Table 2. Descriptive statistics of horizontal curves with gradients (combined curves)

Curve Geometry/ Statistics	Radius of Curve (m)	Curve length (m)	Deflection Angle (Deg)	Width of the road (m)	Superelevation (%)	Tangent Length(m)	Gradient (%)
Mean	126.38	57.4	39.93	7.28	0.05	136.47	1.15
Standard Deviation	88.81	38.21	19.43	0.53	0.03	84.41	4.47
Kurtosis	1.72	7.84	-1.12	0.51	2.37	7.07	-1.54
Skewness	1.16	2.63	0.57	0.72	1.48	2.24	-0.22
Minimum	29.91	22.58	18	6.45	0.01	38	-5
Maximum	355.04	179.03	74	8.49	0.14	400	8.25

From Table 2, it can be understood that all variables are positively skewed. Except curve length and tangent length, all other variables are platykurtic. Like in horizontal curve data, large variation exists in the geometrical data of combined curve also.

3.2 Crash data

Crash data for the past three consecutive years (2016-2018) occurred along these curves were collected from police stations. The crash data collected includes minor, major, fatal and property damage only crashes. Crash frequency were observed to be more on combined curves compared to horizontal curves. It is mainly due to the presence of gradients.

3.3 Driver workload

Driver workload data was collected under free flow conditions during off-peak hours. Physiological measurements of twenty nine car drivers were recorded while they drive along the selected study stretch in a test car. Physiological measures include Heart Rate (HR) and Galvanic Skin Response (GSR). HR and GSR were recorded using sensors attached to earlobe and fingers of the driver, respectively. HR and GSR values thus recorded continuously by both the sensors give output values to a connected laptop. GPS was also connected to record GPS coordinates and the driving speed. The drivers are allowed a buffer time to adjust to the sensor attachments on their body prior to the actual ride on the stretch. Workload was taken as the variation of HR or GSR values between successive elements say, tangent and subsequent curve, for each driver. The average for all drivers, were then calculated. If the variation is more, the workload is more and vice versa. GSR sensors measures the skin conductance which varies with human body sweating. Lower GSR measured value indicates more conductance ie more sweating which shows more workload.

4 DATA ANALYSIS

4.1 Correlation Analysis

Table 3 shows the correlation between geometry and workload variables. From the table, it is clear that radius of curvature, degree of curvature and deflection angle are highly correlated with HR and GSR.

Table 3. Correlation coefficients between Curve Geometry and driver workload

Curve Geometry/Workload	Horizontal curve		Combined Curve	
	HR	GSR	HR	GSR
Radius of Curve (m)	0.252	0.325	-0.181	-0.418
Degree of curvature	0.190	0.248	0.250	0.481
Deflection Angle (Deg)	0.225	0.241	0.480	0.158
Width of the road (m)	0.247	0.557	0.393	0.186
Superelevation	-0.074	-0.192	0.157	0.179
Gradient	-	-	-0.199	-0.239

4.2 Development of driver workload profile

Geometrical parameters, starting and ending chainage of curve, HR and GSR variation between preceding tangent and curve of identified curves in selected study stretch is given in table 4. Driver workload profiles for HR and GSR variation were plotted against the identified significant geometrical variables such as radius of curve, degree of curvature and deflection angle as shown in Figure 1.

Table 4. Geometrical parameters and workload variation of identified curves in study area
(H-Horizontal curve, H.NG-Horizontal curve with negative gradient, H.PG- Horizontal curve with positive gradient)

Cur ve No.	Curve ID	Chainage of point of curvature (m)	Chainage of point of tangency (m)	Radius of Curve (m)	Deflection Angle (Deg)	Degree of curvature (Deg)	GSR	HR
							variation	
1	H1	185	257	829.5	5	2.1	11.85	5
2	H2	857	902	180.4	14	9.5	10.85	6
3	H3	1152	1230	332.8	15	5.2	16.2	7
4	H.NG1	1530	1562	31.3	62	55.0	154.5	9
5	H.PG1	1752	1819	98.8	38	17.4	159	6
6	H4	2469	2541	372.5	10	4.6	13	6
7	H5	3091	3158	478.7	8	3.6	19	10
8	H6	3288	3360	493.8	8	3.5	9	8
9	H.PG2	4010	4070	41.9	71	41.1	204.2	4
10	H.NG2	4220	4390	212.5	59	8.1	200.2	9
11	H.NG3	4690	4735	355.0	25	4.8	346.4	8
12	H.PG4	4935	4988	154.1	24	11.2	49	6
13	H7	5158	5197	145.6	15	11.8	14	7
14	H8	5371	5349	128.0	17	13.4	17.85	6
15	H9	5539	5571	138.8	17	12.4	23	3
16	H10	6071	6110	153.8	16	11.2	17	6
17	H11	6240	6291	198.6	12	8.7	11	5
18	H12	6551	6596	143.7	19	12.0	18.6	7
19	H13	6996	7044	149.6	19	11.5	21	10
20	H.NG4	7224	7269	29.9	74	57.5	429	7
21	H14	10469	10498	29.0	63	59.2	13.9	5
22	H.PG4	10563	10612	51.6	54	33.3	62.6	9
23	H.NG5	12412	12453	136.2	19	12.6	80.2	7
24	H.PG5	13053	13099	169.3	23	10.2	221.6	6
25	H.PG6	13349	13429	111.6	32	15.4	259.5	11
26	H.PG7	13559	13614	185.4	18	9.3	45.8	6
27	H.PG8	13964	13984	58.9	21	29.2	455.2	7
28	H15	14444	14459	41.4	42	41.5	22	4
29	H16	15159	15186	76.1	21	22.6	11.7	8
30	H.NG6	15296	15335	66.8	40	25.7	155.2	8
31	H17	15635	15665	106.2	17	16.2	18.5	7
32	H.PG9	16465	16565	192.4	39	8.9	479.7	7
33	H18	16646	16664	132.6	8	13.0	13.55	4
34	H19	17164	17199	188.0	11	9.1	11.9	5
35	H20	17549	17585	155.1	13	11.1	15.9	6

In fig. 4, X- axis represents the running distance along the highway stretch. Y- axis represents the different geometrical parameters, HR and GSR. The crash frequency on each curve is also plotted to analyse the crash trend on horizontal curves and combined curves. In this graphical representation, the chainage length of 185m-1230m (H1,H2,H3), 2469m-3360m (H4,H5,H6), 5168m-7044m (H7-H13), 10469m-10498m (H14), 14444m-15186m (H15,H16), 15635m-15665m (H17),16646m-17585M (H18-H20) consists of horizontal curves and all other chainages consists of horizontal curve with gradients.

It is observed that heart rate is found to be very sensitive for changes in highway geometry design consistency. But GSR changes only when there is an abrupt change in geometrical variables. It can be found out that GSR variation is more than 100 at the combined curves due to presence of the gradient.

The curve with chainage of 1562m is not in consistence with preceding three consecutive curves in the stretch. It is having lesser radius of curvature, large deflection angle and large degree of curvature (radius of curve as 31.3m, deflection angle 62 ^{o}, degree of curvature with 55^{o} and curve length 29 m, gradient 4%)which makes drivers drive with more workload, higher HR and GSR.

It is found that GSR and HR variation of the curves in the chainage from 5158m to 7224m (H7-H13) is found to be the same. That is mainly because of consistent design of curves i.e, the road geometry conforms to driver expectation. But after the chainage 7224m, there is a sudden change in highway geometry which surprises the driver. Due to that GSR and HR variation is also higher at that particular curve. More number of crashes is observed at the curve 7224m-7269m (H.NG4) which is a horizontal curve with gradient. It can be noted that HR and GSR variation is also more in that curve.

Fig 2. Shows the HR and GSR observed values in the crash prone area (combined curve chainage from 7224m-7269m in Fig.1.). Primary Y-axis represents HR and speed (Km/hour) values and secondary Y-axis represents GSR values. The point of curvature is at the chainage of 62 m in Fig.2 and point of tangency is at chainage of 100 m. It is observed that the drivers have a tendency to reduce their speeds well ahead of an impending curve to comfortably manoeuvre the curve. The variation in HR and GSR is noticeable only at the start of the curve which can be attributed to the increase in drivers stress in his attempt for a safe and smooth ride along the curve. The HR and GSR values remain the same till he gets back to his normal speed denoting the sustained stress the driver is experiencing. The curves before this crash prone stretch are a set of horizontal curves (chainages from 5317 to 7224) and violating his expectations on road geometry, he confronts a combined curve at this location. This invariably affects his HR and GSR which can be taken as an indication of relation between inconsistent road geometric design and driver workload.

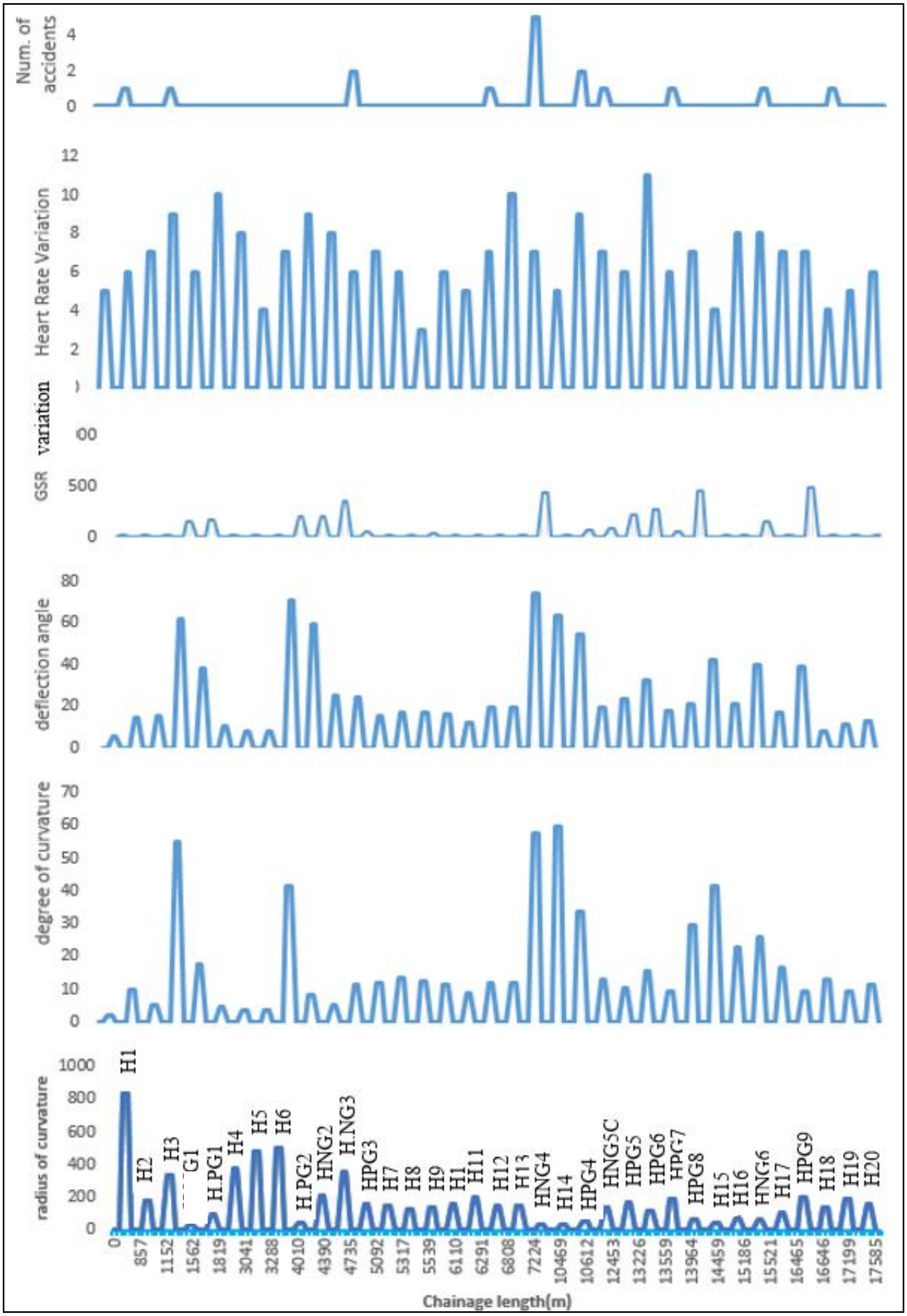

Fig 1. HR and GSR variation along the selected study stretch.

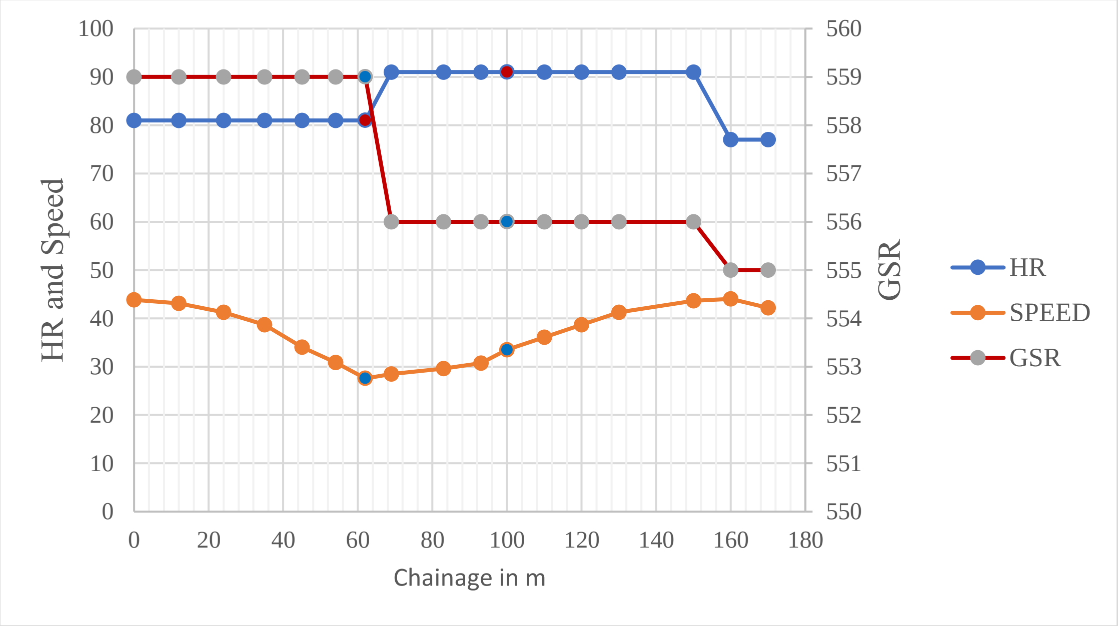

Fig 2. HR, GSR and speed values in crash prone curve

Fig. 3 shows the geographical location of crash prone area in a Google map (Curve No.20 with curve id H.NG4). Geometrical dimensions of the curve is as follows: Radius of Curve=29.9129m, Curve Length = 34.9918 m, Deflection Angle=74° , Degree of Curvature = 57.46°, Gradient=-2.88%

Fig 3. Crash prone curve identified in the selected study stretch

Fig. 4 shows that at a zero crash location, GSR and HR values are not showing any remarkable variation along the curve although the driver is altering his speed to safely manoeuvre the curve. The unchanged values may be because this curve is a part of set of consistent curves and it fully meets driver's expectation of road geometry.

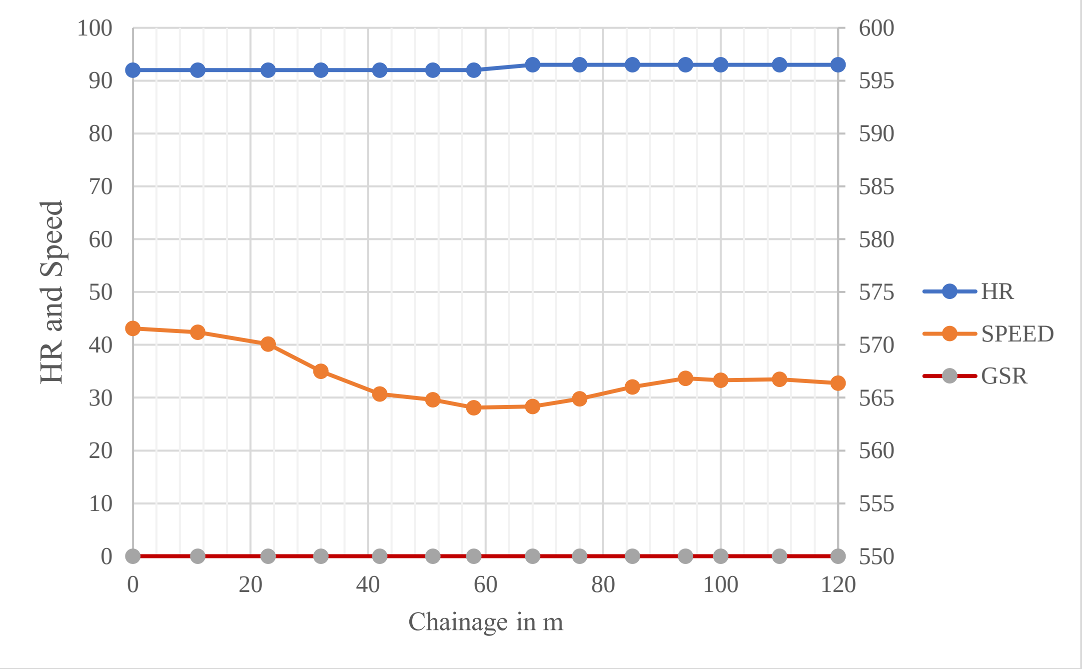

Fig 4. HR measured, GSR measured and speed values at zero crash curve

The analysis of the driver workload in terms of GSR and HR measured values at the crash and no crash locations, asserts the driver's discomfort and stress, whenever they are subjected to inconsistencies in road geometry.

5 CONCLUSIONS

This paper conducted a study on variation of driver workload measures such as heart rate and GSR along the length of a two lane non-urban highway. Correlation study revealed that radius of curve, deflection angle and degree of curvature are the geometric variables which significant influence driver workload. Heart rate values are found to be very sensitive to small changes in geometry, be it on horizontal curves or combined curves. But, significant changes in GSR are only observed in case of horizontal curves with gradients. The continuous workload profile showed that workload varies significantly at locations of inconsistency – a sharp curve after curves with flat radius. Also, such locations are found to have more crashes. A consistent road design makes the drivers comfortable to drive safely to reach their destination without experiencing much stress and hence less chances to commit errors leading to crashes.

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