

Research Article

Traffic Kinematic Wave Propagation by Bituminous Asphaltic Concrete Road Distress

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Abstract: Traveling on bituminous asphaltic concrete roads plagued with potholes and edge subsidence is common in Nigeria and a better understanding of traffic dynamics has both theoretical and practical implications. In this study, we present continuous kinematic wave models of traffic flows at roadway section with and without bituminous asphaltic concrete distress. In particular, traffic kinematics was not treated as shockwave, rather as traffic dynamics that can trigger rarefaction or shockwave. In the paper the hypothesis that bituminous asphaltic concrete with significant distress will trigger traffic kinematic that may accentuate rarefaction or shockwave was investigated. Maximum flowrate polynomial estimation method based on extrapolation of the flows from flow and density curve was used. The method assumes that density at maximum flowrate is not affected by bituminous asphaltic concrete distress, which implies that traffic dynamics are fully the result of travel speed changes. Average traffic shockwave of about -20km/h were caused by bituminous asphaltic concrete with severe distress. Discussion and further studies are presented in the conclusion section.

Keywords: Capacity, kinematic wave, pavement distress, rarefaction, traffic shockwave

INTRODUCTION

Good roads promote socio-economic development; if that is true, then the tests of optimizing road use would call for them to be functional, Ben-Edigbe and Ferguson (2005). Pavement distresses are visible symptoms of functional deterioration of asphalt pavement structures. Three types of distress that an asphalt pavement may develop are cracking, distortion and disintegration. Cracking appears in many forms, if left untreated it may lead to distortion and disintegration. Pavement distortion is a problem caused by compaction. This compaction may occur in the subgrade soil where additional movement or compaction has occurred, or where base compaction has happened. This is not a good situation as it becomes a traffic hazard, permits water to accumulate and eventually makes matters worse. Disintegration is the breaking up of a pavement into small, loose fragments. Two common types of disintegration are raveling and potholes. Raveling is the progressive loss of surface material caused by weather and/or traffic abrasion. Potholes can develop over short periods of time and depending on the size, depth and location there will be a greater or lesser risk to the general public. In any case, the holes get bigger as vehicles drive over them damaging the structure of the road below its surface layer. Department of Transport, (DTp) (1984) road note advice 20/84 suggested that, potholes

are open cavity in road surface with at least 150 mm diameter and 25mm depth. Potholes are an increasing problem on Nigeria's roads causing damage to vehicles and presenting a potential safety hazard. Adverse weather conditions such as rainfall make the pothole situation much worse in Nigeria. Consequently, on roads with pavement distress, drivers are faced with the choice of avoidance or approach at slow speed. Should the lead driver brake abruptly, kinematic waves created in the traffic stream can trigger shock or rarefaction waves. Since functional asphalt pavement distress deals mainly with ride quality and safety of pavement surface, the paper is concerned with estimating traffic kinematic wave induced by pavement distress. By investigating the presence of kinematic wave in the traffic stream, the paper is merely stating that the presence of traffic shockwave is an indication of driver-behavioural problems. Kinematic wave model has been used extensively to explain traffic states and the length of queues along road segments and also in different traffic flow contexts, Xinkai and Henry (2011) and Ngoduy (2011). Kinematic wave and shockwave models are often used interchangeably. Traffic shockwave is a function of road capacity loss whereas kinematic wave model is made up of three components: the fundamental diagram, the conservation equation and initial conditions. Therefore, care should be taken when expressing traffic flow waves in order not to misrepresent traffic kinematic wave for traffic shockwave. The paper asserted that passenger car

equivalent values being an instrument of road capacity estimations cannot be the same for both free-flow and congested conditions according to Seguin *et al.* (1998) and Ben-Edigbe (2010). In Nigeria where the dependence on road transportation is near total, the provision of effective infrastructure services is a crucial factor that would promote socio-economic growth; whereas dysfunctional roadway in effect would lead to decline. The paper presents the results of a study on traffic kinematic waves triggered by bituminous pavement distress on Nigeria roadways. The paper is based on the hypothesis that pavement distress may cause traffic shockwave. Road capacity estimation method based on extrapolation of the flows from flow and density curve was used to estimate partial traffic kinematic waves. The method assumes that density at road capacity is not affected by pavement distress, which implies that traffic contractions are fully the result of speed changes according to Minderhoud *et al.* (1997) and Ben-Edigbe (2010).

MATERIALS AND METHODS

Potholes and edge subsidence appear randomly often without warning are likely to create traffic stream disturbances by reducing traversable road width and increasing the likelihood occurrence of traffic kinematic waves. The paper presents the results of studies carried out in Nigeria. Nigeria is located in West Africa and made up of 36 states and its Federal Capital Territory, Abuja. Nigeria shares land borders with the Republic of Benin in the west, Chad and Cameroon in the east and Niger in the north. Its coast in the south lies on the Gulf of Guinea in the Atlantic Ocean. Nigeria has the largest road network in West Africa and the second largest south of the Sahara, with roughly 108,000 km of surfaced roads. Transportation by road is the most commonly used travel mode in Nigeria today. Traveling on bituminous asphaltic concrete roads plagued with potholes and edge subsidence is common in Nigeria and a better understanding of traffic dynamics has both theoretical and practical implications. Pavement disintegration, deformation and cracking of road pavement are known form of treatable road defects. In the paper the focus is on disintegration of bituminous surfacing. Surface distress is the gradual break-up of the bituminous pavement under the abrasive action of traffic and under the mechanical or chemical actions of weathering, typical examples of defects exhibiting this trend include are potholes and edge-break. Bituminous surfacing may crack for a variety of reasons that include lack of good bond between the surface layer and the course underneath, excessive pavement deflection, expansion and contraction of the sub grade, shrinkage and often, in early stages the crack patterns can indicate the cause. In any case when the cracks have developed over a large area and become

sufficiently wide and numerous to allow the entry of surface water or disturbance of the surface by traffic, the road deteriorates. Defects associated with road deterioration are usually manifested in form of cracking, rutting, ravelling, potholes, roughness, edge break and polished surface among others. Potholes and edge subsidence would often lead to carriageway width shrinkage with negative effects on highway traffic flowrate. Specifically, potholes are open cavity in road surface with at least 150mm diameter and at 25mm depth. Pothole may be defined as any localised loss of material or depression in the surface of a pavement that compromises the ride quality of the pavement. Department of Transport (DTp) (1984) road note advice 20/84 suggested that for validity carriageway lane must not be less than 2.5m, therefore potholes, ravelling and edge damages with transverse widths greater than 500mm on a 6.1m carriageway (allowing 100mm for road markings) would have violated lane width tolerance level. Once the road width tolerance level has been violated, traffic flowrate would become unstable. In a traffic stream, lead vehicle may slow down in response to changing road conditions, sometimes with an abruptness that may trigger traffic shockwaves. It is positive when travelling in same direction as traffic stream and negative when travelling against. Kinematic-wave is one of a number of approximations of the dynamic-wave. Kinematic wave model has been used extensively to explain traffic states and the length of queues along road segments and also in different traffic flow contexts. Kinematic wave and shockwave models are often used interchangeably. For instance, Xinkai and Henry (2011) derived the traffic trajectories of four major shock waves using the model. Ngoduy (2011) used the continuum theory and applied the multiclass approach to display the widely scattered flow-density relationship caused by random driver behaviour. Qiaoru *et al.* (2011) relying on traffic shock wave theory studied the influence of moving bottleneck caused by large trucks in the traffic stream through simulation with VSSIM software. Suzuki and Matsunaga (2010) evaluated the safety of platooned vehicles based on shock wave theory. Duret *et al.* (2010) examined the onset of traffic congestion due to low-speed merging manoeuvres in the traffic stream using shock wave theory. The range of applications of shockwave theory on highway segments can therefore be extensive according to Newell (1993) Kinematic wave theory was proposed jointly by Lighthill and Whitham (1955). Lighthill and Whitham (1955) postulated that there exists some functional relationship between flow and density that may vary with location but not with time. Where location is x and time is t ; then:

$$k(x, t) = k(q(x, t), x) \quad (1)$$

The most widely known high order models still require an equilibrium speed-density relationship:

$$\left[u_f - 2u_f \frac{k}{k_j} \right] \frac{\partial k}{\partial x} + \frac{\partial k}{\partial t} = 0 \quad (2)$$

where,

u_f = The free flow speed and k_j the jam density.

If it assumed that there is no vehicle entering or exiting the traffic stream, then the equation of continuity can be applied to equation 4 to give a partial differential equation 3 for $q(x, t)$:

$$\frac{\partial k(x,t)}{\partial t} + \frac{\partial k(x,t)}{\partial t} = 0 \quad (3)$$

This is an exaggerated assumption nonetheless:

$$S_{w(q(x,t),x)} \frac{\partial k(x,t)}{\partial t} + \frac{\partial k(x,t)}{\partial t} = 0 \quad (4)$$

$$S_w(q, x) = \frac{\partial k(q, x)}{\partial q} \quad (5)$$

Drivers experience kinematic wave whenever he/she adjusts his/her speeds in accordance with the behaviour of the car or cars in front, on observing a brake light, or an opportunity to overtake. After all a wave is the propagation in time and space of a disturbance in a medium. Shockwave is a formation of an abrupt change in traffic stream with compressive characteristics. According to Wikibook (2013) ‘Shockwaves are byproducts of traffic congestion and queuing. They are transition zones between two traffic states that move through a traffic environment like, as their name states, a propagating wave.’ The statement is also supported by Khisty and Hall (2008). Now, if the assertion that, ‘traffic shockwaves are post capacity byproducts is to hold, then shockwaves cannot occur before capacity is reached. So, care should be taken when expressing traffic dynamics in wave so as not to misrepresent shockwave for kinematic wave. Shockwaves discontinuity arises from abrupt changes in density as a result of a disturbance to the flow. Disturbances to traffic may be due to internal or external sources.

As illustrated above in Fig. 1 resultant kinematic wave will operate along lines C, A and B should the lead driver brake abruptly due to changes in traffic, roadway, weather or ambient conditions. Traffic shockwave speeds operate between A and B (Fig. 1); so care should be taken when expressing traffic kinematic so as not to misconstrue as traffic shock wave. As contained in many literatures, flow/density curve has two sections (constrained and unconstrained). The constraint is capacity. The two sections behaved differently. Flow oscillates in the unconstrained section

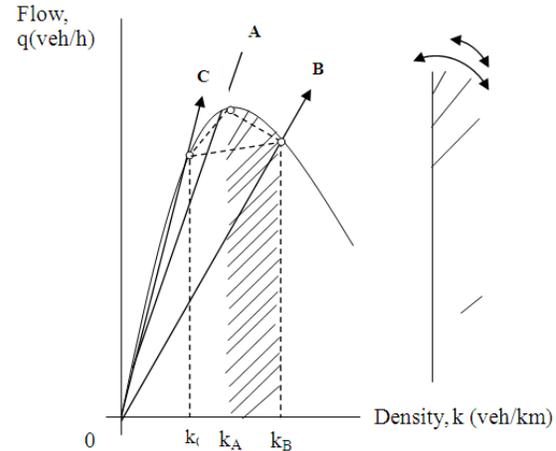


Fig. 1: Flow-density curve

and flowrate contracts in the constrained section. Rarefaction wave is the effect that the kinematic profile with diverging characteristics has thinned out over time. In essence rarefactions are post shockwave formations, keep in mind that shockwave is a post capacity kinematic wave. Rarefaction can occur in circumstance where traffic change is spread across the stream simultaneously, for example at the onset of rainfall or snow. However, rarefaction expansion is limited to pre-capacity section of the flow/density curve (C, A) as shown in Fig. 1. As mentioned earlier, traffic shockwaves are by-products of congestion and queuing whereas rarefaction waves are merely the kinematic effects that thin out over time. In theory, where the flow /density relationship has been used to compute roadway capacity according to Minderhoud *et al.* (1997) and Ben-Edigbe and Ferguson (2005) the critical density is reached at the apex point. Beyond the apex point, traffic flowrate is operating under constrained condition. Equation 1 below has been used extensively in many literatures as speed-flow model equation:

$$q = k_j \left(u - \frac{u^2}{u_f} \right) \quad (6)$$

for $u = u_f - \frac{u_f}{k_j} k$ and $q = uk$

Consider Equation 1 again, for maximum flow:

$$\frac{\partial q}{\partial k} = u_f - 2 \left(\frac{u_f}{k_j} \right) k = 0$$

Then, critical density:

$$k_c = \frac{u_f}{2 \left(\frac{u_f}{k_j} \right)} \quad (7)$$

If k_c is plugged into equation 1 highway capacity (Q) can be estimated:

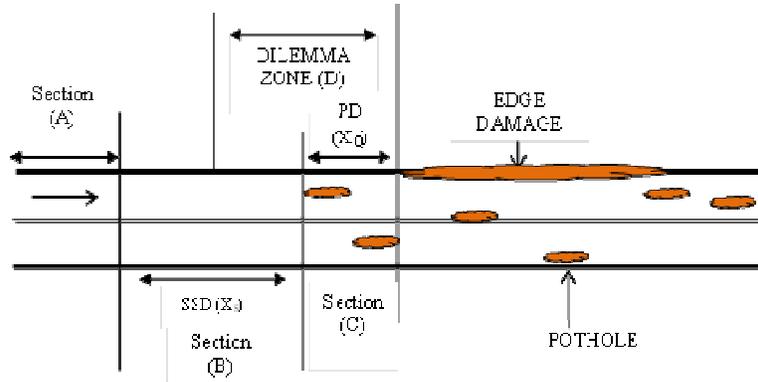


Fig. 2: Typical survey site layout; SSD (Xs): Stopping sight distance; PD (Xo) pavement Distress; Xo: L+W; L: Distressed road length; w: The road width; Dilemma zone, D = Xs-Xo

$$Q = \left(u_f\right) \frac{u_f}{2\left(\frac{u_f}{k_j}\right)} - \frac{u_f}{k_j} \left(\frac{u_f}{2\left(\frac{u_f}{k_j}\right)}\right)^2 \quad (8)$$

where, u_f represents the free flow speed and k_j the jam density.

Shockwaves are one of the major safety concerns because the sudden change of conditions drivers experience as they pass through a shockwave often can cause accidents, it can be argued. All traffic flow models and theories must satisfy the law of conservation of the number of vehicles on the road. Assuming that the vehicles are flowing from upstream to downstream, the continuity equation can be written as:

$$\frac{\partial k(x,t)}{\partial t} + \frac{\partial q(x,t)}{\partial x} = 0 \quad (9)$$

where,

x = Thespatal coordinate in the direction of traffic flow

t = The time

k = The density and q denotes the flow

However, one cannot get two unknowns, namely $k(x; t)$ by and $q(x; t)$ by solving one equation. One possible solution is to write two equations from two regimes of the flow, say before and after a bottleneck so that flow before and after will be same, or:

$$k_1 v_1 = k_2 v_2 \quad (10)$$

From this the dynamicwave equationscan be derived as:

$$k_w = \frac{q-Q_2}{k-k_2} \quad (11)$$

$$S_w = \frac{Q_1-Q_2}{k_1-k_2} \quad (12)$$

$$R_w = \frac{q-Q_1}{k-k_1} \quad (13)$$

where,

k_w = Kinematic wave

s_w = Shock wave (km/h)

R_w = Rarefaction wave (km/h)

q = C (Fig. 1) flow before (veh/h); k = corresponding density (veh/km)

Q_1 = A (Fig. 1) maximum flow before condition (veh/h)

Q_2 = B (Fig. 1) maximum flow after condition (veh/h)

If equation 8 is plugged into equation 11, 12 and 13 then, traffic kinematic and shockwave equations can be re-written as:

$$k_w = \frac{q}{k} - \frac{\left\{ \left(u_f\right) \frac{u_f}{2\left(\frac{u_f}{k_j}\right)} - \frac{u_f}{k_j} \left(\frac{u_f}{2\left(\frac{u_f}{k_j}\right)}\right)^2 \right\}}{k_2} \quad (14)$$

$$S_w = \frac{\left\{ \left(u_f\right) \frac{u_f}{2\left(\frac{u_f}{k_j}\right)} - \frac{u_f}{k_j} \left(\frac{u_f}{2\left(\frac{u_f}{k_j}\right)}\right)^2 \right\}_1}{k_1} - \frac{\left\{ \left(u_f\right) \frac{u_f}{2\left(\frac{u_f}{k_j}\right)} - \frac{u_f}{k_j} \left(\frac{u_f}{2\left(\frac{u_f}{k_j}\right)}\right)^2 \right\}_2}{k_2} \quad (15)$$

$$R_w = \frac{q}{k} - \frac{\left\{ \left(u_f\right) \frac{u_f}{2\left(\frac{u_f}{k_j}\right)} - \frac{u_f}{k_j} \left(\frac{u_f}{2\left(\frac{u_f}{k_j}\right)}\right)^2 \right\}_1}{k_1} \quad (16)$$

As illustrated in Fig. 2 road segment was divided into three sections with Section A as the upstream end and Section C the downstream end, while Section B was the transition section. Each section was fitted with automatic traffic counters in both directions for a continuous period of six weeks. Traffic data were supplemented with pavement condition data. Pavement distress length, width, depth, type, area and number of potholes were recorded. Video cameras were positioned at stations to provide added information

Table 1: Summary of model coefficients

Site	Without distress (Q_1)				With distress (Q_2)			
	Density- β_0	Speed $\beta_1 k$	Flow- $\beta_1 k^2$	R^2	Density- β_0	Speed $\beta_1 k$	Flow- $\beta_1 k^2$	R^2
001	168.5	127.6	2.02	0.982	99.6	50.3	0.44	0.918
002	8.1	123.9	2.22	0.872	39.4	50.3	0.51	0.967
003	99.3	113.3	1.82	0.978	186.3	59.1	0.53	0.974
004	59.5	112.4	1.78	0.968	63.6	49.8	0.49	0.949
005	58.1	108.0	1.82	0.992	49.7	48.1	0.47	0.956
006	69.4	113.3	1.68	0.929	151.9	55.2	0.51	0.981

Table 2: Estimated traffic kinematic and shockwave

Site	PD area m ²	Phnos	qpcu/h	k veh/km	Q_1 pcu/h	k_1 veh/km	Q_2 pcu/h	k_2 veh/km	k_w km/h	s_w km/h
001	262.3	15	624	5	1846	31.4	1338	57.2	13.7	-19.5
002	134.2	13	540	4	1720	28.2	1201	49.3	14.6	-24.6
003	219.6	09	744	7	1664	31.1	1461	55.8	14.7	-8.2
004	125.1	15	720	6	1715	31.6	1202	50.8	10.7	-26.7
005	195.1	10	746	7	1544	29.7	1181	51.2	9.80	-16.9
006	167.7	13	684	6	1841	33.7	1342	54.1	13.7	-24.5

PD-pavement distress; Ph-potholes

on roadcondition.It was observed at sites that heavy good motorists pay very little attention to pavement distress. Consequently, passenger car equivalency values were modified. A simple headway method was used to modify the PCE values. Modified PCE values were found to be lower than those presently used in Nigeria. According to Ben-Edigbe and Ferguson (2005) the study outcomes will not be adversely affected, irrespective of the method adopted in estimating PCE.

RESULTS AND DISCUSSION

Stepwise procedure was used in estimating traffic shockwaves. As shown in Table 1, flow/density model coefficients were estimated and tested for validity.

The model coefficients in equations shown in Table 1 have the expected signs and the coefficient of determinations (R^2) are much greater than 0.85 therefore, it can be suggested that a strong relationship between flows and densities exists. Further test statistics show that the F –observed statistics at 10 degree of freedom is much greater than F critical (4.94) suggesting that the relationship did not occur by chance. Also the t-observed statistic at 10 degree of freedom tested at 5% significance level is much greater than 2 thus suggesting that density is an important variable when estimating flow. Thereafter, traffic waves were estimated using equations 13 and 14. Rarefaction effect was inconsequential, hence ignored.From the results in Table 2, it can be seen that traffic kinematic and traffic shockwave are not the same. Traffic kinematic waves have values from 9.8 to 14.6 km/h whereas traffic shockwave values are from -8.2 to -24.6 km/h. Ensuing waves are not correlated with the size of distress area nor the number of potholes, rather they reflect the abrupt behaviour of the lead vehicle and the extent to which the lead driver reacted to distress. There are evidences in Table 2 to suggest that correlation exists between traffic shockwave and kinematic wave. Traffic kinematic waves cut across the free-flow and

congestion section of the flow/density curve. Traffic kinematic wave can occur without shockwave propagations;whereas traffic shockwave is a function of kinematic wave propagations.The effects of distress on traffic shockwaves were observed to be particularly significant in cases where the percentage of passenger cars was high. Thus, suggesting that passenger cars are more likely to be vulnerable to distress compared with trucks, buses and heavy good vehicles.

CONCLUSION

This study presents a systematic framework for solving kinematic waves arising from traffic flow along bituminous asphaltic concrete road. In particular, traffic kinematics was not treated as shockwave, rather as traffic dynamics that can trigger rarefaction or shockwave. Maximum flowrate polynomial estimation method based on extrapolation of the flows from flow and density curve was used. The method assumes that density at maximum flowrate is not affected by bituminous asphaltic concrete distress, which implies that traffic dynamics are fully the result of travel speed changes. Traffic shockwave of about -20km/h and traffic kinematic wave of about 13 km/h were caused by bituminous asphaltic concrete road with severe distress.The paper concluded that the hypothesis that bituminous asphaltic concrete with significant distress will trigger traffic kinematic that may accentuate rarefaction or shockwave is valid. Also that Pothole and edge damage are significant contributors to traffic shockwave propagations.

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