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Empirical Evaluation of Drivers' Operating Speeds along Curvatures on Single Carriageway Roads

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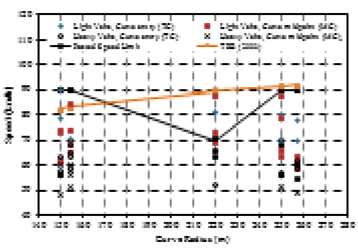
Graphical abstract



Abstract

Choice of vehicle's speed is one of the most important factors for a driver for proper vehicle's control and selecting a wrong speed results in loss of vehicle's control; particularly in negotiating road curvatures. Many of such speed related errors could be attributed to inconsistencies in the road alignment, that surprise the driver as a result of sudden change in road characteristics leading to an excess critical speed, hence, losing the vehicle's control. This inconsistency should be accounted for and controlled by the engineers. This study was carried out to evaluate the speeds of the drivers when negotiating various layouts of road bends, determination of possible factors affecting drivers' operating speed and development of prediction models for operational 85th percentile driver's speed. Speeds of over 4000 vehicles (light and heavy) were collected at 10 road curves of various designs using speed radar meter and video recording system. Speeds were measured at three different points along the curves; the entry, mid and exit points. Preliminary findings from this study revealed that there are some inconsistencies in the features of the existing road curves. The design of the existing curves used in this study can be regarded as fair as the change in the operating speed of light vehicles was found to be higher than 10 km/h; being the established lower limiting value. Likewise, the road curves could also be regarded to fall within a fair and poor design because the average change in operating speed exceeded the limiting value of 20 km/h when compared with the posted speed limit. However, more data would be required to improve the accuracy of the results.

Keywords: Operating speeds; road bends; speeds on horizontal curve

1.0 INTRODUCTION

Statistics of accidents in Malaysia for year 2005 shows that about 68% of the total accidents occurred on rural roads of which around 20% of the entire accidents on the subject road class occurred at curves [1]. About 20% of the total accidents on rural roads (or about 15% of the total accidents for that year) occurred on road bends. One hundred and forty five accidents or about 30% of total accidents in the first half year of 2011 occurred on road bends [2]. Such an alarming trend implies that road curves or bends are among the influencing factors of road accidents. Therefore, road bends and the corresponding transition sections represent the most critical locations when considering measures of highway safety. It is important to study the consistency of road geometric design with driver expectations in order to decrease human error and subsequently decrease accidents rates. In order to relate this statement, current procedure for design speed selection and application has been a concerned to many engineers and researchers for a long time. Growing number of geometric design researchers and practitioners recognized that the design speed concept as applied in United States is unable to guarantee consistent alignment [3].

In general, good geometric design means providing the appropriate level of mobility and land use access for motorist while maintaining high degree of safety. While balancing these design decisions, the designer needs to provide consistency along a roadway alignment to prevent abrupt changes in the alignment that do not match motorists' expectations. Speed is used both as a design criterion to promote this consistency and as a performance measure to evaluate highway and street designs. Geometric design practitioners and researchers are, however, increasingly recognizing that the current design process does not ensure consistent roadway alignment or driver behaviour along these alignments. A design process is desired that can produce roadway designs that result in a more harmonious relationship between the desired operating speed, the actual operating speed, and the posted speed limit. Such an approach produces geometric conditions that should result in operating speeds that are consistent with driver expectations and commensurate with the function of the roadway. It is envisioned that a complementary relationship would then exist between design speed, operating speed, and posted speed limits. While the 85th percentile compares speed data with the one provided and one perceived drivers' perceptions towards curve are the main priority in terms of safety.

This paper describes the preliminary findings of a study carried out to evaluate the operating speeds of the drivers when negotiating the various layouts of road curvatures, determination of the likely factors affecting the operating speed of drivers and development of prediction models for operational 85th percentile driver's speed using regression models of independent parameters such as radius of horizontal curves, slope of vertical curves, superelevation, distance between point of vertical intersection (PVI) and point of horizontal intersection (PHI), etcetera.

■2.0 BACKGROUND

Speed is a major contributing factor in fatal and serious crashes on Malaysian rural roads which contributed about 39% of fatal and 36% of serious crashes in 2011 [2]. In such crashes, drivers generally travel above the posted speed limit. Drivers traveling along a smooth horizontal alignment will not expect a tight curve, so their speed choices will reflect that expectation. The expectation is the same for drivers on tortuous alignment. Road accidents are caused by many factors including road geometry, driver behaviour, weather conditions, speed limits and human factors.

The 85th percentile speed has traditionally been considered in an engineering study to establish speed limit. It is the speed at or below which 85 % of the free flowing vehicles travel. Further, it is the key measure used for evaluating roadways design consistency [4]. On high speed roadways with design speed greater than 100km/h (70mph), the 85th percentile speeds were less than the design speed. However, on low speed roadways in which the design speed is less than 90km/hr (55mph) the average vehicle operating speeds were greater than the design speed [5]. A lot of researches were carried in recent years focused on operating speed and accident analysis. In this study, operating speed is seen as the highest overall speed at which driver travels on a given highway under favourable weather and prevailing traffic conditions on a section by section basis [6]. Operating speed is also defined as the speed at which drivers are observed operating their vehicles during free flow conditions [7]. It is estimated as the 85th percentile of speeds observed at a location under free flow condition [8]. In addition, variation in the speed of vehicle is an indicator of inconsistency in geometric design [9].

In order to make roads safe, it is necessary to build its features to the operating speed. Therefore, vehicle speed is a crucial control element in the road design process. Road plans and construction based on the design concept are supposed to result in consistent alignments. However, over time there has been growing concern about the design speed selection procedure. The main concern is that the design speed is being exceeded by a large number of drivers on roads with lower design speed. Inconsistent speed behaviour and lack of consistency in design of highways were found to be related and identified as a leading cause of accidents on rural highway [10].

In general, the design of a road curve considers two types of alignment, i.e. the horizontal and vertical alignments. The Road Engineering Association of Malaysia (REAM) utilizes equation 1 for selecting the radius of circular curve for roadways.

$$R = \frac{V^2}{127(e+f)} \tag{1}$$

Where V is the design speed in km/h, e is superelevation in fraction and f is the road surface friction.

Equation 1 implies that the design of a road curve does not seem to include the effect of gradient. In Malaysia, the criteria presented in Table 1 are used for the selection of minimum radius for horizontal curve based on design speed [11]. Further, the consideration regarding the effects of gradient and road surface friction is vague.

Table 1 Selection of minimum radius of a horizontal curve [11]

Design speed	Minimum radius (meter)	
(km/h)	e = 0.06	e = 0.1
110	560	500
100	465	375
90	335	305
80	280	230
70	195	175
60	150	125
50	100	85
40	60	50
30	35	30

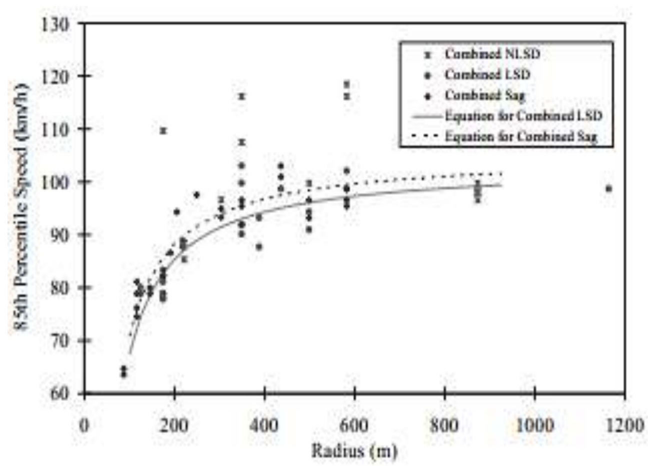
The criteria in Table 1 can be transformed into an equation describing the effects of radius and superelevation on the design speed of a road curve. Such a relationship is shown in Equation 2.

$$V_{ds} = 85.58 - \frac{2452.86}{r} + 0.925e \qquad (R^2 = 0.75) \tag{2}$$

Where V_{ds} is the design speed (km/h), r is the radius of a circular curve (m) and e is superelevation.

Various studies have developed operating speed consistency models for a two–lane rural highway. These models predict the operating speed in terms of the 85th percentile speed based on independent geometric design parameters of two-lane rural highways. Previous study by the Transportation Research Board, TRB [12] suggested that 1/R was the most significant independent variable. Equation 3 which was developed for the combination of sag vertical curves and horizontal curves included data from the 25 sites. Figure 1 shows the result of their research and there is a trend line with equation that predicts the V_{85} (km/h). In this equation, the V_{85} is based on radius of simple curve.

$$V_{85} = 105.32 - \frac{3438.19}{r}, \qquad R^2 = 0.92 \tag{3}$$



NLSD – Non-limited Sight Distance, LSD – Limited Sight Distance

Figure 1 Relationship between V_{85} and Radius for combination curves [12]

In another study, three operating speed prediction models were developed by at different points along horizontal curves [13]. Their study showed that there were significant differences between the operating speed values on the same horizontal curve at the point of curve (PC), the middle of curve (MC) and point of tangent (PT).

Equation 4, 5 and 6 represent the relationships between operating speed and degree of curve at PC, MC and PT, respectively.

$$V_{85} = 9541 - 1.48D - 0.012D^2 \qquad (R^2 = 0.99) \qquad (4)$$
$$V_{85} = 103.03 - 2.41D - 0.029D^2 \qquad (R^2 = 0.98) \qquad (5)$$
$$V_{85} = 96.11 - 1.07D \qquad (R^2 = 0.90) \qquad (6)$$

Where, D = Degree of curvature and V_{85}= 85th percentile operating speed on curve (km/h).

Integrating the prediction models for operating speed with highway design consistency using the operating speed of a vehicle is recommended over design speed in many countries. The approach of developing speed profiles can be used to evaluate existing alignments or during the detailed design stage to fine tune the final design of new alignments [14]. Plotting the operating speed profile of all roads sections for detection of potential risk is a satisfactory method for controlling consistency in roads. In this kind of graph, the operating speed of passenger cars is located on Y-axis and road element with their kilometres located on X-axis. The spots that have excess speed increment or decrease in comparison with successive following or preceding spots are recognizes as inconsistent places. Unravelling the spot especially in project that are designing is very useful because they can be corrected by reviewing and redesigning plan. However, speed measurement in roads at every spot is expensive, so in these scenarios using the equation with acceptable accuracy is advised.

A recent study [15] suggested some criteria for identification of inconsistent spot as follows:

(a) Good design: Change in degree of curvature less than or equal to 5 degree, or a change in operating speed less than or equal to 10 km/h (6.2mph);
(b) Fair design: Change in degree of curvature greater than 5 degree and less than or equal to 10 degree, or a change in operating speed greater than 10 km/h (6.2mph) and less than or equal to 20 km/h (12.4 mph);
(c) Poor design: Change in degree of curvature greater than 10 degree, or change in operating speed greater than 20 km/h (12.4 mph).

A road alignment with consistent features and changes is considered as a good design. A fair design has some minor inconsistencies that may affect driver's behaviour. On the other extreme, a poor design has inconsistencies that cause predicted speed differentials exceeding 20km/h (12.4 mph).

3.0 METHODOLOGY

The basic data required for this study are the speeds of vehicles at the entry, middle and exit points of a road curve. Study sites with various curvature characteristics were identified for field observation of drivers' operating speed based on the following criteria:

(a) good access and safety for the enumerators and equipment during the data collection process,
(b) good overhead vantage points for video recording purposes,
(c) good sight distances (to ensure that the sight distances do not influence the interactions between drivers),
(d) away from the vicinity of intersections, and
(e) no physical features or activities adjacent to or in the course of the roadway that may create an abnormal hazard such as narrow bridges, police station, school, factories and recreational areas.

A total of twenty study sites were considered for this preliminary evaluation, i.e. twelve and eight sites in the states of Perak and Johor, Malaysia respectively. The geometric data for each of the road curves were based on the as–built drawing and also measured using a surveying instrument known as Topcon Hyper II. Table 2 summarises the major characteristics of each sites considered in the study.

Table 2 Geometric Characteristics Sites Studied

Location	Sites	Radius (m)	Gradient (%)	Superelevation (%)
Simpang Pulai, Perak	1 & 11	220	+/–1.624	4.0
	2 & 12	250	+/–1.617	3.5
	3 & 13	150	+/–0.088	5.9
	4 & 14	220	+/–5.710	4.0
	5 & 15	250	+/–4.895	3.5
	6 & 16	150	+/–5.895	5.9
Batu Pahat, Johor	7 & 17	154	+/–0.092	1.3
	8 & 18	154	+/–1.423	1.3
	9 & 19	257	+/–2.451	4.9
	10 & 20	257	+/–4.005	4.9

Speeds of vehicles were measured under free flow traffic and dry weather conditions. This is to ensure that driver's choice of speeds was not influenced by other external factors. Speed data were collected at three points along each travel direction, i.e. Point 1 (TC), Point 2 (MC), and Point 3 (CT), as illustrated in Figure 2. The speeds were measured for two categories of vehicles; light and heavy vehicles.

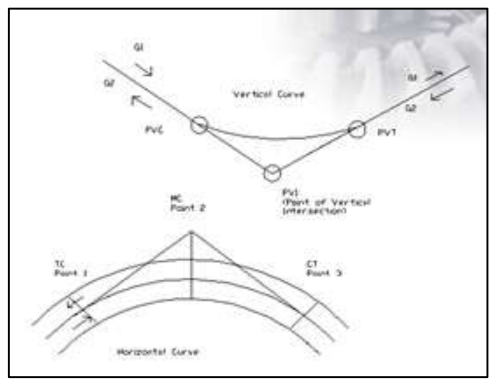


Figure 2 Locations of speed observation points on road curve

The speed data were collected using video recording technique and speed radar meter. At each location, two video cameras were mounted unobtrusively by the roadside to record the passage of vehicles at the beginning and midpoint of the horizontal curve. The exact locations of cameras at each site were influenced by logistics such as vegetation, visibility, and so on. On each occasion data were collected only for the nearside vehicles.

Each of the recordings was played back in a computer to retrieve the relevant data. For each vehicle observed, class and speed were determined. These were achieved using a computer–based event recorder to extract data defining vehicle arrival time and class from the video recording of traffic scene at each of the two positions for each location. Vehicles were classified as either HGV or passenger car. A bus was recorded as an HGV.

For each data extraction and analysis process, the data were stored on a text-formatted data file and transferred to an Excel spreadsheet file. The data comprised of arrival time and classification at each of the two positions for each measurement. The data for each vehicle were matched and the time headway at each position and vehicle speed between positions were determined.

4.0 RESULTS AND DISCUSSIONS

As mentioned in the preceding section, spot speeds of over 4000 vehicles were sampled in this work. The 85th percentile speed at each observation point was deduced from a cumulative plot of speed distribution at the respective points.

Figure 3 illustrates a typical plot for speed distribution for study site 2.

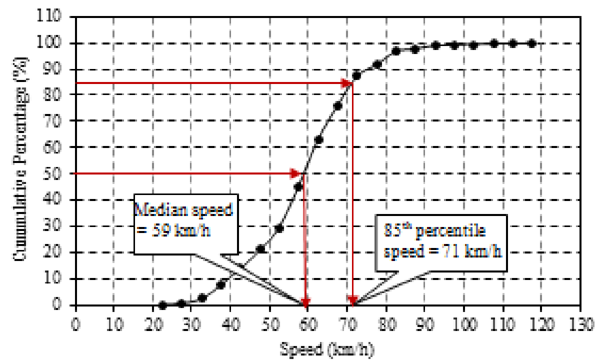


Figure 3 Speed distributions for site 2 at curve entry point

The 85th percentile speeds of light and heavy vehicles at the entry and midpoints of each horizontal curve are as presented in Table 3.

Table 3 Drivers' 85th percentile speed for studied road curves (km/h)

				Light Vehicles		Heavy Vehicles		
Sites	Radius (m)	Gradient (%)	Super-elevation (%)	Entry Curve (km/h)	Mid Curve (km/h)	Entry Curve (km/h)	Mid Curve (km/h)	Speed Limit (km/h)
1	220	+1.624	4.0	81	88	52	71	70
2	250	+1.617	3.5	80	79	56	56	90
3	150	+0.088	5.9	90	73	64	56	90
4	220	+5.710	4.0	81	88	66	64	70
5	250	+4.895	3.5	71	88	57	68	90
6	150	+5.895	5.9	79	74	58	56	90
7	154	+0.092	1.3	71	68	63	60	90
8	154	+1.423	1.3	65	65	59	58	90
9	257	+2.451	4.9	70	63	59	55	90
10	257	+4.005	4.9	78	59	62	60	90
11	220	-1.624	4.0	88	69	64	66	70
12	250	-1.617	3.5	88	63	68	51	90
13	150	-0.088	5.9	71	62	56	48	90
14	220	-5.710	4.0	88	73	71	71	70
15	250	-4.895	3.5	79	66	56	56	90
16	150	-5.895	5.9	73	61	56	60	90
17	154	-0.092	1.3	65	84	65	51	90
18	154	-1.423	1.3	68	74	68	56	90
19	257	-2.451	4.9	59	60	55	49	90
20	257	-4.005	4.9	63	62	60	38	90

It can be seen from Table 3 that the 85th percentile speeds of light vehicles at both entry and midpoint of the road curves are consistently higher than the speeds of heavy vehicles. This is probably due to the characteristics of light vehicles being better than the heavy vehicles in terms of performance capacity that allow the drivers to negotiate the road curves comfortably at relatively high speeds.

Figure 4 shows the variations of 85th percentile speeds of both light and heavy vehicles on the studied road curve segments. Also shown in Figure 4 are the posted speed limits and the estimated 85th percentile speeds based on TRB [12] for comparison. It can be seen from Figure 4 that there is a large variation in the range of about 2%–28%, between the speed limit and the 85th percentile speed derived from the TRB model [12] for the respective road segments.

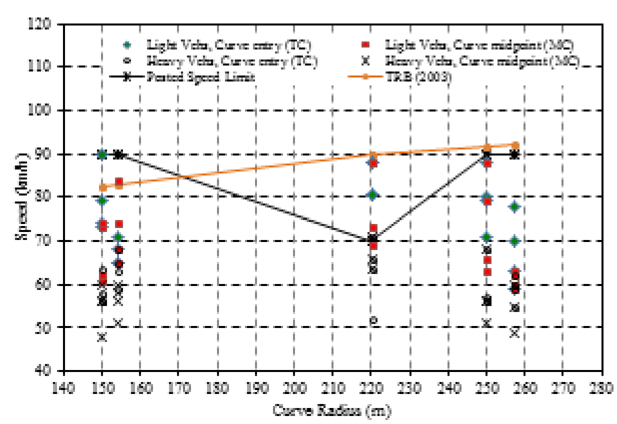


Figure 4 Comparisons of drivers' operating speed with trb [12] and posted speed limit

The data showed that on a road curve with a speed limit of less than 90 km/h, the 85th percentile speeds of light vehicles are much higher than the limit set for that particular road segment.

As the driver enters the entry of curve (point 1), they tend to feel confident and have more control of the vehicle. The drivers speed up all the way and decrease their speed as they reach the midpoint of the curve (point 2) in order to negotiate the curve with ease and safely. However, the 85th percentile speeds of heavy vehicles appeared to be much lower than the speed limit set for the corresponding road segments. This could be attributed to low performance capacity of heavy vehicles compared with that of light ones.

The mathematical models describing the influence of radius, gradient and superelevation on the 85th percentile speeds of light vehicles (LV) and heavy vehicles (HV) at the entry of the road bend (TC) and at the midpoint of the curve (MC) are given by Equations 7, 8, 9, and 10, respectively.

$$V_{85,LV,TC} = 71.80 - \frac{492.32}{r} + 0.07G + 1.60e \tag{7}$$

$$V_{85,HV,TC} = 63.88 + \frac{218.36}{r} - 0.19G - 1.08e \tag{8}$$

$$V_{85,LV,MC} = 79.21 - \frac{190.90}{r} + 1.28G - 1.86e \tag{9}$$

$$V_{85,HV,MC} = 63.25 - \frac{574.72}{r} + 0.49G - 0.72e \tag{10}$$

All variables are as defined earlier.

■5.0 CONCLUSIONS

This paper described the results of an empirical study carried out to evaluate the speeds of vehicles on horizontal curves on single carriageway roads. Based on the field observations and subsequent analysis, the following findings were made:

(a) Previous studies did not explicitly consider the effects of gradient and super-elevation on drivers' operating speed.
(b) There is somewhat inconsistency in the design practice of horizontal curves on Malaysian single carriageway roads when compared with the REAM (2002) design guidelines; especially, in the selection of the design speed and the maximum speed limit for a particular road curve.
(c) Road gradient is one of the factors influencing the speeds on horizontal curve but is not explicitly considered in the current design practices.
(d) The 85th percentile speeds of light vehicles are much higher than the 70 km/h speed limit.
(e) The 85th percentile speeds of heavy vehicles are well below the speed limits for the respective horizontal curves.

The findings from this study suggest that the design procedure of horizontal alignments of single carriageway roads needs further reviews because the current procedure appears to have some degrees of consistencies in terms of the design speeds. This study, however, requires more data to be collected and analysed to verify and ascertain the findings.

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