Impact of Pavement Roughness on Traffic Safety under Heterogeneous Traffic Conditions

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ABSTRACT: Highway safety is a major priority for public use and for transportation agencies. Pavement roughness indirectly influence drivers' concentration, vehicle operation, and road traffic accidents, and it directly affect ride quality. This study focuses on analyzing the influence of pavement roughness on traffic safety using traffic, pavement and accident data on dual and single carriageway operated under heterogeneous traffic conditions in South-west, Nigeria. Traffic crash data between 2012 and 2015 was obtained from the Federal Road Safety Commission (FRSC) and International Roughness Index (IRI) data from the Pavement Evaluation Unit of the Federal Ministry of Works, Kaduna. Crash road segments represented 63 percent of the total length of roads. IRI values for crash and non-crash segments was a close difference of 0.3,This indicates that roughness is not the only factors affecting occurrence of traffic crashes but a combination with other factors such as human error, geometric characteristics and vehicle conditions. Crash severity was categorized into Fatal, serious and minor injury crashes. In all cases, the total crash rate increases with increase in IRI value up to a critical IRI value of 4.4 and 6.15 for Sagamu-Ore road and Ilesha-Akure-Owo road respectively, wherein the crash rate dropped. The conclusion is key in improving safety concerns, if transportation agencies keep their road network below these critical pavement conditions, the crash rate would largely decrease. The study concluded that ride quality does not directly affect traffic crash rate.

KEYWORDS: Pavement conditions, traffic safety, International Roughness Index, crash rate, carriageway.

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I. INTRODUCTION

Most of the roads in Nigeria are in various bad conditions and many of them have become hazardous and source of economic concern in terms of high costs for various road users, loss of lives and property, and loss of highway investment (Abiola, et al 2010). The officials of various transportation departments wait for deterioration of small potholes into craters before correcting it. As roads are constructed and opened to traffic, all sort of activities develop around it and the hopes of people in the locality are raised after completion and opening of the roads to traffic, these hopes and aspirations soon become dashed as the road devolves and its level of service diminishes. (Owolabi and Abiola, 2011). The research focused on Sagamu-Ore expressway and Ilesha-Akure-Owo road which belong to different classes of highway (Single and Dual carriageway) and are considered among the accident prone routes in South-Western Nigeria (Owolabi and Abiola, 2011).

Several factors affect the traffic accident rate such as human factors, vehicular causes, environment, roadway geometry, traffic volume, pavement condition, and their combinations. Studies show that the majority of accidents are caused by human factors such as distraction, alcoholism, stress, physical deficiency and age (Garber and Hoel, 2015). Although pavement condition is not a major factor that affects accidents, maintaining good pavements would likely reduce accident rate. On the other hand, people might argue that when the pavement condition is poor, drivers tend to be more cautious and reduce speed, which in turn might reduce crash rate.

Pavement distress indirectly influence drivers' concentration, vehicle operation, and road traffic accidents, and it directly affect ride quality (Quinn and Hilderbrand 1972; and TRB 2009). The main objective of this study is to investigate the relationship between accident rate and pavement roughness. The study focuses on ride quality as the main distress types that could affect traffic accidents. Accident severity levels are separated in order to investigate which accident severity is largely affected by pavement roughness.

II. LITERATURE REVIEW

Several pavement distresses affect accident rates such as loss of friction, roughness, and rutting. Numerous studies have investigated the effect of loss of friction between pavement and tires on accident rate (Blackburn, 1978; Hall, 2009; Kuttesch, 2004; Noyce, 2005). Most of the studies showed good correlations between pavement friction and crash rate since loss of friction may cause skidding when the pavement is wet. However, limited studies have investigated the effect of pavement roughness on accidents.

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A. Pavement Roughness

Pavement roughness is an expression of irregularities in the pavement surface that adversely affect the ride quality of a vehicle and its operational costs (Masaeid, 1997). The purpose of pavement roughness measurement is to help produce consistent estimations of the ride quality of the pavement surface for network–level pavement management.

Pavement roughness is commonly measured in International Roughness Index [IRI]. This standard scale of roughness measurement is regularly used by the World Bank and it is widely accepted and adopted than any other scale. IRI is expressed in m/Km, mm/Km, in/mile.

Roughness can be termed or described as ‘ride comfort,’ ‘ride-ability,’ ‘smoothness,’ and ‘evenness’ (Sayer, 1986). Roughness is recognized by most traffic authorities as the best measure for ride-quality of road network among many other ways to quantify or assess road pavement. Owolabi and Abiola, (2011) supports and endorses the International Roughness Index (IRI) as the reporting unit for Nigeria roads. In evaluating the surface roughness on the selected section, the IRI roughness scale suggested by Sayers (1986) was followed. Table 1 shows description of the scales used in this study.

Table 1: Rating of the surface roughness following the suggestion by Sayers *et al* (1986)

Scale	Description of road roughness	Roughness Level
0 – 1.5	Airport Runway, Super highways	Excellent
1.6 – 2.5	New pavements	Good
2.6 – 3.5	Pavement with surface imperfections	Fair
3.6 – 5.0	Pavement with frequent depressions.	Bad
5.1 – 11.0	Frequent shallow depressions. Some deep depression.	Poor
>11.0	Deep gullies. Deep depressions – too rough to measure	Collapse

B. Relation between Pavement Condition and traffic Safety

Studies show pavement condition causes small percentage of accidents as compared to human factors such as distraction, alcohol, stress, physical deficiency and age (Garber, 2015). In spite of its small influence on accidents, maintaining good pavements would likely reduce the accident rate.

King (2014) inquired the effect of road roughness on traffic speed and road safety in Southern Queensland, Australia. The study discovered a strong relationship between higher crash rates and increased pavement roughness. Crash rates involving light vehicles were more affected by increasing roughness than crashes involving heavy freight vehicles.

Chandra et al. (2012) reported that crash rates tends to decrease as pavement condition improves from poor (IRI value of 11) to good (IRI value of 2.5), and then increases beyond this value. It is an assertion that very good pavement conditions are generally associated with higher speeds and subsequently higher crash rates

Cairney and Bennet (2008) determined the relationship between pavement condition characteristics and roadway traffic crashes in Victoria, Australia. They concluded that there was good relationship between roughness and crash rate following a polynomial relationship. However, no clear relationship could be established between pavement rutting and crash rate. Also, the extreme pavement roughness which was associated with high crash rate was only over a small proportion of the road network analyzed.

Li et al. (2013) results showed that crashes of higher severity occurred on roads with poor pavement condition compared to the roads with fair and good pavement condition. It equally observed that roads with very good pavement condition with vehicle travelling at high speed records relatively higher severity crashes. Purposefully having rougher pavements to achieve moderate speed roadways was suggested as a potential solution to avoid high severity crashes. However, another study by Li (2014) indicated that pavement with poor pavement conditions are responsible or cause for higher crash rates.

Tehrani et al. (2012) supported that there was an established relationship and good correlation between rut depth and crash rate for the studied segments. On the contrary, a study performed by Cenek and Davis (2004) showed that there is no significant correlation between IRI and safety.

Chan et al. (2010) investigated and established a relationship between accident frequency and pavement condition using IRI, rut depth and PSI as parameters for pavement characteristics. The results showed that IRI and PSI were significant in all types of models, whereas the rut depth model performed better in anticipating the accidents that occurred during night time only.

Roughness may have an advantage or benefit on preventing crash occurrence, as drivers reduce their travelling speed and are more alert, there is a limit as to where pavement roughness goes from being a safety benefit to becoming ride discomfort.

III. MATERIALS AND METHODS

This section highlights the data collection, processing and analysis that have been performed in the study. The data included traffic crash information, traffic volume (AADT), and IRI that were used in the analysis. The section also highlights the crash rate approach that was used in the study. The listed two types of data were collected for the years between 2012 and 2015: traffic crash data was obtained from the Federal Road Safety Commission (FRSC) and International Roughness Index (IRI) data from the Pavement Evaluation Unit of the Federal Ministry of Works, Kaduna. The pavement quality data records pavement roughness and surface distress information on each year between 2012 and 2014, and it is recorded on kilometer post basis. AADT and IRI on each segment for year 2015 are obtained on site by the research team to complement the data obtained for previous years.

A. Site Selection Criteria

Sagamu-Ore Expressway and Ilesha-Akure-Owo roads are among the accident prone routes within the south-western region, Nigeria (fig. 1). The routes are made up of mixed traffic operating on various transport modes and different vehicles class available in the road segment. The different types of vehicle have different characteristics affected by the environment surrounding the road. Such characteristics play a key role in the analysis of traffic flow characteristics, road capacity and road pavement.

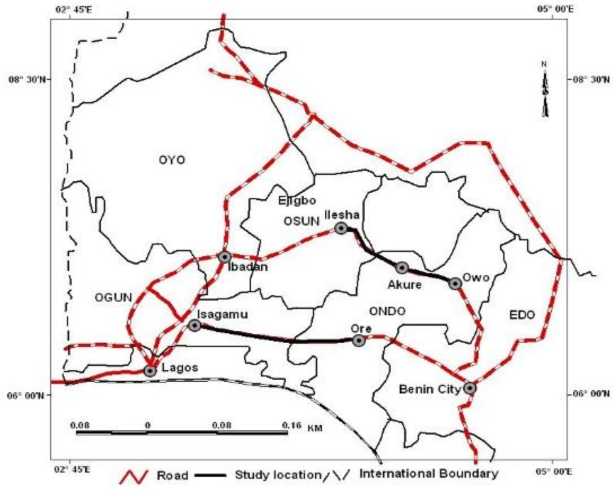

Figure 1: Map showing the studied roads.

The pavement condition of the roads at the time of the research ranges from fair to unsatisfactory. The pavements are characterized by cracks, rutting, depression and potholes that makes the riding quality poor. For the purpose of analysis, Sagamu-Ore Expressway and Ilesha-Akure-Owo road were divided into 74 segments and 55 segments respectively, with each section being 2km; the main factors that influenced the choice of length of road section were the road features, and road landmarks. Table 2 shows the characteristics features of study routes

Table 2: Characteristics of Case Study Routes.

Highway Class	Case Study Route	Length (Km)	No of Section
Dual Carriageway	Sagamu-Ore	149	74
Single Carriageway	Ilesha-Akure-Owo	110	55
Total		**259**	**129**

B. Crash Data

Traffic crash data were obtained from the FRSC units along the two selected routes, reported between the year 2012 and 2015. The crash severity was divided into three categories, namely Fatal, Serious and Minor injury crashes as described in Table 3.

Table 3: Summary of Severity Type.

	Severity Type	Description
1	Fatal Injury Crash	Death and Incapacitating Injury
2	Serious Injury Crash	Serious and non-incapacitating Injury
3	Minor Injury Crash	Bruises, light or non-injurious crash

According to WSDOT (2005) and Owolabi *et al*, (2012), a widely accepted approach to quantify crash rate is using a method which focuses on AADT and length of the road segment. This calculates the crashes per million vehicle kilometres travelled (VKT), the formula is expressed with Eq. (1):

$$CR = \frac{C \times 1{,}000{,}000}{V \times 365 \times N \times L} \quad (1)$$

where:
C is the total number of road traffic crashes in the study period
V is the Average Annual Daily Traffic (AADT)
N is the years for study period
L is the length of the roadway segment in kilometres

IV. RESULTS AND DISCUSSION

Data analysis was carried out to determine the relationship between crash rate and IRI. This section presents the results that show the relationship between the crash rate and IRI for all crashes put together and for each of the crash injury severities separately.

A. Statistics

Table 4 presents the basic statistics of the traffic volume (AADT), pavement roughness (IRI) and crash rate severity types obtained from the two selected routes. It can be noticed from the table that there are variations in IRI, AADT and crash rate values between the two selected routes.

Table 4: Statistical summary of the two selected routes.

	Variables	Min.	Max.	Mean	Std. Dev.	Variance
Sagamu-Ore Express way	AADT	12833	14618	13447.4	650.7	423458.9
	IRI	2.200	15.0	4.435	3.424	11.721
	Total Crash Rate	0.000	0.488	0.155	0.144	0.021
	Fatal Crash Rate	0.000	0.142	0.036	0.042	0.002
	Serious Crash Rate	0.000	0.325	0.069	0.078	0.006
	Minor Crash Rate	0.000	0.178	0.050	0.053	0.003
Ilesha-Akure-Owo Road	AADT	10344	12156	11159.7	784.1	614890.9
	IRI	2.1	12	3.645	2.220	4.930
	Total Crash Rate	0.000	0.864	0.233	0.247	0.061
	Fatal Crash Rate	0.000	0.150	0.034	0.041	0.002
	Serious Crash Rate	0.000	0.451	0.096	0.108	0.012
	Minor Crash Rate	0.000	0.601	0.103	0.137	0.019

B. Roughness Analysis

The results (as shown Figure 2) indicated a glaring pavement deficiencies on Sagamu-Ore road: about 60% of all sections on Sagamu-Ore road fall under fair pavement condition (Pavement surface imperfection), while about 18%, 11% and 8% are categorized as Bad (Pavement with frequent depressions), Poor (Frequent shallow depressions) and collapse (deep depressions) state respectively. On Ilesha-Akure-Owo road, largest percentage of 40% are in fair state, followed by 18%, 15% and 4% for Bad, poor and collapse state respectively.

Both selected routes exhibit unfavorable distribution, the observations and results fall within the range of “fair pavement” category. Ilesha-Akure-Owo road are of better pavement condition than Sagamu-Ore road, about 24% of total section are categorized as good roughness level, while partly 4% of Sagamu-Ore road are in good state.

Examination of sectional variations show that Ilesha-Akure-Owo road pavements appear to be in better condition than Sagamu-Ore expressway pavements, with average IRI value of 3.65 (figure 3), than Sagamu-Ore expressway with average IRI value of 4.44.

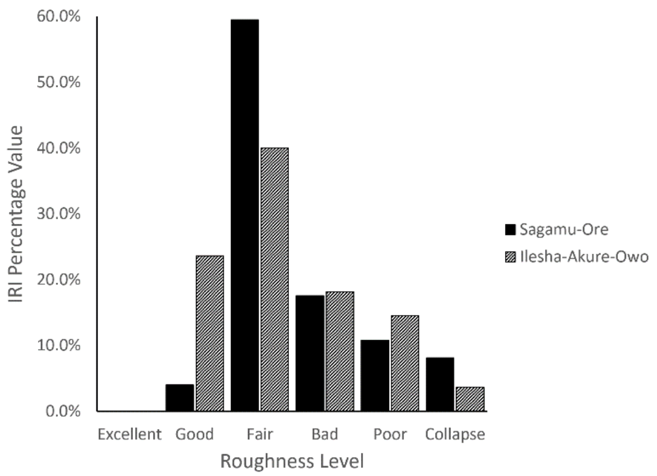

Figure 2: Distribution of International Roughness Index (IRI) on the two selected routes by roughness level.

C. Crash Investigations: Crash Segments vs. Non-crash segments

The study divided the entire study routes into crash and non-crash segments. Crash segments are the sections along the study route on which at least one accident occurred in the study period. On the other hand, non-crash segment is defined as the sections along the study route on which no crash occurred during the study period. One measure of the effect of roughness on the number of accident is to compare the average roughness values of non-crash segments with those of crash segments. Table 5 presents percent of length and the average IRI of crash and non-crash segments. A larger roughness average of crash segments than those of non-crash segments prove a negative effect on crash rate.

Table 5: Percent of length and the average IRI of crash and non-crash segments.

	Percentage Length		Average IRI		
	Crash Segment	Non-Crash Segment	Crash Segment	Non-Crash Segment	Overall Avg
Sagamu-Ore Expressway	60.8%	39.2%	3.66	4.44	4.93
Ilesha-Akure-Owo Road	65.5%	34.5%	3.45	3.65	3.75

Table 5 shows that crash segments represent 60-66 percent of the total length for the two selected routes using constant 2km segments interval. The table also shows that ride quality values of crash and non-crash segments are very close in each of the two selected routes. This suggests that ride quality is not the only factor influencing number of traffic crashes but in combination with other factors such as traffic volume, geometric characteristics, human factors, etc. By assigning the status of ‘crash segment’ or ‘non-crash segment’ to the selected routes, and then finding the average roughness of both categories, another approach to understanding the relationship between pavement roughness and crash rate is to determine the differences between crash segments and non-crash segments.

It is analysed by finding the average roughness value per section for crash segments and non-crash segment. It is evident from fig. 3, that the roughness on crash segments was higher than the roughness on non-crash segments for the two selected roads, the difference between average IRI values for crash segment, average overall IRI values, and average IRI values for non-crash segment. The findings show that there is a relationship between high roughness values and crash rates.

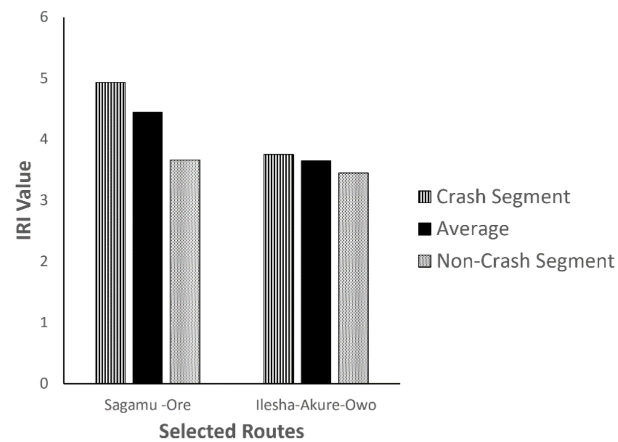

Figure 3: Ratio of crash segment and non-crash segment on the two selected routes.

D. Ride Quality and Crash Rates Analysis

Another measure of the effect of ride quality on the number of traffic accident is to evaluate the relationship between crash rates and IRI values for different accident severity types. Since accidents are relatively rare, both crash and non-crash segments were used for the analysis. If crash segments only were used, the large percentage of non-crash segments left will affect the analysis and skew the results

For each selected route, the points on the crash rate vs IRI graph are scattered, with no definite pattern, as shown in Fig. 4 and Fig.5. They show there is no established relationship between roughness and crash rates. Hence, IRI values were categorized into roughness level as indicated in Table 6 and

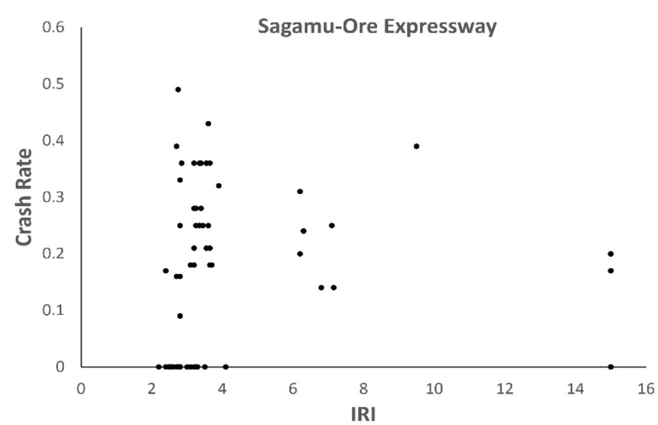

Figure 4: Crash rate vs IRI graph for Sagamu Ore Expressway.

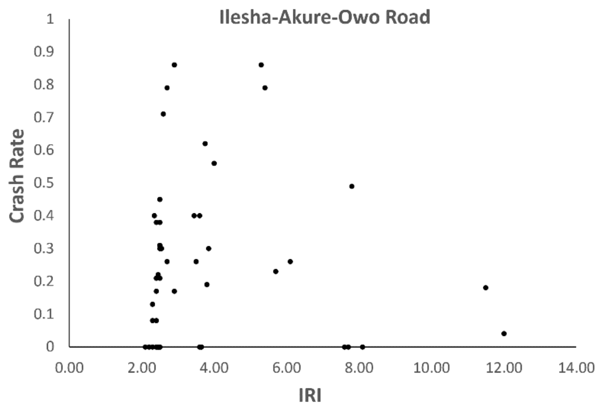

Figure 5: Crash rate vs IRI graph for Ilesha-Akure-Owo Road.

Table 7. For every segment, average variables were calculated for each of roughness level from the entire data, each curve fitting graphs were plotted (Fig. 6 and Fig. 7) to describe the effect on average IRI on different average crash rate severity types. Table 8 presents summary of IRI critical values of crash severities on the selected routes.

Table 6: Average Crash Rate vs Average IRI data for Sagamu-Ore Expressway.

Roughness Level	Avg. IRI	Avg. Total Crash Rate	Avg. Fatal Crash Rate	Avg. Serious Crash Rate	Avg Minor Crash Rate
Excellent	0.000	0.000	0.000	0.000	0.000
Good	2.333	0.057	0.011	0.000	0.045
Fair	2.914	0.126	0.032	0.056	0.038
Bad	3.650	0.238	0.049	0.118	0.071
Poor	6.944	0.229	0.048	0.117	0.073
Collapse	15.00	0.125	0.028	0.034	0.062

Table 7: Average Crash Rate vs Average IRI data for Ilesha-Akure-Owo Road.

Roughness Level	Avg. IRI	Avg. Total Crash Rate	Avg. Fatal Crash Rate	Avg. Serious Crash Rate	Avg Minor Crash Rate
Excellent	0.000	0.000	0.000	0.000	0.000
Good	2.335	0.128	0.029	0.053	0.046
Fair	2.550	0.253	0.037	0.101	0.116
Bad	3.685	0.273	0.024	0.130	0.119
Poor	6.713	0.329	0.052	0.117	0.160
Collapse	11.75	0.110	0.022	0.066	0.022

Table 8: Summary of IRI critical values of crash severities.

Selected Route	*Critical IRI Values*			
	Average Total Crash Rate	Average Fatal Crash Rate	Average Serious Crash Rate	Average Minor Crash Rate
Sagamu-Ore Expressway	4.4	4.8	4.4	4.4
Ilesha-Akure-Owo Road	6.15	6.4	3.75	6.15

I. Sagamu-Ore Expressway

Figure 5 shows the similar relationship between average crash rate and average IRI values for all the crash severity types. All the graphs show that bad pavement roughness does not basically increase rate of traffic crash. Deterioration in pavement roughness, which shows increase IRI value from 0 to 4.4 indicate increase in Total, Fatal injury and minor injury crash rate, in the same trend, increase in IRI value from 0 to 4.8 indicate increase in serious injury crash rate. Increase in IRI value (decrease in pavement roughness), beyond these critical values result in decrease in crash rate for all severity types. This generally indicate that, when the roughness is at critical deterioration level, it reduces the speed of the travelling vehicle, hence it reduces the probability of crash. This suggests that if the IRI value is kept below a certain limit value, crash rate can be significantly reduced.

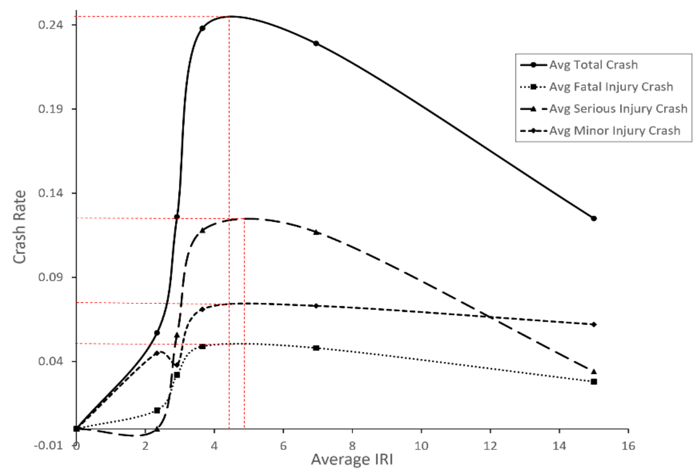

Figure 6: Crash rate vs Average IRI graph on Sagamu-Ore Expressway.

II. Ilesha-Akure-Owo Road

Figure 6 presents a relationship between average crash rate and average IRI values. Like the case of Sagamu-Ore expressway, all graphs show that bad pavement roughness does not basically increase rate of traffic crash. Deterioration in pavement roughness, which shows increase IRI value from 0 to 6.15 indicate increase in total crash rate and minor injury crash rate, in the same trend, increase in IRI value up 3.75 and 6.4 indicate increase in serious injury crash rate and fatal injury crash rate respectively.

Decrease in pavement roughness, beyond these critical values resulted in decrease in crash rate for all severity types. It seems apparently right that pavement roughness results in both impacts: a positive impact is due to unfavourable pavement roughness that slows down driving speed and reduce crash rate, and a negative impact is due to tendency of drivers to increase speeds on new smooth roads. As such, the net impact for a specific pavement condition may be positive or negative depending on factors such as the initial pavement condition, severity of crash, or type of crash.

E. Critical Safe Pavement roughness values

As indicated earlier, the crash rate essentially increase with the increase in IRI up to a certain critical value, after which the crash rate begins to decrease. This is similar for the two different classes of highway under consideration in this study.

Therefore, it is important to objectively define the critical IRI values below which crashes can be kept to a minimal rate. If a transportation agency maintains its pavement condition so that the IRI values do not exceed these critical values, accidents can be significantly reduced. Figure 8 indicates that to maintain a total crash rate on 0.15 and below on dual carriageway of Sagamu-Ore expressway, the IRI value must not be between IRI value of 3.0 and 13.2, likewise figure 9 indicated that to maintain a total crash rate on 0.15 and below on single carriageway of Ilesha-Akure-Owo road, the IRI value must be not be kept between IRI value of 2.45 and 10.85.

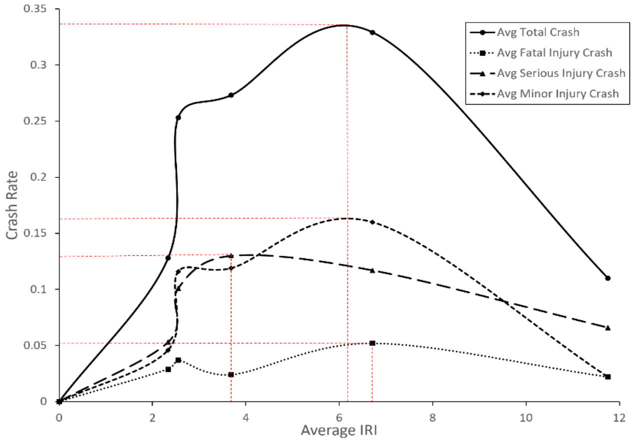

Figure 7: Crash rate vs Average IRI graph on Ilesha-Akure-Owo Road.

If a transportation agency does not keep its road network below these critical pavement conditions, the crash rate would largely decrease. The recommendation that safety can be improved by keeping roughness below a certain critical level is in full agreement with the concept of pavement preventive maintenance. Studies show that if an agency applies maintenance treatments early in the age of the pavement, the pavement would stay in a good condition for a long time (IHS, 2004). Therefore, applying maintenance treatments such as chip seal, pothole patching, rut sealing or thin overlay at early ages, not only would keep pavement in good condition for a long time, but also would make the road safer.

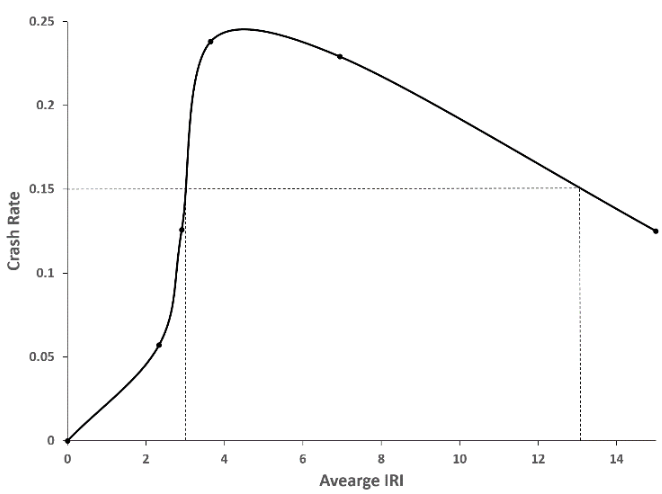

Figure 8: Range of critical IRI values for 15% crash rate on Sagamu-Ore expressway.

The overall results differ slightly from both the Australian and European International studies which show linear relationship between crash rate and roughness, but the results in this study shows that there is a substantial decrease in crash rate after a limit value or a particular roughness value has been exceeded.

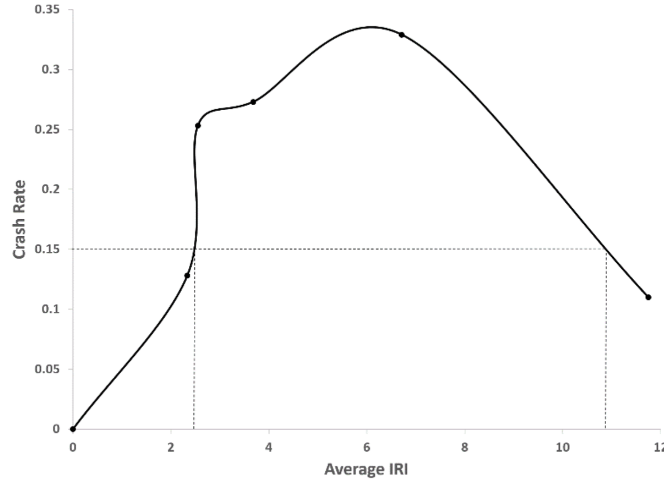

Figure 9: Range of critical IRI values for 15% crash rate on Ilesha-Owo-Akure Road.

V. CONCLUSIONS AND RECOMMENDATIONS

This study investigates the effect of pavement ride quality measured by the international roughness index (IRI) on traffic crash rate. These pavement condition parameters were obtained to develop relationship between pavement roughness and rate of traffic crashes at different severity types. One of the challenges of the research work was collecting the data from various sources, and obtaining common grounds for data matching and integration.

A. Conclusions

The following conclusions can be drawn from the results of this study.

i. IRI values of crash and non-crash segments on each selected routes were close to each other. This indicates that roughness are not the only factors influencing crashes, but combination with other factors such as roadway geometry, traffic volume, and other pavement distress measures.

ii. There is an established relationship between IRI and crash rate in all cases, concluding that crash rate increase up to a critical IRI value, above which crash rate starts to decrease. This phenomenon occurred for respective crash severity types, and for crash rate on the two selected roads.

iii. The critical IRI values to maintain crash rate below 0.15 are IRI values between 3.0 and 13.2 and 2.45 and 10.85 for Sagamu-Ore expressway and Ilesha-Owo-Akure road respectively.

B. Recommendations

The average critical values of IRI concluded in this study need to be used with caution because of the methods adopted in taking measurements between the selected routes. Traffic crashes are rare and uncommon events, therefore, more studies with large amounts of crash data and pavement data are required to confirm the results of this study. Future studies need to combine the effect of IRI with other contributing factors such as traffic volume, roadway geometry, human behavior, and environmental factors.

The results can be applied by traffic authorities in decision making, and should be validated in further research. It is suggested that the results can be implemented in order to make our road network a safer and more reliable transportation system for all users.

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