EFFECTS OF CENTRIPETAL FORCE AND HIGHWAY DETERIORATION ON VALLEY CURVES OF NATIONAL HIGHWAYS (A CASE STUDY OF ENUGU - AWKA EXPRESSWAY)

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ABSTRACT

This paper investigated the reasons for the ever presence of many potholes and alligator cracks at valley curves in most national highways, using Enugu – Awka express way as a case study. From the ensuing studies carried out on the case – study highway, it was discovered that centripetal force increases the axle load of vehicles by about 20% - 30% for pavements on valley curves, thereby causing serious damage to pavements at valley curves. A visual contrast which was discovered during the investigation seriously underscores the findings: where a summit curve and a valley curve occurs at same location on the two-lane-dual carriage way, the lanes going uphill are often totally free from potholes, while those going downhill a rife with ever widening potholes. Based on the above findings, it was recommended that road designers should provide sufficient thickness of road surfacing and base courses to counter the effect of centripetal force at valley curves. This thickness should be minimum at the beginning of the curve and maximum at the center of the curve, i.e should increase with increasing centripetal force along the length of transition curve. This should be done without compromise to high quality of construction materials and workmanship.
Keywords: highway vertical curves, centripetal force , road pavement, potholes.

INTRODUCTION

Highway Vertical Curves

Highway vertical curves are curves found on the longitudinal profiles or vertical alignment of highways. It is either a valley curve or a summit curve.

Summit curves are mainly parabolic curves joining a rising and falling gradients at two tangents A and B, fig.1.1. Length of summit curves is dependent on the stopping and overtaking sight distances. On the other hand, valley curves, which are curves joining a falling and rising gradients, fig.1.1, consists mainly of two transition curves. Transition curves are curves of gradually increasing curvature, which allows the effect of centripetal force to be gradually dissipated for the comfort of the passengers. Its radius is maximum at the tangent points and minimum at the middle of the curve; junction of the two transition curves.

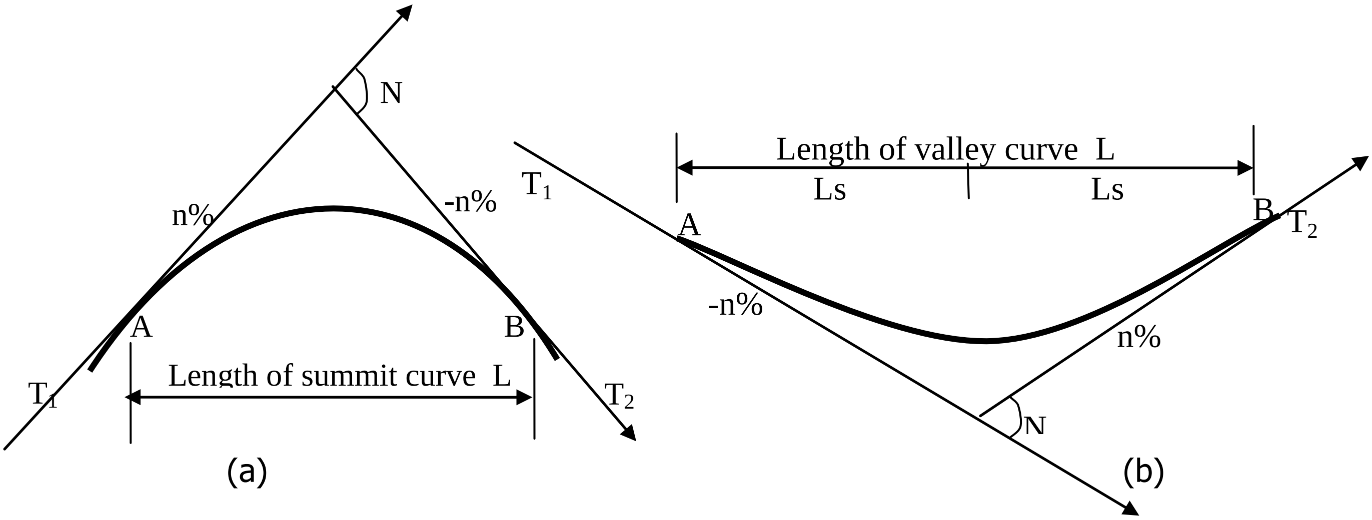

Fig 1.1 (a) Summit curve, length L

(b) Valley curve, length L =Ls+Ls.

Where Ls is length of one transition curve.

Thus, the length of a valley curve is the sum of the lengths of the two transition curves (L = Ls+Ls). The length of a valley curve L depends on the rate of change centripetal acceleration, design speed and deviation angle as given in the equations 1.1 and 1.2 (B.L.Supta and A.K Supta, 2005).

$$L = 2L_S = 2\left(\frac{NV^3}{C}\right)^{1/2} \text{-------(1.0)}$$

$$L_S = \frac{V^3}{CR} \text{-------------------(2.0)}$$

Where L is the length of the valley curve

Ls is the length of on transition curve

V is the design speed

C is the rate of change of centripetal acceleration

R is the minimum radius of the curve at the junction of the two transition curves.

From the above expressions, it can be deduced that the management of centripetal force in road design is geared, mainly to the comfort of the passenger and the durability of the vehicles; and not to the durability of the road itself. This is because the centripetal force eventually reaches its maximum values at the center of the valley curves and inflicts serious damage on the road, which progressively grows from cracks to potholes.

Road Pavement

A road pavement is a crust of granular earthen materials constructed over the base of original ground to transfer load safely to it in triangular dispersion. A road pavement can be classified as flexible or rigid pavement; and in most cases roads pavements are capped with bituminous surfacing called wearing course. A rigid pavement has a concrete base under the bituminous surface, while a flexible pavement has only the bituminous surface at grade level. Rigid pavement spreads loads more evenly than the flexible pavement and it is preferred where the sub grade is very weak. Fig 1.2 shows the components of a flexible pavement in cross-section with the axle load spread in triangular dispersion to the sub grade. This pattern of load spread causes more pressures on the wearing course and base course than on the sub grade (fig 1.2).

Failures such as potholes and cracks are caused by excessive pressure which often develops on the base and wearing courses, while wavy depressions are caused by excessive total load, perhaps from a two-wheeled heavy truck, which may not cause much pressure at the surface of the road, because of the large contact area, but heavy enough to cause the sub grade to depress. However, road failures occur gradually through plastic deformation from repeated loads and not from a single load.

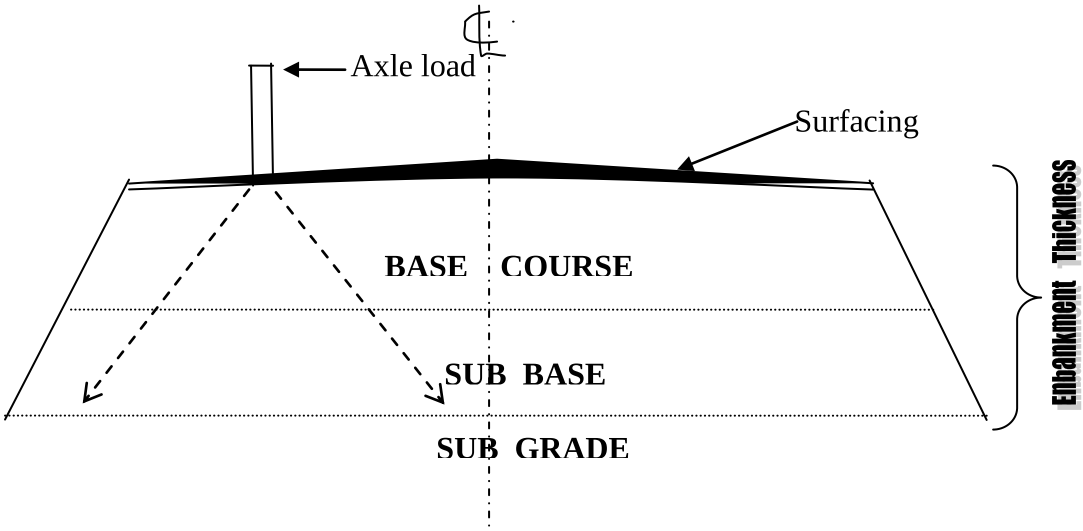

Fig 1.2 : components of a flexible pavement

Centripetal Force

The force on a body moving along a curved path, and which is always directed to the center of curvature of the path of motion is called centripetal force. For an automobile moving in a valley curve, the reaction of the road surface with the tyres must develop sufficient centripetal force, pointing towards the center of curvature at any instant, to keep the automobile in track, otherwise it would move away tangentially to the curve into the ground. The centripetal force added, by means of vector algebra, to the weight of the automobile forms the total reaction of the road surface to the axle load of the automobile.

The same analogy is applicable to automobile moving in a summit curve, but in this case it is some part of the weight of the automobile that is spent to prevent the automobile from leaving its path tangentially into the air. This part of the weight of the automobile is equal to the centripetal force. The remaining part of the weight produces the reaction on the road.

Thus, the vector sum of the weight of an automobile and the centripetal force gives the total reaction of the road surface to the axle load of the automobile. This resultant vector is a minimum value for a summit curve and a maximum value for a valley curve.

To explain this mathematically, consider the curve (a valley curve) in fig 1.3(i). A particle P moves down the curve with a velocity vector $\mathbf{V_A}$ at point A and a velocity vector $\mathbf{V_B}$ at B very close to A. Let $\mathbf{e_n}$ and $\mathbf{e_t}$ be the unit vectors in the respective directions of the co-ordinate axis attached to the moving particle P. The unit vector $\mathbf{e_n}$ always points to the center of curvature of the curve, while the unit vector $\mathbf{e_t}$ is always tangent to the curve and always perpendicular to $\mathbf{e_n}$ at any instant and position of the particle P.

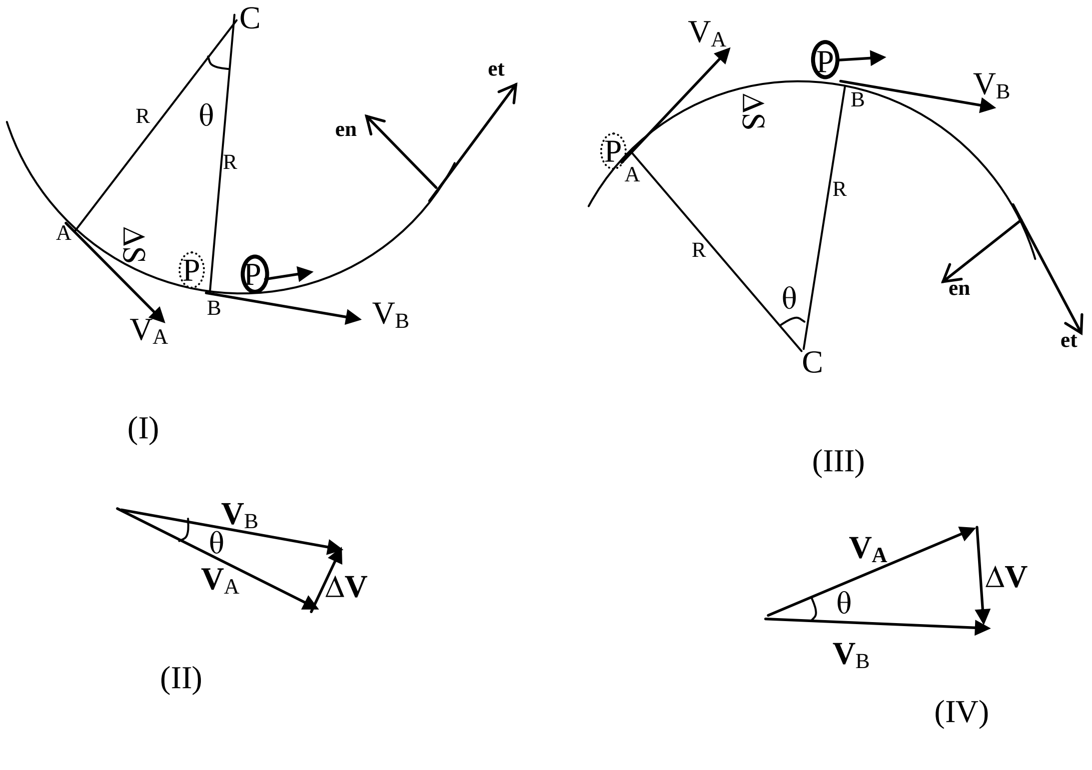

Fig 1.3

(i) Shows the position and velocities of particles P in a valley curve.
(ii) Vector triangle of the velocities V_A and V_B of particle P in fig 1.3. i
(iii) Positions and velocities of particle P in a summit curve.
(iv) Vector triangle of velocities V_A and V_B in fig 1.3 iii.

Since points A and B on the curves are very close to each other velocities $\mathbf{V_A}$ and $\mathbf{V_B}$ have approximately the same magnitude. Drawing the two velocities from the same point O, we obtain the change in velocity from the vector diagrams fig 1.3 (ii) or 1.3 (iv).

$\Delta\mathbf{V} = V\theta\mathbf{en}$ - - - (3.0)

The change in velocity vector $\Delta\mathbf{V}$ is obviously pointing towards the center of curvature of the curve, in the direction of **en**. However,

$\theta = \Delta S / R$ - - - - - (4.0)

Therefore $\Delta\mathbf{V} = V\left(\Delta S / R\right)\mathbf{en}$ - - - 5.0

From the basic definition of acceleration (change in velocity divided by time) we have

$\mathbf{a} = V\left(\frac{\Delta S}{t}\right) 1/R\,\mathbf{en}$

$\mathbf{a} = V^2 / R\ \mathbf{en}$ - - - - - - - - -(6.0)

This acceleration vector has a magnitude V^2 / R , while **en** is the unit vector defining the direction of **a**.

Thus

$a = V^2 / R$ - - -(7.0)

The centripetal force is then the product of the mass of the particle and it acceleration, obviously directed toward the center of curvature and being generated by the reaction of the particle and the curved surface. This force prevents the particle from moving away in the direction of its velocity (tangentially).

$\mathbf{F} = \frac{W}{g}\frac{V^3}{R}\ \mathbf{en}$ - - - (8.0)

The magnitude of **F** is

$F = \frac{W}{g}\frac{V^3}{R}$ - - - - (9.0)

The total reaction from the curved surface on the particle is given by the vector sum of the weight and F, i.e.

Reaction on the surface =

$W + \frac{W}{g}\frac{V^3}{R}\ \mathbf{en}$ - - (10.0)

At the middle of the curve equation 10.0 reduces to the scalar addition of the two forces, since the two directions are approximately co-linear.

Reaction at the middle of curve =

$W \pm \frac{W}{g}\frac{V^3}{R}$ - - (11.0)

Where W is the weight of the particle, g is the acceleration due to gravity, V is the velocity of the particle and R is the radius of curvature at the middle of the curve.

Equation 11.0 is a minimum for a summit curve and a maximum for a valley curve; i.e while part of the weight of the particle (centripetal force) has to counter the force tending to push the particle away in the direction of its velocity for a summit curve, additional reaction equal to the centripetal force must be added to the weight of the particle to stop it from moving into the ground for a valley curve.

If the above explanations are applied to a motorway, then the valley curves will obviously be more loaded than the summit curves. The next section defines the enormity of this load and the detrimental effects which it has on the valley curve as shown by the investigation carried out in Enugu – Awka Express Road.

INVESTIGATION AND METHOD

Road deteriorations at valley curves by potholes along Enugu – Awka Expressway was investigated.

The levels of deteriorations by potholes was noted visually and grouped accordingly as follows: nil', 'very mild', 'mild', 'heavy', and 'very heavy' deteriorations. The length of each valley curve was measured using 50-meter measuring tape. The deviation angles was estimated from the observed slopes. The minimum radius of curvature for each valley curve was calculated from the formula

$$R = {}^{L_S}\!/_{N} \qquad - \qquad - \qquad - (12.0)$$

Where R is the required minimum radius, Ls is length of one transition curve and N the deviation angle in radian.
The results obtain are tabulated in table 2.1.
Note that the figures given in table are rounded off to the nearest whole number. The approximate percentage increase in road reaction above the weight of the automobile was also calculated using $\frac{100V^2}{gR}$. Design speed used is 80km/h. Table 2.2 summarizes the results in table 2.1

table2.1 result of investigations carried out on vertical curves along awka-enugu express way

S/N	Location of Curve	Curve Length (M)	Deviation Angle (Degree)	Minimum Radius of Curve (M)	Approximate increase in Road Surface Reaction Above W (%)	Level of deterioration
1.	Between NNPC-Mega Filing Station and UNIZIK Junction.	200	20^0	573	9%	Mild
2.	Between Post-Primary School Service Commission and Tourist	200	30^0	382	13%	Heavy

	Hotels.					
3.	100 Meters behind Ugwuoba Cattle Market.	150	10^0	859	6%	Nil
4.	100 Meters ahead of Ugwuoba-Cattle Market.	50	30^0	96	52%	Very Heavy
5.	Between Oji-River Disabled Peoples' Home and Oji-River Junction.	250	15^0	955	5%	Very Mild
6.	Between Enugu-State Water Scheme Booster Station and Nkwo-Ezeagu Market.	200	15^0	764	7%	Mild
7	Between Umumba-Nndiuno Market and Mumdim-Obeleagu Umanna.	150	35^0	246	21%	Heavy
8.	Between Obeleagu-Umanna and Owaimezi Bus Stop.	150	40^0	215	24%	Very Heavy
9.	Between Owa-Imezi Bust Stop and the proposed Enugu-State International Market.	300	20^0	259	6%	Very Mild
10.	Between Onyeama Hill and Onyeama Mines.	200	30^0	382	13%	Heavy

Table 2.2 Increase in Deterioration Levels with Radius Of Curvature And Road Surface Reaction Along Awka-Enugu Express Way

S/N	Minimum Radius of Curvature (R)	Approximate Increase in Road Surface Reaction %	Level of Deterioration
1.	96	52	Very Heavy
2.	215	24	Very Heavy
3.	246	21	Heavy
4.	382	13	Heavy
5.	573	9	Mild
6.	764	7	Mild
7.	859	6	Very Mild
8.	955	6	Very Mild

DISCUSSION OF RESULTS

Many factors contribute to pothole formation on bituminous road surface, but table 2.1 shows that centripetal force is the major factor in valley curves (or vertical curves in general). This is proved by the fact that the level of deterioration in table 2.2 increases with increasing curvature ($^1/_R$) and centripetal force. In fact locations marked 'Very Heavy' and 'Heavy' deteriorations in table 2.1 have once or twice been closed to traffic between 2005 to 2008 (last 3years) to enable the Federal Road Maintenance Agency to effect a repair on the road, which often evolved total replacement of the surfacing. Such problems occur where the radius of curvature range from 90m to 500m, and with percentage increase in road surface reaction ranging form 13% to 50%.

The rest of the curve have little or no deteriorations and are marked as 'Nil', 'Very Mild' and 'Mild' deteriorations with their radius of curvature ranging from 550m to 900 meters

Another useful observation (not shown in the table) is the absence of potholes on summit curves. Also, many vehicles exceed the design speed of 80km/h in valley curves, nowadays, showing that the deterioration caused by centripetal force at valley curves should be a matter of concerned to all stakeholders to increase the durability of roads and reduce accidents.

CONCLUSION AND RECOMMENDATIONS

The following suggestion are given to reduce accidents in valley curves and to increase the durability of vehicular highways:

1. Use of superior materials and improved workmanship should not be compromised at the valley curves during construction for any reason.
2. The thickness of the surfacing and base courses should be increased progressively and proportionally with the increase in centripetal force from radius of 500m to the minimum radius of curvature at the center of the valley curves i.e. the base of the valley curve should be thickened by increasing the thickness of base and wearing courses to fight the effect of centripetal force.
3. This should be well stated in the contract document to avoid neglect.

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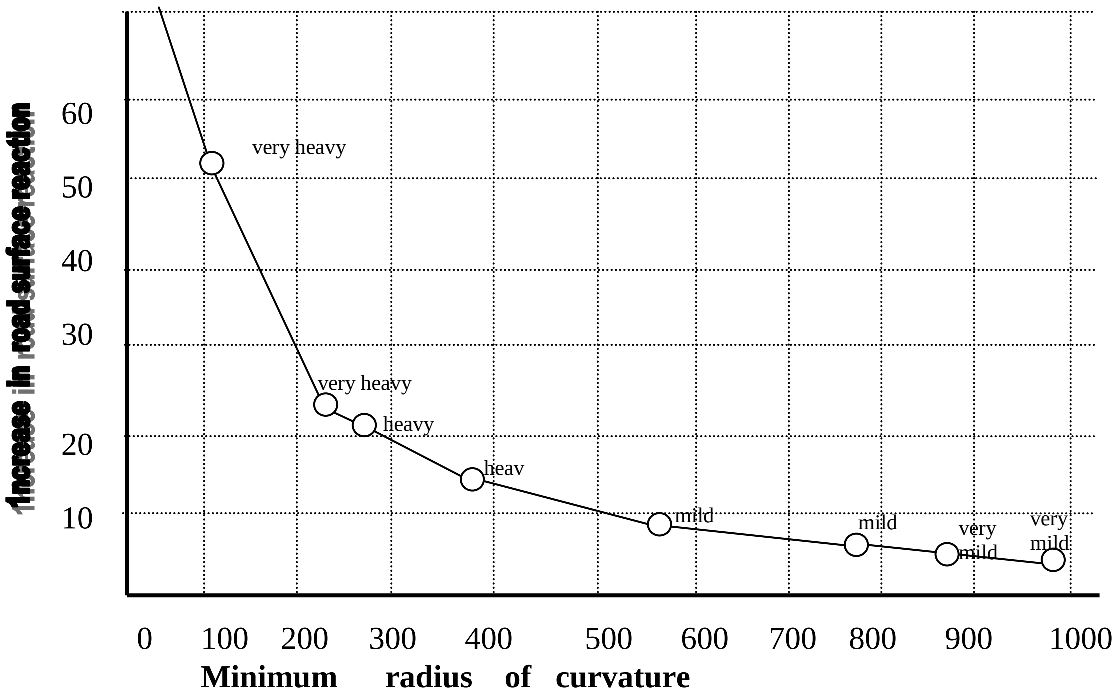
APPENDIX

I. Graph of percentage increase in road surface reactions VS Radius of curvature.



II. List of Notations

L	Curve length.
Ls	Transition length.
N	Deviation Angle.
C	Rate of change of centripetal acceleration.
R	Minimum radius of curvature.
T	Tangent to the curve n% slope (per cent) of tangent to the curve
V	Design speed.
$\mathbf{V_A}$	Velocity vector of particle at point A.
$\mathbf{V_B}$	Velocity vector of particle point B.
e_n	Unit vector normal to the curve.
e_t	Unit vector tangent to the curve.