EASING THE BURDEN OF TRAVEL:
Can Roadway Capacity Modelling Help?

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SUMMARY OF PRESENTER'S BIODATA

Professor Hashim is a Civil Engineer who specialises in Transportation Engineering. He teaches at the Department of Civil Engineering, Bayero University, Kano where he trains both undergraduate and postgraduate students. He has supervised 18 Master of Engineering students in both Geotechnical Engineering and Transportation Engineering and has served as external Examiner to more than 18 Master of Engineering students in Transportation at the Ahmadu Bello University, Zaria. Currently, he is supervising 3 PhD and 10 MSc students in Transportation Engineering. He has published 37 articles in both conference proceedings and reputable local and international journals.

Professor Hashim Alhassan is a member of the Nigerian Society of Engineers (NSE) and a Registered Engineer with the Council for the Regulation of Engineering in Nigeria (COREN). He is also a member of the Materials Society of Nigeria, Nigerian Environmental Society and the Waste Management Society of Nigeria. Furthermore, he is a pioneer member of the Transportation Growth Initiative, a multi-disciplinary transportation action group that promotes research, development and best practices of all modes of transportation in Nigeria.

As an active member of his professional body, he participates as a resource person for his local branch. He also participates actively in the organisation of conferences for both his professional body and his Faculty and as a chairperson as well as panelist for technical sessions. He served the Nigerian Society of Engineers, Kano Branch as General Secretary for six years (1999 - 2005) and the NSE, Kabuga Branch a newly created branch as Technical Secretary with resounding success.

Professor Hashim is an active engineer in practice as well. He has designed and supervised 7 different roads for the Kano State Government at various times. The design and supervision of the Rigafada/Umarawa Residential Development Road Network Project in 2009 (Phase I) now popularly called "Kwankwasiyya Housing Estates". He participated in the Water Demand Assessment for the Greater Kano Water Distribution Network Study for Wardrop Nigeria Ltd under the auspices of the defunct PTF in 1996. He supervised "The Kano Traffic Study 2009" for the renewal of the road network in the Central Business Area of Kano.

Born on 15th September 1962, Professor Hashim hails from Adakawa area in Dala Local Government Area of Kano State. He had his B.Eng. degree at Bayero University, Kano in 1990 and his MSc (Transportation Engineering) at the prestigious Ahmadu Bello University, Zaria 1996. In 2009, he travelled to Malaysia where he did his PhD in Transportation Engineering. His research interests include Highway Capacity Studies, Transportation System Management, Traffic Signal Design and Capacity, Travel Demand Studies, Accident Studies, Pedestrian Studies, Area Traffic Control and Management, Road safety, Vehicular interaction Studies, GIS in Transportation.

He is married with 7 children and speaks Hausa and English fluently.

Easing the Burden of Travel: Can Roadway Capacity Modelling Help?

In the Name of Allah, The Most Beneficent; The Most Merciful.

"...And they carry your loads to a land you could not have reached except with difficulty to yourselves. Indeed your Lord is Kind and Merciful.

And [He created] horses, mules and donkeys both to ride and for adornment. And He created other things you not know." (Surat an Nahl: 7-8)

The Vice Chancellor
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Distinguished Past Inaugural Lecturers
Invited Guests
Family, Friends, Colleagues, Students
Ladies and Gentlemen
Assalamu Alaikum,

Preamble

It is a great honour to stand before this distinguished gathering to present my inaugural lecture. I wish to express my appreciation and support to the Vice-Chancellor, Professor M. Y. Bello for re-invigorating this important academic activity in this great university and for calling on us to be counted among those to contribute to this great endeavour. This lecture is an opportunity for me to inform colleagues in the University and the general public, about my research career so far; and to give an update on my current and future research directions. The aim of this lecture is to present the state-of-the art in road traffic modelling especially the capacity of roadways and to highlight the contributions of the presenter in this field. The presentation will also emphasise the implications of roadway capacities to sustainable road network and traffic management in Nigeria.

Introduction

For as long as the human race has existed, transportation has played a significant role by facilitating trade, conquest, and social interaction while consuming a considerable portion of time and resources. The modes of transportation as well as the travel infrastructure have changed as mankind increased in civilisation and technology. Before every other form of transportation, humans travelled on foot. The inconveniences associated with travelling on foot were directly proportional to the distance travelled and if goods were involved, the journey was even more formidable. Fortunately, human beings learned to use animals such as donkeys, horses and camels for transportation from 4000 BC to 3000 BC. In 3500 BC, the wheel was invented in Iraq and the first wheel was made from wood.

In the 17th and 18th century, many new modes of transportation were invented such as bicycles, trains, motor cars, trucks, air planes, and trams. In 1906, the first car was developed with an internal combustion engine. Many types of transport modes such as boats, trains, air planes, and automobiles were based on the internal combustion engine. A variety of each of the above mentioned transport systems have been added to the system making travel more convenient, safer, faster and reliable. Whereas the travel needs of the ancient man was to search for food, water, shelter and to make war or peace, the modern man has more reasons to travel than his ancient counterpart. Today we travel to go to school, work, shopping, leisure, medicare, social gatherings, sports, and uncountable number of discretionary trips.

A modern roadway transportation system consists of three elements: The road network, i.e. the surface on which the vehicles move; the vehicles which convey people and goods to various destinations and the human element that steers the vehicle to a safe destination. Sustainable and efficient transportation is one of the most important factors for the survival and progress of modern civilisation. However, the demand for transportation often overwhelms the available facilities for much of the time, resulting in severe constraints to traffic flow. This is caused mainly by the ever-growing urban population coupled with greater affinity to own cars and the lack of space within the urban conurbations to accommodate more expansion of road facilities. This imposes a natural constraint in the movement of persons and goods. As traffic grows in the midst of inadequate infrastructure and constraints in the flow, proven techniques and innovative ones are required to ensure free flow traffic.

Roadway Capacities

One consequence of modern travel is that there are few prepared surfaces for travel which everyone must use- the roadways. The number of people that desire to travel varies by time of day, by day of week, by month or season of the year and in response to singular events such as construction detours, accidents or other incidents and even severe weather. The traffic demand varies in time in ways that are quite inefficient. Therefore traffic engineers need to document these complex variation patterns and to evaluate the impact of ITS technologies and other measures on traffic demand. The maximum sustainable traffic flows on roadways is called its capacity. When traffic capacity decreases, travel inconvenience increases.

The definition of roadway capacity given in the Nigerian Highway Manual state that capacity is the ability of a road to accommodate traffic under given circumstances. The manual calls for the recognition of the physical features of the road and prevailing traffic conditions as the circumstances in question, Federal Ministry of Work and Housing (2013).

Also the definition of road capacity in the Highway Capacity Manual (TRB, 2010) emphasises the volume of flow, time frame involved, location, road geometry, observation period, roadway conditions, traffic mix and the regulations governing the movement of vehicles as the factors governing the capacity of roadways. The regulations governing the movement of vehicles on highway facilities are uniform and do not vary on a given road network. These can be found in the manual on uniform traffic control devices (FHWA, 2009). The other parameters involved in traffic flow evaluation affect the end result when any of these parameters change. First, traffic volume is associated with the unit of vehicles that pass a point or section of a highway. The volume varies widely between the time of day and day of the week. It also varies between the seasons of the year. The range of traffic volume for a typical day is from zero vehicles when there are no vehicles on the road to the maximum possible number of vehicles which coincide with the jam density. Between these two extremes, traffic fluctuates by time of day and day of week.

Secondly, to make any sense of this parameter requires a time unit to be associated with the observed numbers of vehicles on the road. The time unit of one hour is usually used to see traffic volumes trends in a day. Smaller units of time could also be used to study trends over short periods. Time units of 5-minutes, 10-minutes, 15-minutes are commonly used for detailed studies of volume (Polus and Pollatschek, 2002), (Minderhoud, Botma and Bovy, 1996), (L. Elefteriadou, Roess and McShane, 1995). What value of time to use therefore depends on the need of the study and the ability to observe the phenomenon under consideration? These are based on the premise that the averaging internal produces identical independent observations.

The third issue about road capacity is that its observed value at different locations on a road network give dissimilar values (Jiyoun Yeon, Sarah Hermandez and Elefteriadou, 2009). Furthermore, even at the same locations capacity values vary between number of lanes and road geometry. The observation period needed to see the maximum flows on a road must be at least one hour during the peak periods (Minderhoud, et al., 1996). Shorter periods may be necessary depending on the averaging interval used. Longer periods are the more common to acquire data over the trend of traffic flow. Further still, the physical roadway conditions such as lane and shoulder widths, lateral clearances, horizontal and vertical alignments and the storage width at intersections at any point in a network will influence the capacity values to be measured (Khisty and Lall, 1996). Traffic composition in terms of the variety of available vehicles and the proportion of each in the traffic stream also affects the value of capacity to be obtained.

Road capacity loss on a road link is the difference in flow rate above the capacity of the link or section. For the purpose of computing road capacity loss, the road capacities of the sections under consideration must be known, as such road capacity definition must be clearly stated. Thus the definition of capacity contained in HCM (TRB, 2010) is stated as follows *"In general, the capacity of a facility is the maximum hourly rate at which persons or vehicles can reasonably be expected to traverse a point or uniform section of a lane or roadway during a given time period under prevailing roadway, traffic and control conditions"*. The values of capacity have been questioned on the basis of reproducibility (Hall and Agyemang-Duah, 1991). They have also been found inadequate on the basis of the definition as it does not cover all situations for which capacity evaluation is required (Hall and Agyemang-Duah, 1991; Lorenz and Elefteriadou, 2001.), (L Elefteriadou and Lertworawanich, 2003) have further added that the current definitions of capacity are impracticable and inadequate for freeway systems. Finally (Jiyoun Yeon, et al., 2009) have affirmed that the traditional use of the value of capacity as deterministic is not correct. Thus both definitions of capacity contain inherent limitations in the measurement, value and applications of road capacity in traffic flow management. It is worthwhile to mention that the research efforts put into determining the value of road capacity underscores its significance in traffic flow management.

Significance

Road Capacity is significant because it's an important indicator of road performance and can point road managers in the right road maintenance and traffic management direction. Determination of road capacity is one of the main outputs in traffic studies and traffic theory analysis. Its value is a key input for facility selection, design and rehabilitation. It is used to determine the number of design lanes required on a new facility as well as assess the performance of an existing highway section to see if it can cope with the current traffic demand as well as the expected demand in the future. The three parameters of traffic namely: speed, flow and density are often employed to describe the operational state of any given traffic stream. The fundamental diagram illustrates the observed relationships between these significant parameters. The relationships are shown in figures 1, 2 and 3 respectively.

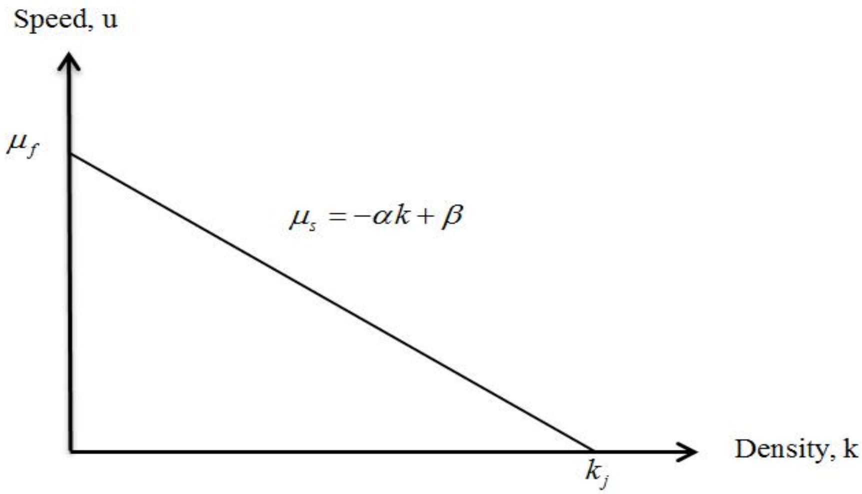

Figure 1: *Speed Density Relationships of Fundamental Diagram*

In figure 1 above, speed and density are related such that as density increases speed decreases and vice versa. These two parameters enable traffic engineers to relate travel demand directly to congestion on the freeway. Speed is the distance covered in a specified unit of time usually expressed in kilometres per hour (km/hr).

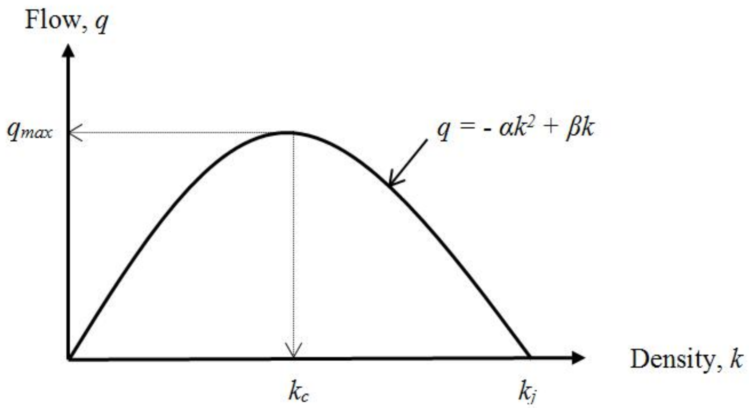

Figure 2: *Flow-Density Relationships of Fundamental Diagram*

The flow is the number of vehicle units that pass a given point or section in a unit of time. The relationship between flow and density is shown in figure 2 above. As flow increases, so is density. A point of maximum flow is reached above which vehicles rearrangement brings about closer packing within the available space. The maximum possible attainable number of vehicles per unit distance is the jam density and this situation considerably hinders flow.

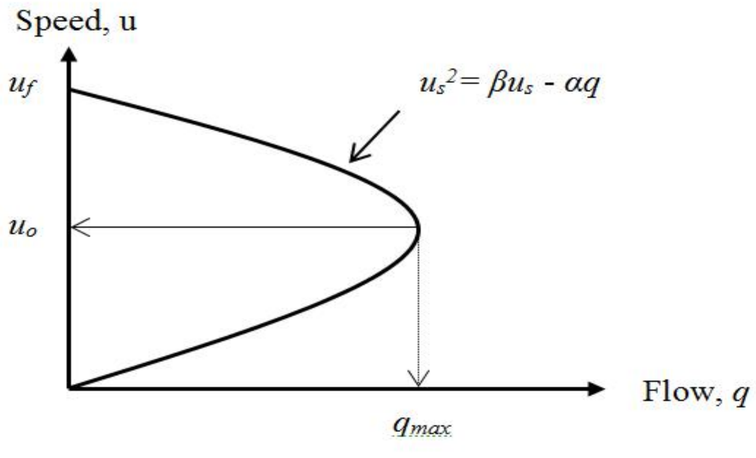

Figure 3: *Speed-Flow Relationships of Fundamental Diagram*

The relationship between speed and flow is shown in figure 3. Naturally, as the flow increases the speed decreases up to a maximum flow. Above this, the flow is dramatically reduced due to inter vehicle close packing. The quantity and quality of the flow is thus affected.

Traffic stream is made up of different types of vehicles and the road terrain is not uniform, some sections may require an ascending grade, another section a descending grade and yet another may be rough even though they appear to be straight. Therefore the performance of different terrains as well as the performance characteristics of the vehicles in the traffic stream is accounted for by way of passenger car equivalency values. These values are applied to vehicle volumes when converting to flows that accommodate all of the above features.

Passenger Car Equivalency Values

Passenger Car Equivalent or Unit is the aggregate of the relative number and composition of the different types of vehicles in the traffic stream converted to a single measure of the quantity of traffic flow. Passenger Car Equivalent was first mentioned in the Highway Capacity Manual (HRB, 1965) to depict the relative displacement of other vehicle categories in traffic to obtain a standard unit of capacity flow measurements. It is thus, an alternative way to state the capacity of a given section of a roadway. If the traffic mix could be determined, the flow along any section of a highway could be stated as either vehicle per hour or passenger cars per hour per lane etc. Measurement of the PCE values of most vehicles has not been conclusive because the PCE values are affected by factors similar to capacity. Studies on PCE values have concentrated on signalised intersections (Rahman, Okura and Nakamura 2003), congestion locations (A. Ahmed, Younghan and Hesham, 2005), mid-block sections (Rahman and Nakamura, 2005), and by simulation (Mallikarjuna and Ramachandra, 2006), (Nathan and Elefteriadou, 1999) and (Aggarwal, 2008.). These locations are important because they are where vehicle-vehicle interactions are greatest and the effect of other vehicles on the traffic stream easily discernible. The methods of PCE evaluation have also attracted some research attention; these include speed (HRB,1965) and (L. Elefteriadou, Torbic and Webster, 1997); delay (Cunagin and Messer, 1983), density (Webster and Elefteriadou, 1999); speed and density (Huber, 1982), and queue discharge factor (F. A. Ahmed, Fred and Emily, 2002). In any case, the use of such equivalents is central to road capacity analysis where mixed traffic stream are present.

Level of Service

Level of service is a measure of the quality of traffic flow of a roadway or a section of it. Level of service denotes the speed, convenience, and comfort experienced by drivers. The level of service has six ratings A to F that are used to evaluate the performance of a highway and planning for new facilities. Level of service A is the highest level and deteriorates gradually to the worst level F. The concept of level of service allows planners to design and operate highway facilities to a certain service quality. Facilities designed to level of service A are generally operated as high volume high speed facilities with complete restriction of access to abutting property. Driver selection of his desired speed is attainable and there is no restriction to driver manoeuvrability in inter-vehicle interactions. Typical facilities in this category are freeways and motorways. The distinguishing feature is the number of available lanes typically four, five and six in one direction.

Level of service B is the next in lower rank to A. There is slight degradation of speed because of increased interaction between vehicles. Drivers are still able to select their desired speed and travel with relative comfort. Facilities of this type are expressways and interurban arterials. Restriction of access to abutting property is relaxed and designated access points are indicated. Typical number of lanes is three lanes in one direction with weaving sections at at-grade intersections or ramps at grade separated junctions. Service level C has marked manoeuvrability problems and speed is highly restrictive at peak flows. Access to adjacent property is not restricted. Speed levels are much lower than their Level A and B counterparts. Most service level C facilities are urban highways with two lanes in one direction complimented by ramps or weaving sections at change points.

Facilities with level of service D to F are typically of the same standard. Single carriageway roads meant to serve the urban areas and economic activities within the urban setting. The quality of the flow is therefore a function of the flow rates and the Average Daily Traffic on each facility. High flow rates invite restrictive flow, hindered manoeuvrability and queue build up results. Where heavy vehicle composition is high traffic instabilities are a common feature. Bottlenecks and congestion are common with Level E service quality. In view of the interaction between different users of the transportation facilities, incidents are very high and the complex nature of their mobility requirements gives a warrant for control of the movements. When the service quality degrades to level F, small incidences result in prolonged delays and the traffic is characteristically of the stop and go type.

All facilities from service level A to F may occasionally suffer service quality degradation. A facility operating at service level A may suffer quality loss if flow rates increased to cause severe hindrance to manoeuvrability. Similarly, over the long term increase in vehicle population and growth in the number of attraction points of a particular highway might cause disproportionate rise in demand for travel far in excess of designed service level. Certain features of the roadway system impede the smooth flow of traffic and ambient conditions contribute to flow disturbance. Thus it is critical to continuously assess the performance of highways to ensure sustainability of qualitative service. Travelling convenience is therefore closely associated with the provision of an appropriate level of roadway service without exceeding the capacity.

Factors Influencing Road Capacity

Roadway capacity is constrained by factors associated with traffic, ambient and road conditions. Traffic conditions refer to the mix of vehicles and proportion of each in the traffic stream. Ambient conditions are usually weather, visibility, level of pedestrian activity, illegal parking and trading activity among others, while road conditions include curved sections, grades, and in-homogenous lane sections. Our concern is measuring the number of vehicles passing a given point on the road link under dry and rainfall, during daylight and peak and off-peak periods. As shown in figure 4, road capacity decreases relative to increase in poor weather conditions. Capacity loss which will result from heavy rainfall will increase inconvenience to drivers.

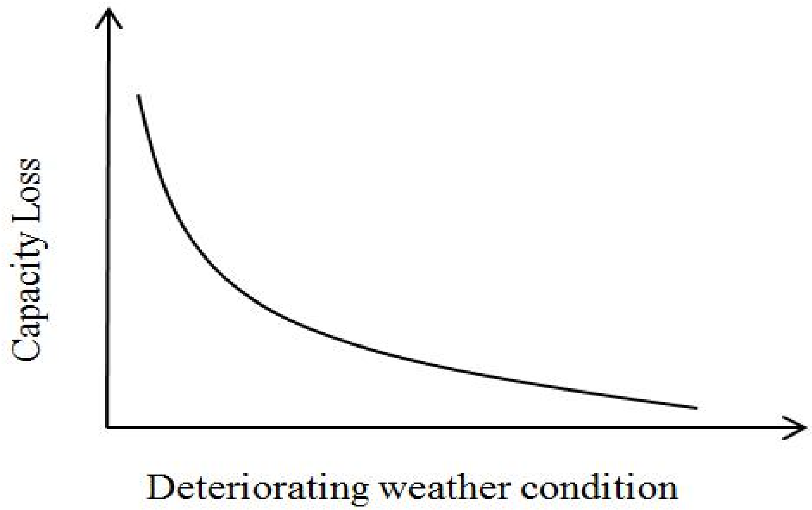

Figure 4: *Capacity and Adverse Condition*

Highway Capacity Estimation Methods

Highway capacity can be estimated through simulation as well as by direct empirical methods. They can also be estimated using the guidelines in the Highway Capacity Manual (HCM) (TRB, 2000). The HCM approach has been questioned by many researchers and will not be pursued further. Simulation methods involve modelling the flow with any appropriate traffic flow models and deriving the capacity in accordance with the model parameters. That has been found to often conflict with practical values. Empirical methods require observation and collection of data at a highway point or section and determining the capacity from the observed data. The remaining part of this section will dwell on direct empirical methods. (Minderhoud, et al., 1996) have given a detailed account of empirical highway capacity estimation methods and classified the methods as shown in Figure 5. Data required for capacity estimation include traffic volume, headways, speed, density and /or occupancy. The choice of location for observations may be at one or more cross sections. In some instances a bottleneck may be the best location. Congestion occurring upstream may enable a consistent flow to be observed downstream of the bottleneck. The following methods are used for capacity estimation; observed headways, observed volumes, observed volumes and speeds and observed volumes, densities, speeds.

Problems with Estimation Methods

All of the above mentioned estimation methods are associated with problems in their estimations except the volume, densities and speeds method. These are:

- They require traffic to be observed in bottleneck locations such as such as work zones (Rahim, Ahmed and Madhav, 2004), peak periods, on-ramps and flows with high HGV content (Cunagin and Chang, 1982).
- There is need for a sustained and uninterrupted flow of traffic through a section to see the limit. This is often unattainable.
- It is not possible to determine if the flow is being hindered upstream or downstream of the section.
- Even under sustained flow conditions, traffic flow values vary unpredictably over a wide range of conditions
- Highway capacity estimation methods using volume data assumes a fixed value of capacity,
- The traffic state upstream and downstream of the point or section is not known.
- Capacity estimation based on volumes and speeds also require observations in the vicinity of a bottleneck and do not furnish information on the distribution of densities at the observation point or section.

Observed Volumes, Densities and Speeds

The use of observed volumes, densities and speeds in the estimation of highway capacity requires three macroscopic parameters. They are: q (traffic volume), u harmonic mean speed, and k density (or occupancy). With these, the so-called fundamental diagram (FD) can be constructed from any two variables. The use of fundamental diagram offers four advantages that other methods lack. First the traffic state can be determined at any point required; this gives full information required to assess traffic performance. Secondly, data need not be acquired at a bottleneck location to see the state of traffic at capacity. And thirdly, two variables suffice to construct the fundamental diagram. The third parameter is derived from the continuum theory of traffic flow:

$$q(flow) = v(speed).k(density) \qquad 1$$

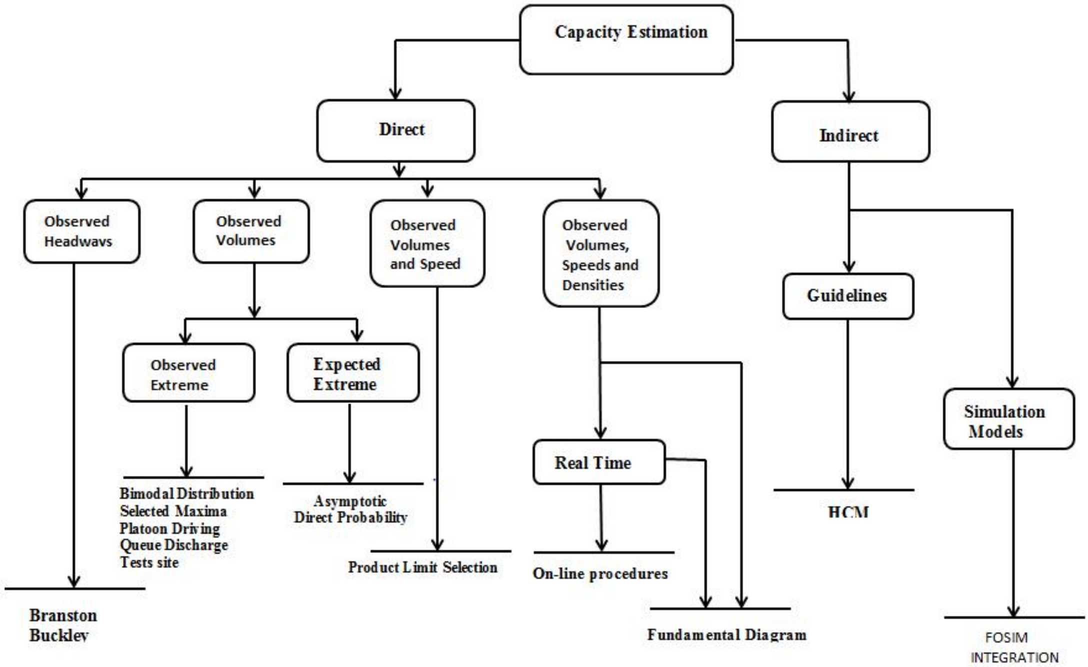

Figure 5: *Classification of Roadway Capacity Estimation Methods (After Minderhoud et.al. 1996)*

Finally, the fundamental diagram approach could be used to model different conditions of the flow. A fundamental diagram is constructed for each condition and these are superimposed on the same graph for comparison. (van Aerde, 1995) used the FD to study single-regime speed-flow-density relationships. Rakha (2008) also used the fundamental diagram to study the impacts of weather on freeway traffic stream. (Billot, 2009) applied the bivariate speed-flow relations to study the effect of adverse weather on traffic. Other uses of the fundamental diagram include its use in evaluating the PCE values of heavy vehicles in the traffic stream as in the study by (Stephens and Immers, 2008).

For capacity studies data generated from any site need to span over a long period to make curve fitting possible. If the observed traffic state is unstable or even congested the results of the curve fitting depend too much on the type of curve selected because of the great variance in these values Minderhoud *et al*. (1996). To evaluate the capacity, the fundamental diagram is constructed from the flow density relationship. In this case, the maximum intensity is located at a certain critical density, k_c.. The capacity value can graphically be derived from the fundamental diagram. Different models are available to fit the data and so the value of capacity depends on the model chosen. The capacity can also be derived by calculating the maximum of the curve, where the derivative of the function equals zero.

The averaging interval for observation and aggregation is arbitrary. High flow of traffic can vary between very short periods say, 1min and may occur less frequently over longer periods. (van Toorenburg, 1986) recommends 15-min intervals because independence of observations could be assumed and the averaging intervals can be defended. Furthermore, local fluctuations are smoothed out and the maximum traffic volume can hold for more than the duration of the interval. To improve the methods of capacity estimation, it is necessary to identify highway features and incidences that degrade the flow rates or capacity and these are discussed next.

Highway Capacity Disturbances

Highway features that are known to affect capacity are curve sections, grades, merging lanes, intersections, work zones and on - off ramps. These features are locations on the highway network where changes in alignment are met, or the geometry of the roadway changes. Drivers cope with these situations by reducing speed. At high flow rates the flow breaks down at these locations, queues build up and capacity is lost. Some researchers are of the view that to measure capacity on a roadway, the measuring site must be located downstream of a constrained point or congested location. This ensures that consistent flows emerge from the bottleneck Minderhoud *et al.* (1996).

Highway curve sections, grades, merging and diverging lanes (number of lanes) are specifically catered for in the HCM (TRB, 2000) as reduction factors because of the drop in capacity that occurs at such locations. It is therefore not surprising that most capacity studies in normal or dry weather are carried out in the vicinity of fixed bottlenecks where the flows emerging from the bottlenecks are the highest. Elefteriadou, Roess, and McShane, (1995) for instance measured the capacity and observed the breakdown phenomena at freeway-ramp junctions. Similarly, Lorenz and Elefteriadou (2001) studied the capacity and the mechanism of flow breakdown at two freeway-ramp merge junctions in Toronto, Canada and suggested a modification of capacity definition. Further work in this area was done by Eleferiadou and Lertworawanich, (2003). Their work identified four maximum flow rates which could be taken as the value of capacity. These are: the breakdown flow, the maximum pre-breakdown flow, the maximum discharge flow and maximum queue discharge flow. The variability in the value of capacity will remain a debatable issue in the future because the issues surrounding it cannot be resolved by capacity considerations alone. Geometric design and safety and economic considerations are also accorded priority in highway engineering practice. Most new highway facilities are adequate in capacity at the time of their completion. However, changes in land use such as housing development, industrial estate location, social amenities expansion, etc, attract additional traffic demand on the road to reduce the capacity during its life.

Traffic incidences also contribute their share of capacity reduction on highways. Traffic incidence may be defined as any disturbance to traffic flow which results in speed reduction but does not lead or cause an accident. At high flow rates such incidences may lead to queue build-ups, congestions and excessive delays. Leading causes of traffic incidences are reduction in speed for no apparent reason, roadway obstacles, load spillage on highways, and phantom jam. Traffic incidences may also result from peak flows during rush hours and disabled vehicles left standing in the road particularly heavy vehicles. The effects of some of these disturbances are temporal in nature and may not recur at the same location again. The congestion arising from these disturbances may not recur if the disturbances are removed. Recurring congestion are those that occur due to repetitive incidences such as peak hour flows. The capacity related problems caused by recurring traffic incidences may require a transportation study to evaluate the demand and supply aspects of the system. In most cases, a capacity study is carried out to determine if adequate capacity exists for current and future demand for transportation.

Capacity reduction may also result from poor pavement conditions, movement through a work zone and road closures. In this case there is a physical restriction to movement and the traffic contracts leading to speed reductions and queue build up. Road networks with timely maintenance interventions do not present prolong changes in capacity. Pavement maintenance and work zones contribute to capacity drop because the repair lane or the work zone has taken a lane or lanes out of service. The traffic flow pattern prior to the work zone and the transitions into the work zone are not the same. Furthermore, there are additional design features such as temporary traffic barriers, reduced lane widths, and crossover sections which influence vehicle speeds, (Douglas *et al*., 2007). Consequently, a bottleneck forms and capacity drop results. Road closures may have significant impact on capacity if adequate measures are not taken to inform the travelling public to use alternative routes. Even then, the alternative routes will experience demand beyond the ADT for the routes due to additional demand from the closed route and this could stretch to capacity limits particularly at peak periods. The strength of the disturbances to highway capacity on roadways may vary from one road network to another yet similarities may exist. Typical case studies need to be discussed to identify problems related to capacity on a particular network.

Highway Capacity Loss and Trapezoidal Flow Contraction

The issues affecting highway capacity loss or reduction have been discussed earlier. It is credible to say that highway capacity loss or reduction can be attributed to traffic flow contraction. Traffic flow contraction itself emanate from speed changes on the highway. Based on our discussions so far, the fundamental diagram approach is more appealing than other capacity estimation techniques to analyse two traffic flow conditions. The method yields complete traffic state information other methods cannot provide. A bivariate fundamental diagram is drawn for each traffic condition and these are superimposed for comparison. Works of this nature have been carried out by (Mallikarjuna and Ramachandra, 2006), (Billot, 2009) and (Ben-Edigbe, 2010).

Mallikarjuna and Ramachandra (2006) citing Huber (1982) used two flow rates for a traffic stream to compute the PCE of different vehicles. The base flow rate comprise of only passenger cars while the mixed flow rate contains mixed traffic with proportions of trucks. The impedance of each traffic stream was plotted against the flow and the impedance of base flow (cars) was compared with that of the mixed traffic to evaluate the PCE value of trucks. Billot (2009) studied the impact of rain on the fundamental diagram by comparing the fundamental diagram of no-rain condition to two rain conditions. He employed the speed-flow fundamental diagram to assert that rain decreases free flow speed under both conditions and that the decrease in capacity was due to changes in microscopic behaviour of drivers' time headways.

Ben-Edigbe (2010) applied the fundamental diagram to two pavement conditions in which one operated in normal condition (no distress) and the other was in distress (adverse condition). He then obtained new functions for speed, flow and density under adverse conditions. Changes in traffic flow conditions between normal and adverse conditions such as rain, dust storms, snowfall, or pavement distress can be used to explain traffic behaviour under those conditions and to determine the resulting flow rate changes to see if the capacity of the section is compromised under the adverse condition. The bivariate flow-density relationship can be used to analyse any such conditions and to obtain information on the traffic state of the roadway section under those adverse conditions. This is usually done in tandem with speed density diagrams in order for the information on the traffic state to be complete. Figure 7 is a typical flow density diagram with traffic in normal and adverse condition. Traffic in normal operation will fluctuate between zero to the maximum flow. Various states of flow can exist between the zero and the maximum flow. Generally, at high flow rates traffic operates at low speeds and vice versa. This situation could be described as normal traffic or free flow state.

Flow rates at maximum or the capacity of the highway facility and beyond, leads to rearrangement of vehicles and more drastic reduction in speeds results. In this situation, traffic becomes highly sensitive to perturbations. Traffic may recover from light perturbations

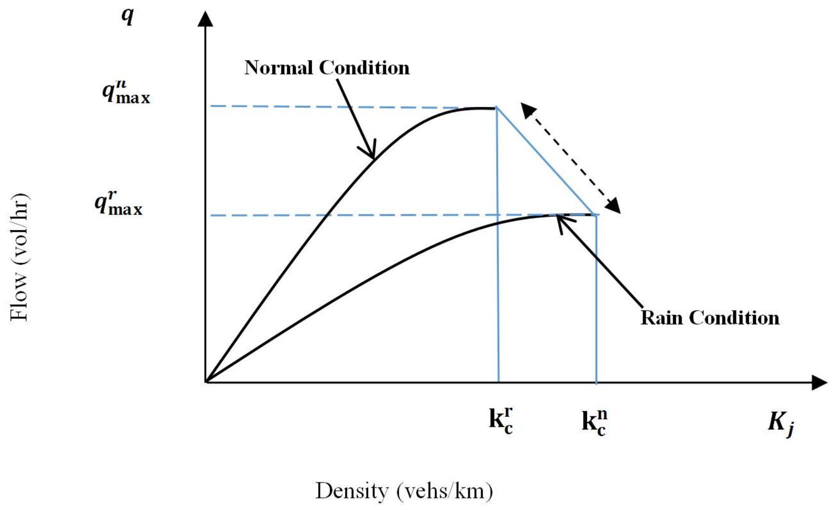

Figure 6: *Fundamental Diagram of Traffic for Normal and Rain Conditions*

but could be subjected to prolonged instabilities in the presence of strong perturbations. Also multiple perturbations to the flow may similarly lead to long instabilities. When instabilities persist on a road, the traffic flow becomes slow, and more close packing of vehicles occurs. Traffic is said to be congested. The causes of traffic congestion and therefore reduction in capacity have already been discussed earlier. From Figure 6, it is clear that traffic in normal condition would have to be constricted for the flow to be transformed into adverse condition. This constriction could be from fixed bottlenecks as well as from rainfall. The shape of the flow from the normal to the adverse state takes a trapezoidal shape and hence the term "trapezoidal flow contraction". The flow rate change from normal traffic to adverse traffic flow indicates the strength or weakness of the perturbation. A weak perturbation will give a low flow rate change and traffic could recover if the perturbation goes away. In the presence of a strong perturbation, higher flow rate change occurs and traffic instabilities persist for long times. To emphasise once more, rainfall adds to the variability in highway capacity, it is therefore pertinent to have a closer examination of rainfall measurements and intensities.

Our Research

Having discovered that disturbances to highway capacity include adverse weather we focussed on the impact of rainfall on capacity loss. One important question that needed to be answered was to what extent rain affects highway capacity loss.

However it must be added that when considering the influence of rainfall on capacity it is pertinent to question the extent to which peak travel also affects the outcome of road capacity loss. Irrespective of significant level, peak hour travels will cast doubt on the capacity loss outcome. This is so because peak hour travel has driving constraints imbibed within the traffic stream, thus making it a capacity loss condition that must be removed in the analysis.

Therefore it is postulated that the influence of rainfall under off peak travels will depict a scenario where the main driving constraint is rainy conditions. For traffic operating in the free-flow regime, typical flow-density diagrams between the rainy and the dry conditions could be represented as shown in figure 7. One important attribute of rainfall is that it does not restrain the traffic stream as physical bottlenecks do. Consequently rainfall spells that do not endure do not bring about a remarkable change in traffic states.

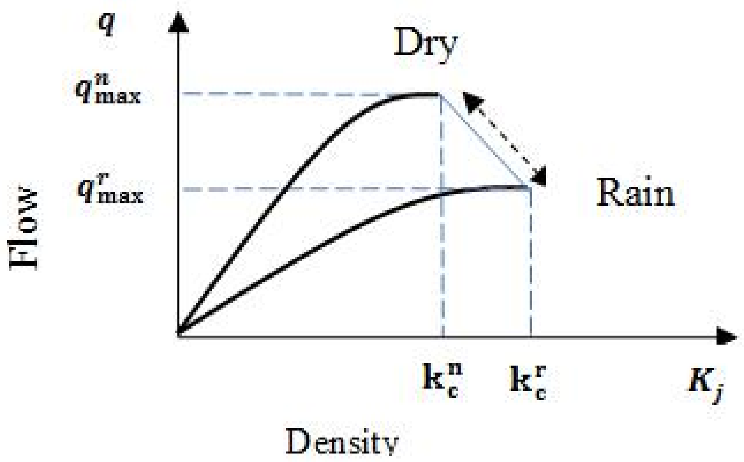

Figure 7: *Traffic Flow Contraction between Dry and Rain Conditions*

The diagram shows flow contractions between the rain and dry conditions and traffic density shifts in the free flow regime. In normal operations, the traffic state is depicted by ($q_{max}{}^n$, $k_c{}^n$), and the rain condition induces a shift or flow contraction from $q_{max}{}^n$ to $q_{max}{}^r$. The response of the traffic density is to shift from $k_c{}^n$ to $k_c{}^r$. From the flow-density plots the shifts for light rain and dry conditions are marginal. However, these widens for moderate rain conditions and widens further for heavy rain. This indicates that rainfall disturbances cause fluctuations to the flow which bring about a loss of capacity. Thus we can infer that:

There is a significance change in capacity between the 'with' and without rainfall conditions. There are no other factors other than rainfall that affected the traffic flow loss at the surveyed sites. Average loss of capacity was attributed to rainfall prevalent per surveyed road length per carriageway lane.

The estimated percentage of capacity loss is substantial; the reason being that capacity was estimated rather than measured directly. It must be noted that estimated capacity periods are dependent on time of rainfall, since rainfall is the control parameter in the study. The hypothesis that rainfall can influence roadway capacity loss remains valid. The results of the capacity loss is shown in Table 1.

Table 1: *Summary of Road Capacity Using Standard and Modified PCE Values*

Parameter	No Rain	Light Rain	Medium Rain	Heavy Rain
		Standard PCE		
SITE I	2115	1954	1779	1709
SITE II	1624	1448	1441	1427
SITE III	1987	1298	1273	-
SITE IV	1995	1768	1445	-
		Modified PCE		
SITE I	1842	1748	1619	1488
SITE II	1500	1558	1357	1228
SITE III	1655	1323	990	-
SITE IV	1851	1521	1067	-

Clearly, the capacity losses are considerable. For light rain conditions capacity losses range from 0.7per cent to a maximum of 23.3per cent for all sites. Capacity losses under moderate rain conditions are in the range of 3.8 per cent to 45.7 per cent. Under heavy rain the range of capacity losses is 8.9 per cent to 39.9 per cent.

The study also shows that it is not only possible to formulate a model on road capacity loss resulting from rainfall parameters but also that it is possible to verify the underlying hypotheses and assumptions of the model. In passing, it can be mentioned that by using historic database and the values of independent variables for similar highway, road capacity loss can be predicted; however, care should be taken not to extrapolate beyond the range of the observed data in the study.

Once the values of the explanatory variables have been established and tabulated, the ordinary least-squares estimation procedure was used to check the relevance of the variables. These values (independent variables) are then used as base for predictive computation of road capacity loss.

The conclusions we have drawn so far show that rainfall has significant impact on road capacity loss. Should the rainy conditions be stopped, road capacity loss would surely be improved substantially.

Highway Capacity Analysis Using Modified PCEs
The impact of rainfall on traffic flow is to cause speed reduction and flow contraction. Speed reduction and flow contraction also lead to bunching of traffic and bring about high vehicular interactions. Two implications of traffic bunching is the effect on PCE values of vehicles and traffic flow shock waves. The PCE values used in the NHDM are shown in Table 2.

Table 2: *Passenger Car Equivalency Values in the NHDM*

Type of Vehicle	Equivalent Value in p.c.u's			
	Rural Standards	Urban Standards	Round About Design	Traffic Signal Design
Passenger Cars	1.00	1.00	1.00	1.00
Motorcycle	1.00	0.75	0.75	0.33
Light Vans	2.00	2.00	2.00	2.00
Medium Lorries	2.50	2.50	2.80	1.75
Heavy Lorries	3.00	3.00	2.80	2.25
Buses	3.00	3.00	2.80	2.25

The study investigated into the implications of rainfall for passenger car equivalency values and found that:

- Rainfall affects PCE values
- Rainfall decreases PCE values for commercial vehicles relative to passenger cars.
- That the estimated percentage of road capacity loss is substantial.
- That the suggestion that depicts roadways in Malaysia as having PCE values of PC=1, LGV =2.0, HGV = 3.0 is somewhat misleading and may require further research works.

Table 3: *PCE Evaluation for Dry Weather Condition*

Vehicle Type	**Speed (m/s)**	**Density (veh/km)**	**Spacing (m/veh)**	**Headway (sec/veh)**	**PCE unit**
		Site I			
Passenger car	17.47	10.56	94.70	5.42	1.00
Light Goods Vehicles	16.98	10.56	94.70	5.58	1.03
Heavy Goods Vehicles	17.18	10.56	94.70	5.51	1.02
		Site II			
Passenger car	18.22	10.52	95.06	5.22	1.00
Light Goods Vehicles	17.88	10.52	95.06	5.32	1.02
Heavy Goods Vehicles	18.15	10.52	95.06	5.24	1.00
		Site III			
Passenger car	20.39	6.14	162.87	7.99	1.00
Light Goods Vehicles	19.55	6.14	162.87	8.33	1.04
Heavy Goods Vehicles	18.80	6.14	162.87	8.66	1.08

Generally, the modified PCE values gave lower road capacities but higher capacity loss because the modified PCE values were smaller and took account of prevailing road and traffic conditions. These are shown in Table 3.
Since PCE values are central to roadway capacity calculation it follows that the problem of passenger car equivalency values in road capacity analysis cannot be ignored.

On the one hand it shows the potential of commercial vehicles gaining control of road by exploiting the presence of rainfall. On the other hand it exposed the weakness of passenger cars as mode of transport during rainfall. The headways in this study increase with increase in rainfall intensity.

For the free flowing conditions, lower PCE values than the standard values are to be expected. Additionally, the PCE values increases again with rain intensity and still well below the standard. The implication of this on highway capacity computations under adverse weather conditions is that, there are decreases in highway capacity using modified PCE values. The trend continues as the rain intensity increases.
Under heavy rain intensity, two factors seemed to influence the result. First there is decrease in the number of heavy vehicles in the traffic stream making them less contributive to the final capacity value obtained. Second, the increase in the headways of heavy vehicles make them interact less with cars and the capacity decreases compared to the value obtained using standard PCE values.

Implications of Rainfall for Shock Waves Velocity Propagations
Traffic flow shock waves are formed when there is a discontinuity of flow on a highway section. This 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. The weather element and specifically rainfall disturbances to traffic flow has been under focus. We have further argued that flow contraction may have implications for PCE of vehicles as well as shock wave propagation.

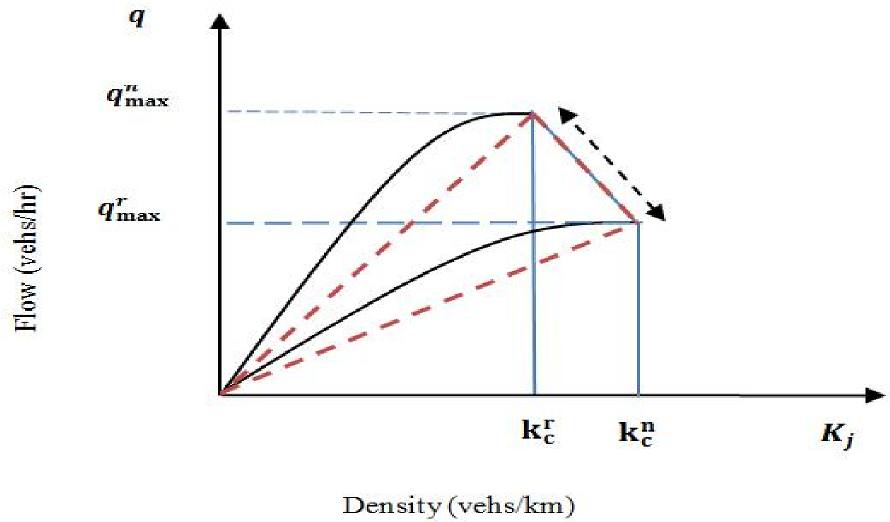

Figure 8: *Shock Wave Triangle Representation under Rainfall*

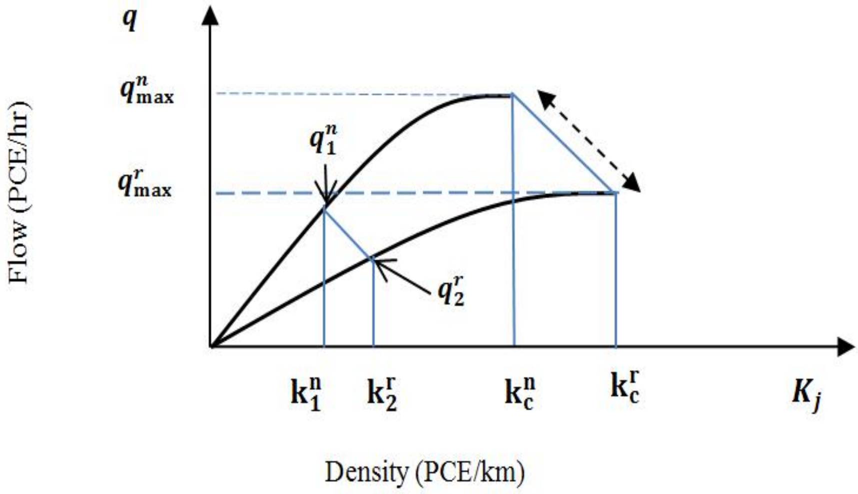

Figure 9: *Existing State of Traffic on Flow Diagram.*

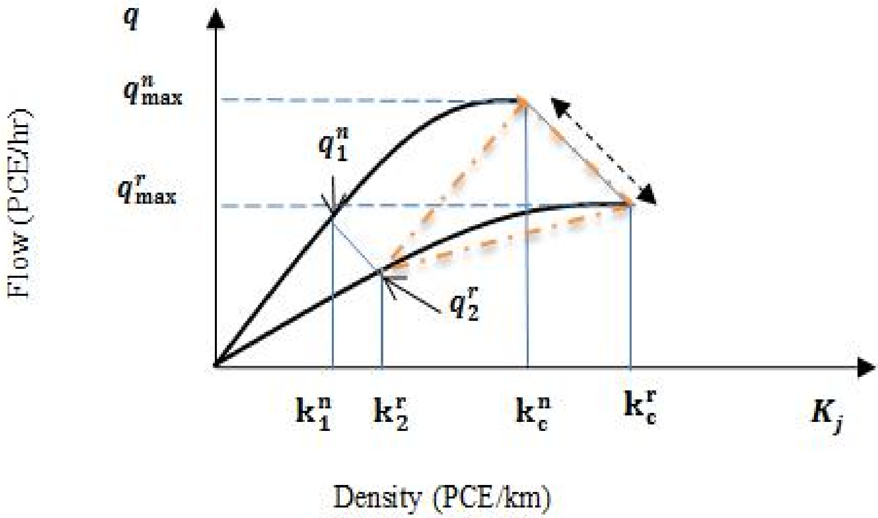

Figure 10: *Traffic Shock Wave Triangle*

In other words, rainfall does not act as a physical barrier to traffic flow. Lagging vehicles that catch up with the leader are unable to clear and a queue may form if overtaking is not possible. The leading vehicle becomes the discontinuity in the flow W_s and forms the boundary between the incoming flow and the discharge away from the leading vehicle. The parameters q_n and u_n are the flow rate and the speed of the stream towards the leading vehicle W_s while q_r and u_r are the corresponding flow rate and speed away from the leading vehicle. The shock wave speed is the difference between the flow rates of the incoming flow to the leading vehicle and the flow rates away from it divided by the difference in their densities. The equation is stated below;

$$W_s = \frac{q_1 - q_2}{k_1 - k_2} \qquad 2$$

We show the existing state of traffic with parameters (q_1^n, k_1^n) representing the dry condition and the parameters (q_2^r, k_2^r) representing the rain condition. The parameters (q_{max}^n, k_c^n) and (q_{max}^r, k_c^r) represents the maximum flow at capacity and the critical densities for both dry and rain conditions. Clearly, rainfall is the cause of flow contraction from q_1^n to q_2^r at the current state and from q_{max}^n to q_{max}^r at the capacity state. Therefore any shock wave evolving must relate to these points and this is shown in Figure 10.

Shock Wave Evaluation

It has been shown earlier that roadway capacity can be written as:

$$q = -\beta_0 + \beta_1 k - \beta k^2 \qquad \mathbf{3}$$

and critical density as: $\boldsymbol{k_c = \frac{\beta_1}{\beta_2}}$

Let q = q_2 and congested density $k_2 = k_c$ so that equation 1 can be re-written as:

$$W_s = \frac{q_1 - \left\{-\beta_0 + \beta_1 k - \beta_2 k^2\right\}}{k_1 - \left\{\dfrac{\beta_1}{\beta_2}\right\}} \qquad \mathbf{4}$$

To evaluate the speed and direction of the shock wave, we recall the traffic state parameters for the existing and capacity states obtained from the analysis earlier in the presentation for the four sites. The state of traffic for site I is shown below in Table 4 and the shock wave evaluation is shown in Table 5.

Table 4: *Traffic State for Site I*

Parameter	Dry	Light Rain	Medium Rain	Heavy Rain
		Existing		
Volume (PCE/hr)	667.00	854.00	695.00	683.00
Speed (Km/hr)	63.35	61.53	59.03	56.90
Density (PCE/km)	10.56	13.90	11.88	12.12
		Predicted		
Volume (PCE/hr)	2004.85	1837.41	1684.91	1210.90
Speed (Km/hr)	34.88	35.53	33.51	34.36
Density (PCE/km)	57.48	51.72	50.28	35.24

Table 5: *Shock Wave Evaluation and Summary of Results*

Rainfall	q_1	q_2	$q_1 - q_2$	k_1	k_2	$k_1 - k_2$	Ws (km/h)	Comment
				Site I				
Light	667	1837	-1170	11	52	-41	28	Positive
Moderate	667	1685	-1018	11	50	-39	26	Positive
Heavy	667	1211	-554	11	35	-24	23	Positive
				Site II				
Light	680	1739	-1059	11	53	-42	25	Positive
Moderate	680	1643	-963	11	49	-36	25	Positive
Heavy	680	1450	-770	11	43	-32	24	Positive

Table 5: Shock Wave Evaluation and Summary of Results (Continued)

Rainfall	q_1	q_2	$q_1 - q_2$	k_1	k_2	$k_1 - k_2$	Ws (km/h)	Comment
				Site III				
Light	454	1342	-887	6	34	-28	32	Positive
Moderate	454	1113	-658	6	29	-23	29	Positive
Heavy	-	-	-	-	-	-	-	-
				Site IV				
Light	487	1174	-687	7	30	-23	30	Positive
Moderate	487	1084	-597	7	29	-22	27	Positive
Heavy	-	-	-	-	-	-	-	-

Shock Wave Implications under Rainfall

For all rainy conditions, shock waves do not form. Instead rarefaction faction waves form with speeds varying between the rain intensities. The highest speed of the waves is at Site III with 32km/hr. The lowest speed was recorded at site I with 23km/hr. Also all the waves travel in the direction of the prevailing traffic stream. Rainfall disturbances under free–flow conditions may not be a hindrance to traffic flow. The chi-squared test carried out indicated that the waves did not form by chance.

Drivers' response to changing weather conditions depend on the volume of flow and sensitivity of the lead driver at the onset of rainfall. Traffic mix are an important determinant of traffic flow contraction. Traffic flows and vehicle speeds drop significantly, while density increases during rainfall. Interestingly, all types of vehicles suffer proportional discomfort as weather conditions continue to deteriorate at all sites.

Traffic management present exceptional challenges under congested and ambient conditions, when congested conditions and bottlenecks coincide with rainfall the challenges could be daunting. Consequently, research is needed in study areas devoted to congested rainfall conditions. This will reveal how rainfall combine with congested conditions to impact on highway capacity and driving discomfort.

Implications of Roadway Capacities for Sustainable Road Network and Traffic Management in Nigeria

State of the Road Network in Nigeria

The national arterial road network is currently estimated to be nearly 200,000km, with an asset value of around $31.5bn. The Nigerian road network consists of Federal roads, (17.6 per cent), State roads (15.7 per cent) and Local government roads (66.7 per cent). The Federal roads carry 70 per cent of freight and services and 90 per cent of the socio-economic activities in the country. Federal arterial roads are largely single carriageways but are dualised on important links justified by travel demand. The roads are often beset by poor maintenance, inadequate or non-existent pavement markings and poor control of access to abutting property. In urban areas, proper control is not established on them causing long distance travellers to be interfered by local traffic.

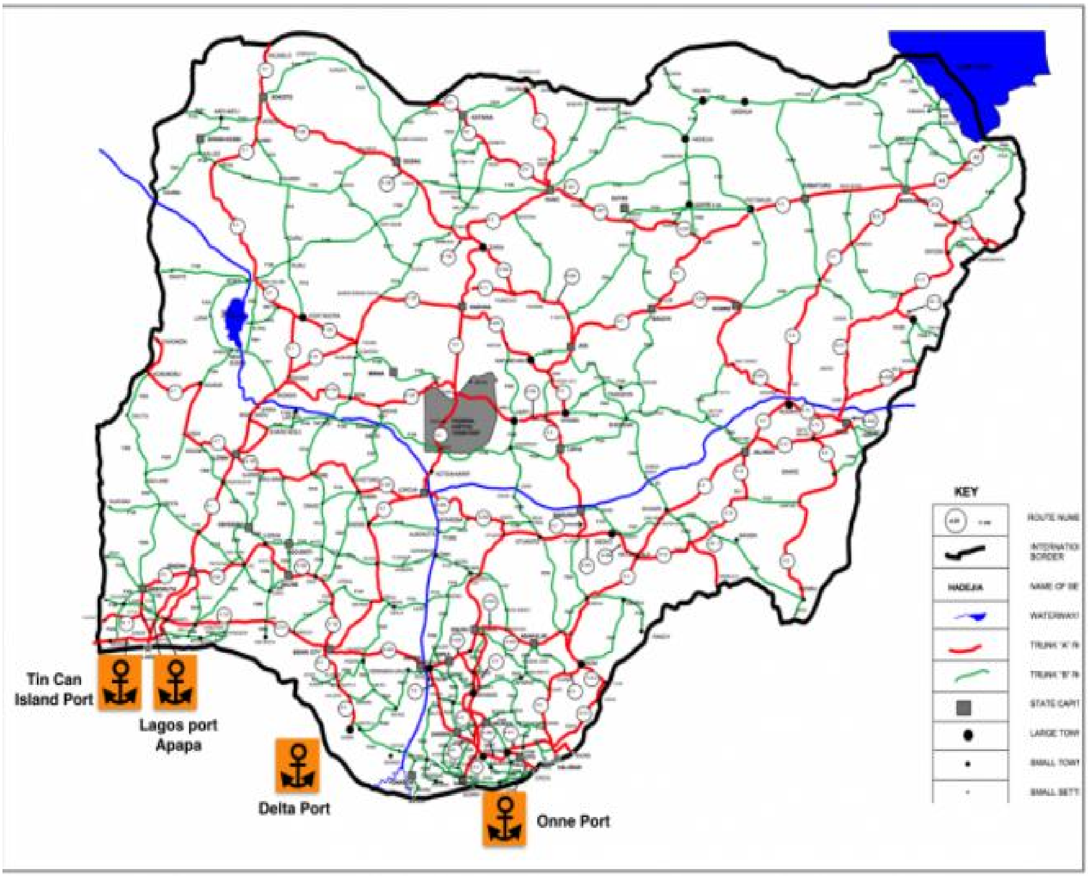

Figure 11: *Arterial Road Network of Nigeria*

The arterial road network is not resilient and also not robust. There are no alternative routes in the event of disruptions by adverse weather. Often, aggrieved users such as heavy vehicle operators deliberately interrupt flow by cutting out road segments to vent anger against government. Also when communal clashes occur along major arterials, road users are left to fend for themselves. These are all indicators of poor monitoring of road performance which takes a high toll on road users.

Constraints in the network

In Nigeria most arterial highways are built to pass through dense urban environments without taking care to protect through traffic, thus allowing local traffic to interfere with the mobility needs of travellers. Local traffic add to the stream flow, interrupts traffic and considerably reduces the speed of the traffic stream. In time, traffic delays occur, congestion develops and accidents and other undesirable effects manifest on the roadway. This situation arises mainly because the roadways are designed and operated for multi-functional use.

Figure 12: *Multifunctional use of the A2 Arterial Roadway in Kaduna.*

In Kano State, the situation is no different as roadways are built without consideration of its functionality and place in the road hierarchy. Consider for example the A2 along the Kurna corridor, in Kano. Roadside activity and local traffic dominate the through traffic causing unnecessary delays.

Figure 13: *Multifunctional use of the A2 Arterial Roadway in Kan*o

In areas of dynamic land development, it is important for jurisdictions to develop access standards that achieve a balance between property access and functional integrity of the road system. Studies show that implementing access management provides three major benefits to transportation systems:

- Increased roadway capacity (increased convenience)
- Reduced crashes
- Shortened travel time for motorists

All of the three benefits cited above are essentially the result of minimizing or managing the number of conflict points that exist along a corridor. Imagine the two extremes of the same corridor. In the least intrusive example, no minor-street conflicts exist. Traffic flows freely down an unencumbered corridor "pipe" influenced only by density, weather, and integrity of the roadway. When minor-street conflicts (i.e., "laterals") in the form of driveways and streets are introduced, the mainline flow must adjust speeds and sometimes lanes to avoid all manner of delay and conflicts introduced by the myriad combination of slowing, turning, merging, entering, and stopped vehicles. In many locations, it is necessary to completely stop the mainline flow (via signals) so the minor-street vehicles can even gain opportunity to enter the flow. In short, steady progression is interrupted, and often at uneven intervals.

The growth of direct access links to arterials and highways and the poor management of roads in relation to turning and through traffic contribute to the deterioration of the functional integrity of the roadway system. The development of new land uses and access points coupled with the traffic volumes reduces the speed and capacity of the adjacent roadways and increases congestion and accidents.

Access management can ameliorate these problems by reducing and separating the conflict points through various techniques such as creating dedicated turn lanes, limiting the number of left-turn access points by installing medians, and promoting driveway consolidation.

Figure 14: *A Highly Congested Arterial Roadway*

Figure 15: *Arterial Roadway with Access Control*

Challenges

The road and highway system is an important asset for the circulation of people and goods, for sustaining the economic and social life of a city or region. Roads are also expensive assets, and it is not prudent to simply add on new capacity in the roadway system when it is not able to cope with the growing traffic volume.

A more efficient and cost-effective solution would be to examine closely the structure and flows in the existing roads and highways, and to evaluate the possibility of easing or removing the bottlenecks to smooth traffic flow. This can be done by providing a system of high speed facilities independent of the existing arterial road network and connected to them at strategic locations to ease access and egress for effective mobility. Access management is all about better managing existing capacity, and ensuring that new roads are built to last in the face of future land developments. It is important to evaluate the capacities of various segments of the arterial road network and fashion out strategies to improve the performance of our roads.

Conclusion

The convenient, comfort and the ease of travel on our road network is largely dependent on managing capacity and access to our arterial network. Our road network, our convenience.

Future Research Directions

The presenter is working with his MSc and PhD students to understand and evaluate the capacities of roadways in Nigeria. These are non-existent. Studies are currently on-going along Ningi – Bauchi highway, Kano-Daura Highway, Kano-Zaria dual carriageway and Kano – Hadejia road. Capacities loss studies under various traffic constraints such as work zones, on and off ramps, Peak periods and adverse pavement conditions are being studied to clearly understand how Nigerian drivers respond to such situations.

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First and foremost, I am grateful to Almighty Allah (SWT) for making us submissive to His will, for nourishing and sustaining our souls, and for being gracious and merciful to me, to witness this important event today. The journey to this great event today started in 1986 when I first enrolled as a direct entry student to pursue a Civil Engineering Career. I am therefore eternally grateful to Bayero University, Kano for that opportunity that has culminated in this Inaugural Lecture today, after acknowledging my contribution as worthy of recognition as a Professor of Transportation Engineering. I must humbly say that this is the first time someone from this part of the country has attained that status and throughout Nigeria there are no more than 5 Professors in Transportation Engineering. I shall keep the flag of BUK flying higher and higher until I have no strength in me to do so.

I indebted to my parents Alhaji Salihu Alhassan and Hajiya Hadiza Alhassan for the upbringing, care, love and support throughout the course of my career. My PhD supervisor, Professor Johnnie Ben-Edigbe who is in Kwazulu Natal University now helped to shape my opinion on Traffic Management. I thank him for his innumerable efforts. I appreciate my siblings, Ibrahim, Late Latifa, Farouk, Furera, and Mahmoud for their concern and care. My children have also been very understanding during difficult times and remain strong in support of my pursuits. My wife Halimatu Sadiya was there to stand by me through thick and thin. She is the latent driving force behind my success. My children Mustapha, Furera, Hadiza, Aisha, Anisa, Abdulshakur and Mohammad Ridwan have been supportive and are eager to step into my shoes. My cousins Sadat, Habib, Bilkisu, and Fauziyya have been very supportive and I thank them all. Others too numerous to mention here include nephews, nieces, in-laws, schoolmates and friends.

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References

Alhassan, H. M. and Ben-Edigbe, J. (2010b). Effect of rainfall on microscopic traffic flow parameters. *Proceedings, Malaysian Universities Transportation Research Forum and Conference*, Putrajaya, Malaysia, 117-126. Universiti Tenaga National. ISBN: 978-967-5770-08-1 www.uniten.my

Alhassan, H. M. and Ben-Edigbe, J. (2011a). Highway capacity loss induced by rainfall. *Proceedings: International Conference on Advanced Science,Engineering and Information Technology,* (Hotel Equatorial Bangi-Putrajaya, Malaysia), 231-239. www.insight.com ISBN: 978-878-983-423-66-4-9 [cited in google, Copernicus and DOAJ among others]

Alhassan, H. M. and Ben-Edigbe, J. (2011b). Effect of Rainfall Intensity Variability on Highway Capacity. *European Journal of Scientific Research*, *49*(1), 123-129. www.eurojournals.com [scopus,google scholar]

Alhassan, H. M. and Ben-Edigbe, J. (2011b). features of macroscopic traffic stream under rainfall conditions. SEPKA. Faculty of Civil Engineering Research Forum. www.utm.fka.my

Alhassan, H. M. and Ben-Edigbe, J. (2011c). Highway capacity prediction in adverse weather. *Journal of Applied Sciences*, *11*(12), 2193-2199. www.sciencealert.com [cited in google, scopus, DOAJ]

Alhassan, H. M. and Ben-Edigbe, J. (2012a). Effect of rain on probability distributions fitted to vehicle time headways. *International Journal on Advanced Science, Engineering and Information Technology*, *2*(2), 31-37. www.insight.com [cited in google Scholar]

Alhassan, H. M. and Ben-Edigbe, J. (2012a). Evaluation of passenger car equivalent values under rainfall. Proceedings of the International Conference on Traffic and Transportation Engineering, 26, 6-10.Hong Kong. www.ipcsit.com [cited in google scholar, scopus]

Alhassan, H. M. and Ben-Edigbe, J. (2012b). Effect of rainfall on traffic stream characteristics during peak and non-peak hours. *International Journal on Advanced Science, Engineering and Information Technology*, 2(2), 49-54. www.insight.com [cited in google scholar]

Alhassan, H. M. and Ben-Edigbe, J. (2012b). Effect of rainfall on passenger car equivalent values used in highway capacity loss determination. *Proceedings of International Engineering Conference (Encon2012), Sarawak, Malaysia*, 132-138.

Alhassan, H. M. and Ben-Edigbe, J. (2012c). Are traffic flow shock waves induced by rainfall disturbances? *Proceedings of the 3rd International Technical Conference (ITC2012) Kuala Lumpur, Malaysia*, October 6-7. pp797-806. ISBN: 978-967-0167-09-1. [Cited in google and many others]

Alhassan, H. M. and Ben-Edigbe, J. (2012g). Extent of highway capacity loss due to rainfall. *World Academy of Science, Engineering and Technology.WASET, No 349, Issue 72*, pp1889-1896. www.waset.org/conference [scopus, google scholar]

Alhassan, H. M. and Ben-Edigbe, J.(2014). Effect of rainfall on traffic flow shock wave propagation. *Journal of Applied Sciences*, *14*(1):Pp54-59. www.sciencealert.com

Alhassan, H. M. and Johnnie, B. E. (2010a). Influence of rainfall intensity on traffic flow rates measuring techniques. *Proceedings Third International Graduate Conference on Science, Engineering and Humanities (IGCSEH2010), Universiti Teknologi Malaysia, Skudai, Johor, Malaysia*, Paper ID 161, 1-6. www.utm.my/IGCESH2010

Alhassan, H. M., Mashros, N. and Ben-Edigbe, J. (2013). Determining flow-density asymmetric curve using direct empirical approach. *Caspian Journal of Applied Science Research. VOL 2,* pp256-261. ISSN: 2251-9114http:// www.cjasr.com [cited in Thomson ISI,ISC,Index Copernicus, EBSCO HOST, Electronic journals library, Journal seek, etc.].

Alhassan, H. M., Sundara, P. and Ben-Edigbe, J. (2012). Discriminate peak and off-peak motorway capacity modelling. *International Conference on Civil and Environmental Engineering for Sustainability, Universiti Tun Hussein Onn. Johor Bahru, Malaysia*. [cited in google].

Alhassan, H.M and Nordiana Marshros (2015). Modelling of pedestrian speed-density and volume-density relationships in outdoor walkways. *Journal Teknologi, Volume 73*, Issue 4, pp91-97.

Alhassan, H.M. (2012a). Performance evaluation of transport modes at a ground access area and the implication for passenger delays. *International Journal of Engineering Research and Applications. Vol 2,* Issue 4, 767-775. *www.ijera.com* [cited in google, scopus, DOAJ etc]

Alhassan, H.M. (2013). Reliability of single lane road capacity subjected to rainfall disturbances. *International Journal of Emerging Technology and Advanced Engineering, Vol 3,* Number 2, pp 587-594. IJETAE. ISSN 2221 8386. *www.ijetae.com* [cited in google scholar, Copernicus, EBSCO, DOAJ etc.].

Alhassan, H.M. and Ahmed, M. T. (2012). Characterisation of solid waste incinerator bottom ash and the potential for its use. *International Journal of Engineering Research and Applications.* Vol 2, Issue 4, 516-522. *www.ijera.com* [cited in google, scopus, DOAJ, etc]

Alhassan, H.M. and Arafat, S.Y. (2015). Road safety performance evaluation of selected roads in Kano. Proceedings of International Conference on Safe, Efficient and Sustainable Road Transportation in Nigeria. Nigerian Building and Road Research Institute (NBRRI), pp58-67.

Alhassan, H.M. and Garba,M.(2013). Determination of an optimum curing age for sub-grade soils stabilised with ordinary Portland Cement. *International Journal of Engineering Research and Applications.* Vol 3, Issue 1, 941-949. www.ijera.com [cited in google, scopus, DOAJ, etc]

Alhassan, H.M. and Michael, I.C.(2013). The efficacy of sulphonated petroleum products in the stabilization of marginal lateritic soils. *International Journal of Emerging Technology and Advanced Engineering.* Vol 3, Number 1, pp 14-23. IJETAE. ISSN 2221 8386. www.ijetae.com [cited in google scholar, Copernicus, EBSCO, DOAJ etc.]

Alhassan, H.M. and Sabiu,F.A.(2013). Effects of crude oil, low point pour fuel oil and vacuum gas oil contamination on the geotechnical properties of sand, clay and laterite soils. *International Journal of Engineering Research and Applications. Vol 3,* Issue 1, pp1947-1954. www.ijera.com [cited in google, scopus, DOAJ, etc].

Alhassan, H.M. and Suleman, R.A. (2012). Assessment and modelling of the swelling behaviour of black cotton soils from north-east nigeria. *International Journal of Science and Applied Technology.* Vol 2, Number 11, IJSAT. ISSN 2221 8386. www.ijsat.com [cited in google scholar, Copernicus, EBSCO, DOAJ etc.]

Alhassan, H.M. and Yakubu, M.(2012). Modelling and prediction of sulphate ion concentrations in sulphate–bearing soils using a spectrophotometer. *International Journal of Science and Applied Technology, Vol 2*, Number 12, pp61-67. IJSAT. ISSN 2221 8386. www.ijsat.com [cited in google scholar, Copernicus, EBSCO, DOAJ etc.]

Alhassan, H.M.(2012b). Modelling of passenger delays at a multimodal transport access point of a university campus. *British Journal of Applied Science and Technology*, *Vol. 2*, Issue 2. 199-212. www.sciencedomain.com [ProQuest,HINARI,CAB abstract,DOAJ, Google Scholar]

Alhassan, H.M., Haruna, G.Y. and Sanusi, D.(2018) Potential of glass cullet as aggregate in hot mix asphalt. *Nigerian Journal of Technology, Vol., 37*, Number 2.

Alhassan, H.M.and Olaniyi, L.F.(2013). Effect of "ionic soil stabiliser 2500" on the properties of black cotton soil. *British Journal of Applied Science and Technology*, *Vol. 3*, Issue 3. pp406-416. www.sciencedomain.com [ProQuest, HINARI, CAB abstract, DOAJ, Google Scholar]

Hashim Mohammed Alhassan (2013). Assessment of operational performance and level of service of the minibus mode in Kano. *Journal of Engineering and Technology. Volume 8,* No 2, pp29-35.

Hashim Mohammed Alhassan (2014). Temporal trends in pedestrian characteristics. *Journal of Engineering and Technology. Volume 9,* No.2 Pp34-41

Hashim Mohammed Alhassan (2016). Characterisation and modelling of pedestrian flow parameters for hospital and academic environments. *Jurnal Teknologi, Volume 72*, Issue 1, pp1-6.

Johnnie Ben-Edigbe, Hashim Mohammed Alhassan and Aminu Suleiman (2013). Selective estimations of empirical roadway capacity. *Journal of Engineering and Applied Sciences,Vol. 8,* Issue 1, pp71-76. www.medwelljournals.com [cited in google scholar, EBSCO HOST, DOAJ, etc]

Murtala Umar, Hashim Mohammed Alhassan, Ado Yusuf Abdulfatah and Ahmed Idris (2013). Beneficial use of class-c fly ash in improving marginal lateritic soils for road construction. *European Journal of Geotechnical Engineering, Vol. 18*, pp2815-2822. [cited in google scholar, EBSCO HOST, DOAJ, etc]

Nordiana Mashros, Johnnie Ben-Edigbe,Hashim Mohammed Alhassan,and Sitti Asmah Hassan (2015). Investigating the impact of rainfall of travel speed. *Jurnal Teknologi, Volume 71*, Issue 3, pp33-38.

Nura Bala and Alhassan, H.M. (2015). Road safety audit of Kano-Zaria highway. Proceedings of International Conference on Safe, Efficient and Sustainable Road Transportation in Nigeria. Nigerian Building and Road Research Institute (NBRRI), p21-29.

Sitti Asmah Hassan, Lavine Wong, Nordiana Mashros, Hashim Mohammed Alhassan, Nor Sabahiah Abdul Sukor, Munzilah Rohani and Anil Minhans (2016). Operating speed of vehicles during rainfall at night: Case study of Pontian, Johor. *Jurnal Teknologi, Volume 78*, Issue 7-2, pp9-18.