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Research Article

Quantifying Travel Time Delay Induced by Bituminous Asphaltic Concrete Pavement Distress

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Abstract: The aim of this study is to investigate the extent of travel time delay induced by bituminous asphaltic concrete pavement distress.Travel time delay is the difference between the actual time required by motorists to traverse a roadway section under pavement distress condition and the corresponding travel time under pavement distress-free condition. Pavement distresses are visible symptoms of functional deterioration of asphalt pavement structures. Since functional asphalt pavement distress deals mainly with ride quality and safety of pavement surface, the paper is concerned with estimating travel time delay caused by pavement distress. Consequently, a 'with and without' asphalt pavement distress impact study was carried out in Nigeria. Typical stretch of 500 m two-lane roadway was divided into three parts: free-flow, transition and distress sections. 24hr-traffic volumes, vehicle speeds and types were taken continuously for six weeks. Functional distress types and sizes were collected at all sites. Results show that about 18s total travel time delay would result from100m road length. The paper concluded that potholes and edge subsidence irrespective of how acquired will trigger significant travel time delay.

Keywords: Delay, distress, flow, pavement, speed, travel time

INTRODUCTION

About 80% of state-built roadways in Nigeria are plagued with physical defects especially potholes and edge subsidence. Unlike road humps that are installed with warning signs, potholes and edge subsidence appear randomly often without warning. Potholes and edge damage are likely to exacerbate traffic injury as well as create traffic stream disturbances by reducing traversable road width. Potholes and edge subsidence are often deft road conditions for motorists to navigate. If edge damage is thrown in the mix, drivers' are faced with a bigger dilemma because of restricted lane width. 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 shockwaves. The purpose of this study is to evaluate the quality of traffic movement along a route plagued with asphaltic pavement distress and also determine the locations, types and extent of traffic delays. HCM (Highway Capacity Manual) (2010) defines delay as "The additional travel time experienced by a driver, passenger, or pedestrian." Delay is thus the difference between an "ideal" travel time and the actual travel time. Since the definition of delay depends on a hypothetical "ideal travel time," delay is not always directly measurable in the field according to HCM. Travel Time Delay is the difference between the actual time required to traverse a section of street or highway and the time corresponding to the average speed of traffic under uncongested condition. It includes acceleration and deceleration delay in addition to stopped delay.The paper presents the outcome of travel time delay study on bituminous asphaltic concrete road with pavement distress.

MATERIALS AND METHODS

Bituminous asphalt concrete pavement irrespective of the number of carriageway lanes consists of a series of structural layers generally.The function of road surfacing is to enable good ride quality to be combined with the appropriate resistance to skidding and to resist crack propagation. Typical examples of road surface defects include are raveling, potholes and edge-break among others. Pothole may be defined as any localized loss of material or depression in the surface of a pavement that compromises the ride quality of the pavement. Potholes and edge subsidence can appear in varying sizes and depths to motorists who are not familiar with the route without warning, thus exacerbating the likelihood of traffic accidents. Potholes are open road surface cavity with at least 150mm diameter and 25 mm depth, UK Department of Transport (DTp)(1997). They grow in size and depth as wateraccumulatesin the hole andpenetrate into the base and sub grade, weakening support in the vicinity of the

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pothole. If edge subsidence is thrown into the pavement distress mix, motorists are faced with a bigger riding problem. At the moment there is a growing disquiet amongst road users with regards to the poor conditions of the road surface and preventable increase in travel time induced by distressed pavements.Travel time is a useful guide for measuring the effectiveness of roadways. It is a function of travel speed and distance traveled. It can be computed with Eq. (1) shown:

$$T = t_f \left\{1 + a\left(\frac{v}{Q}\right)^b\right\} \quad (1)$$

where,
T = Predicted travel time over length of road
v = Flow
Q = Capacity
t_f = Travel time at free flow speed;
'a' = The ratio of free-flow speed to the speed at capacity
'b' = Determines how abruptly thecurve drops from free-flow speed.

Dowling *et al*. (1997) adjusted equation1 such that 'a' = 0.20 and 'b' = 10. These updated curves generally involved the use of higher power functions that show relatively little sensitivity to volume changes until demand exceeds capacity, when the predicted speed drops abruptly to a very low value. Since the study is interested in predicting travel time where volume/capacity (v/c)<0.90, then a = 0.20 and b = 10. If the coefficients are plugged into equation 1, then predictive travel time shown below can be used:

$$T = t_f \left\{1 + 0.2\left(\frac{v}{Q}\right)^{10}\right\} \quad (2)$$

Note that free-flow travel time (t_f) in Eq. (2) is a function of road length (L) and free-flow speed (v_f). It can be written as:

$$t_f = \frac{L}{v_f} \quad (3)$$

Note also that capacity in equation 2 can be computedby various methods. It has been shown by Ben-Edigbe (2010) and Johnnie and Astrid (2013) that capacity (Q) in Eq. (2) can be estimated as shown below:

$$Q = (u_f)\frac{u_f}{2\left(\frac{u_f}{k_j}\right)} - \frac{u_f}{k_j}\left(\frac{u_f}{2\left(\frac{u_f}{k_j}\right)}\right)^2 \quad (4)$$

For maximum flow:

$$\frac{\partial_q}{\partial_k} = u_f - 2\left(\frac{u_f}{k_j}\right)k = 0 \Rightarrow k_c = \frac{u_f}{2\left(\frac{u_f}{k_j}\right)}$$

where,
q = Flow
u_f = The free-flow speed
k_c =Critical density
k_j = The jam density

As mentioned earlier, travel time delay is the difference between the actual travel times required to traverse a road section with functional pavement distress and the time corresponding to the average speed under pavement distress free condition. It includes acceleration and deceleration delay in addition to stopped delay. A vehicle approaching a pavement distress area would have gone through three driving sections (free-flow, transition and pavement distress). After the free-flow section, vehicles enter the transition zone with reduced speed (v_z) so that the travel time is adjusted to transition travel time (t_τ) and estimated as:

$$t_\tau = \frac{2L}{v_f + v_z} \quad (5)$$

where, delay is defined as an extra time spent by drivers against their expectation then the delay (d_d) due to deceleration (from $v_f$to vz) is:

$$d_d = t_\tau - t_f = \frac{2L}{v_f + v_z} - \frac{L}{v_f} \quad (6)$$

This delay is called deceleration delay because it occurs when vehicles decelerate before entering the pavement distress area. Delay when vehicles travel through the pavement distress zone is the difference between the travel time needed to pass through the pavement distress area at reduced speed and the travel time needed to pass the same length of the roadway without pavement distress at free-flow speed. If the length of a pavement distress area is L*m*, then the delay (d_z) of a vehicle travelling within the pavement distress area can be calculated as:

$$d_z = L\left(\frac{1}{v_z} - \frac{1}{v_f}\right) \quad (7)$$

Delay in Eq. (10) is incurred from reduced speed through the pavement distress area. Upon exiting the pavement distress area at reduced speed vehicles accelerate and choose speed. Time needed to reach the free-flow speed is a delay tied to loss time. The distance (s) travelled due to speed change from v_z to $v_f$is:

$$s = \frac{v^2 f - v^2 z}{2a} \quad (8)$$

where, a denotes average acceleration, Time needed for a vehicle to accelerate from v_z to $v_f$is:

$$t_1 = \frac{v_f - v_z}{a} \quad (9)$$

Assuming no asphalt pavement distress area, time needed for a vehicle to travel the same distance is:

$$t_2 = \frac{s}{v_f} = \frac{v^2 f - v^2 z}{2 a v_f} \tag{10}$$

Therefore, the delay for a vehicle to accelerate to free-flow speed is the difference between time t_1 and t_2:

$$d_a = t_1 - t_2 = \frac{v_f - v_z}{a} - \frac{v^2 f - v^2 z}{2 a v_f} \tag{11}$$

Given the bituminous asphaltic pavement distress scenario described so far in the paper, it is necessary to know the distribution of vehicle arrivals into the distressed zone. Sometimes vehicle queue can occur during free-flow period because vehicle arrival is ransom and probabilistic. Nonetheless queuing is a delay function that can be analysed with the application of queuing theory. Where the distressed zone is assumed to be a server with entry and exit points for vehicles in order of arrival, the average arrival rate of the vehicles is the traffic flow rate and the service rate of the system is the capacity of the distressed zone. Because of the randomness of road traffic, the queuing system can be represented as a system with Poisson arrivals, exponentially distributed service times and one server. Basically queuing theory assumes that vehicle arrivals are independent, motorists do not leave or change queues, large queues do not discourage motorists and the mathematics of waiting lanes has exponential distributions, Ngoduy (2011). Frankly these assumptions are slightly exaggerated; nevertheless, they provide reasonable answers. The queuing systems are usually described by three values: arrival distribution, service distribution and number of servers. M/M/1 where the rate of arrival is exponentially distributed, hump service times are exponentially distributed and there is only one hump, Li*et al.* (2011). Note that M denotes Markovian or exponentially distributed. Now if motorists are arriving at exponentially distributed rate λ, then the probability that there will be k driver after time t is:

$$P_k(t) = \frac{(\lambda t)^k}{k!} e^{-\lambda t} \tag{12}$$

where, utilization = ρ = λs = faction of time the hump is busy.

Based on Erlang's queuing theory the expected number of vehicles in the queue is:

$$E_{(n)} = \sum_{n=0}^{\infty} n P(n) = \frac{q_\lambda}{Q - \lambda} \tag{13}$$

The average waiting time that an arrival vehicle spends before entering the asphalt pavement distress area is:

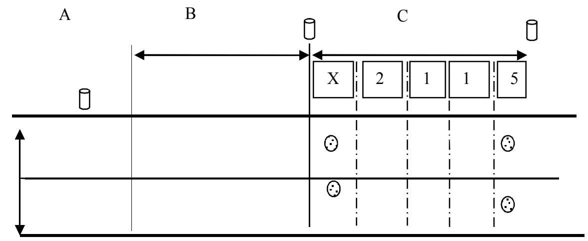

Fig. 1: Typical survey site layout; ATC denotes automatic traffic counter;-PD⊙denotes⊟pavement distress; Surveynote that A/W denotes pavement distress area

$$d_w = E_{(m)} = \frac{q_\lambda}{Q(Q - q_\lambda)} \tag{14}$$

where,
Q = Average departure rate from the queue
$q\lambda$ = Traffic flow arrival rate

Because there is a probability that the queue will be zero, the average queue length will not be one less than the average number in the queue. The average queue length (or the average number of vehicles in the waiting line) is:

$$E_{(m)} = \sum_{n=1}^{\infty} (n-1) P(n) = E(n) - q_\lambda / Q = \frac{q_\lambda^2}{Q(Q - q_\lambda)} \tag{15}$$

where,
E (w) = Average time a vehicle spends queuing
E (m) = Average queue length
E (n) = Expected number of queue
Q = Average departure rate from the queue and
$Q\lambda$ = Traffic flow arrival rate. In sum total travel time delay is:

$$d_T = V_h(d_d + d_z + d_a + d_w) \tag{16}$$

where,
v_h = Hourly flow of arrival vehicles at hour i.

Each survey section was fitted with 24 h automatic traffic counters in both directions and data recorded continuous period of six weeks. The road section used for the study was not a bottleneck. This was needed to remove peak-hour effect from ensuing outcomes. In sum, vehicles will traverse from free-flow to transition, then pavement distress area and finally exit the zone as illustrated in Fig. 1. The road is divided into subsections of 100m with the road register marker posts used for reference. Then for each distress mode, the extent and severity of the defect are recorded as shown in Table 1. Each surveyed road segment was divided into free-flow (A), transition (B) and pavement distress (C) section as shown in Fig. 1. The length of asphalt pavement distress area was limited to 100 (*Xm*,Fig. 1) at all sites for ease of computation and also

Table 1: Pavement distress area

Site	A/W m^2	Potholes (nos)	Depth (mm)	Length (m)	Width (m)
001	265	15	350	84.60	2.15
002	135	13	220	49.90	2.71
003	220	09	300	133.1	1.65
004	125	15	250	42.40	2.95
005	195	10	300	54.20	3.60
006	170	13	200	31.50	2.39

because the transition length is 100m. Transition length was taken as a function of Stopping Sight Distance (SSD) and computed using equation 17 below:

$$SSD = \left\{\frac{v^2}{2a} + vt\right\} \tag{17}$$

where,
v = Vehicle speed
t= Reaction time is 2.5s and deceleration rate (a) is $3.4 m/s^2$

RESULTS AND DISCUSSION

Observation at surveyed sites, trucks are less affected by pavement distress than passenger car and it can be argued that the passenger car equivalent values of trucks or buses are either the same or somewhat lower than those of passenger cars on roadways with significant number of potholes and edge subsidence. In order to take into account the effects of pavement distress on vehicles Passenger Car Equivalent (PCE) values were modified. PCEs can be defined as the ratio of the mean lagging headway of a subject vehicle divided by the mean lagging headway of the basic passenger car according to Seguin *et al*. (1998). Lagging headway is defined as the time or space from the rear of the leading vehicle to the rear of the vehicle of interest; it is composed of the length of the subject vehicle and the inter-vehicular gap. Since this is not the focus of the study, a simple headway method was used to derive PCE values for the road sections. In Table 2 and 3, results of computed model coefficients are summarized. Note that estimated model coefficients for all sites have the expected signs and the coefficients of determinations (R^2) are much greater than 0.85 therefore, it can be suggested that a strong relationship between flows and densities exists and the model equations could be used to estimate maximum flow rate. 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 that 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.

Average travel time delay per 100m stretch of road length with pavement distress is about 18s. If travel time delays areread in conjunction with pavement distress measurements, it can be seen from Table 4 and 5 that travel time delay does not depend entirely on the size of the pavement distress area. For example site 001 has the highest pavement distress area ($265 m^2$) with total delay of 18.42s per 100m length; compared to site 004 ($125 m^2$) with total delay of 18.07s per 100m length. Site 003 has the least number of potholes (9) spread over the entire 100m length. Site 003 has 30.95s total travel time delay suggesting that pavement distress spread has effect on travel time. However, the highest travel time delay occurred from average waiting time that an arrival vehicle spends before entering the asphalt pavement distress area. Site 5 with 10 number of potholes has second highest travel time delay of 19.31s and the average waiting time that an arrival vehicle spends before entering the distress area is 13.03s. Pavement distresses at site 005 cover the whole road width probably explaining why travel time delay is second highest. If an assumption of 5m road space per vehicle is applied, the maximum queue length would be 20 vehicles per 100m pavement distress road length of a two-lane highway.

Table 2: Summary of model coefficients

	Section without distress			
Site	*Density*-β_o	Speed $\beta_1 k$	Flow -$\beta_1 k^2$	R^2
001	168.5	127.6	2.02	0.98
002	8.10	123.9	2.22	0.87
003	99.3	113.3	1.82	0.97
004	59.5	112.4	1.78	0.96
005	58.1	108.0	1.82	0.99
006	69.4	113.3	1.68	0.92

Table 3: Summary of model coefficients

	Section with distress			
Site	*Density*-β_o	Speed$\beta_1 k$	Flow-$\beta_1 k^2$	R^2
001	99.6	50.3	0.44	0.91
002	39.4	50.3	0.51	0.96
003	186.3	59.1	0.53	0.97
004	63.6	49.8	0.49	0.94
005	49.7	48.1	0.47	0.95
006	151.9	55.2	0.51	0.98

Table 4: Travel time delay parameters

Site	V_f(s)	t_f(s)	V_z(s)	qλ	t_t
001	35.4	2.82	16.67	0.51	3.80
002	34.2	2.91	15.83	0.48	4.00
003	31.5	3.17	15.00	0.46	4.30
004	31.2	3.21	15.00	0.48	4.33
005	30.0	3.33	16.67	0.43	4.29
006	31.5	3.17	15.28	0.51	4.28

Table 5: Total travel time delay

Site	V_h	d_d	d_z	d_a	(d_w)	d_T
001	1846	0.98	3.17	4.42	9.850	18.42
002	1650	1.09	3.39	4.40	9.700	18.58
003	1504	1.13	3.49	3.89	22.44	30.95
004	1577	1.12	3.46	3.79	9.700	18.07
005	1449	0.96	2.67	2.65	13.03	19.31
006	1701	1.11	3.37	3.77	9.850	18.10

CONCLUSION

The paper presents the outcome of travel time delay study on bituminous asphaltic concrete road with pavement distress. Travel time was taken as the actual time required by a motorist to traverse a road section under prevailing condition. Pavement distress was taken as physical constraints on roadway significant enough to act as vehicles speed reduction impediments to an otherwise free traffic flow. Based on the discussion in the previous section it is correct to conclude that:

- There is a significance change in travel time between road length the 'with' and without distress.
- Average travel time delay was attributed to pavement distress per surveyed 100m road length.
- Estimated travel time delay is substantial, the reason been that travel time was estimated rather than measured directly.
- Pothole and edge subsidence are significant contributor to travel time delay.
- Travel time delay is not solely dependent on the size and depth of asphalt pavement distress.

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