

**KWAME NKRUMAH UNIVERSITY OF SCIENCE AND  
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**Congestion-Aware Routing (CAR):**

**Vehicular Traffic Routing based on Real-Time Road Occupancy Estimates**

By

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degree of

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Department of Computer Engineering, College of Engineering

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## DECLARATION

I hereby declare that this submission, to the best of my knowledge, contains no material previously published nor material which has been accepted for the award of a degree by this or any other University, except where due acknowledgment has been given in the text.

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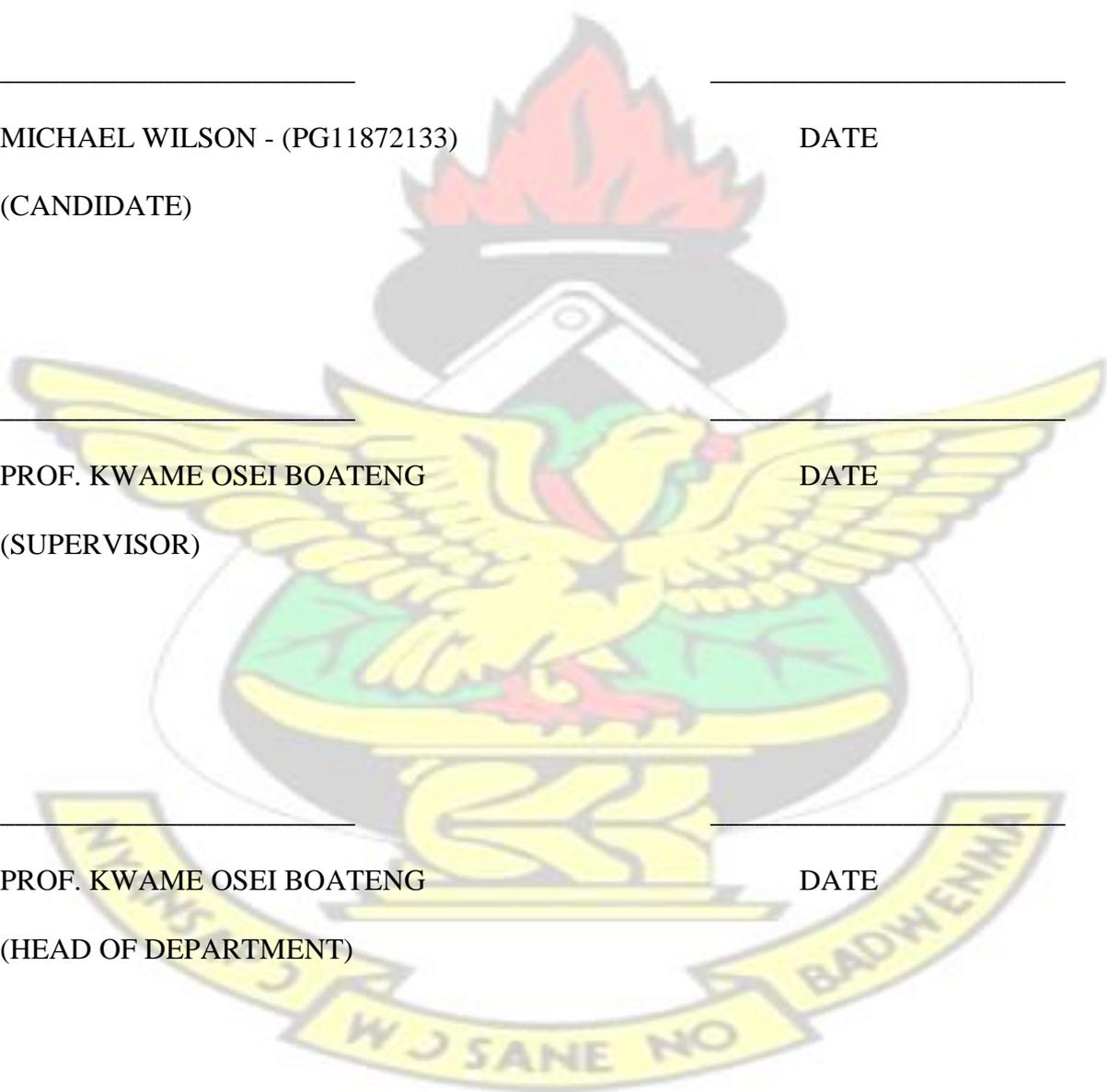
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## ABSTRACT

Burgeoning of data and road networks have been a major bolster for the global economy. These two sectors have been in competition for a while and whichever wins tends to render the other obsolete. I believed if there were transportation systems that would allow people to teleport from one continent to another in a split second at a lesser cost than the cost of sending an email, half of email users would switch from emailing to face-to-face message delivery. Traffic congestion, however, plaques the roads of most cities globally but especially in developing countries. Data networks have however, attained a state of better traffic management and transfer protocols, proper control algorithms, optimized routing and better traffic decongestion strategies as compared to road networks. This thesis work attempts to address the problem of routing vehicular traffic in order to ameliorate vehicular traffic congestion. Fair routing is effected using real-time data. Routing information is in the form of which route provides the fastest set of interlinked road segments between any departure-destination pair of nodes of road network. Routing traffic in such a way minimizes the overall traffic congestion on road networks. The thesis adopts a routing algorithm used in data networks and modifies it for application to vehicular traffic routing in road networks. The adopted algorithm is Dijkstra's Shortest Path First (SPF) algorithm. To adapt SPF algorithm to the solution of the traffic congestion problem, the concept of classical Proportional Integral Derivative (PID) controllers and the Eddie model of traffic modeling are exploited. The PID controller concept is used to adjust road occupancy data acquired from a sensor network superimposed on the road network. Simulations have been performed to show the computations involved in deriving travel time from road occupancy data. Also, a hypothetical road network has been used to illustrate the vehicular traffic routing algorithm. Finally the method is implemented as a mobile application that draws data from a database server on the sensor network of a road subnetwork in Accra, Ghana. A use case is presented. It has been shown that the method is more practicable and easier to use than a method in literature—Spatial and Traffic Aware Vehicular Routing (STAR).

## DEDICATION

This work is dedicated to the Almighty God, for His mercies that still endures for me and my family.

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## LIST OF ABBREVIATIONS

BFS	Breath First Search
DVLA	Driver Vehicle and Licensing Authority
NIC	Network Interface Card
PID	Proportional Integral Derivative
SPF	Shortest Path First
STAR	Spatial And Traffic-Aware Routing
TCP/IP	Transmission Control Protocol/Internet Protocol



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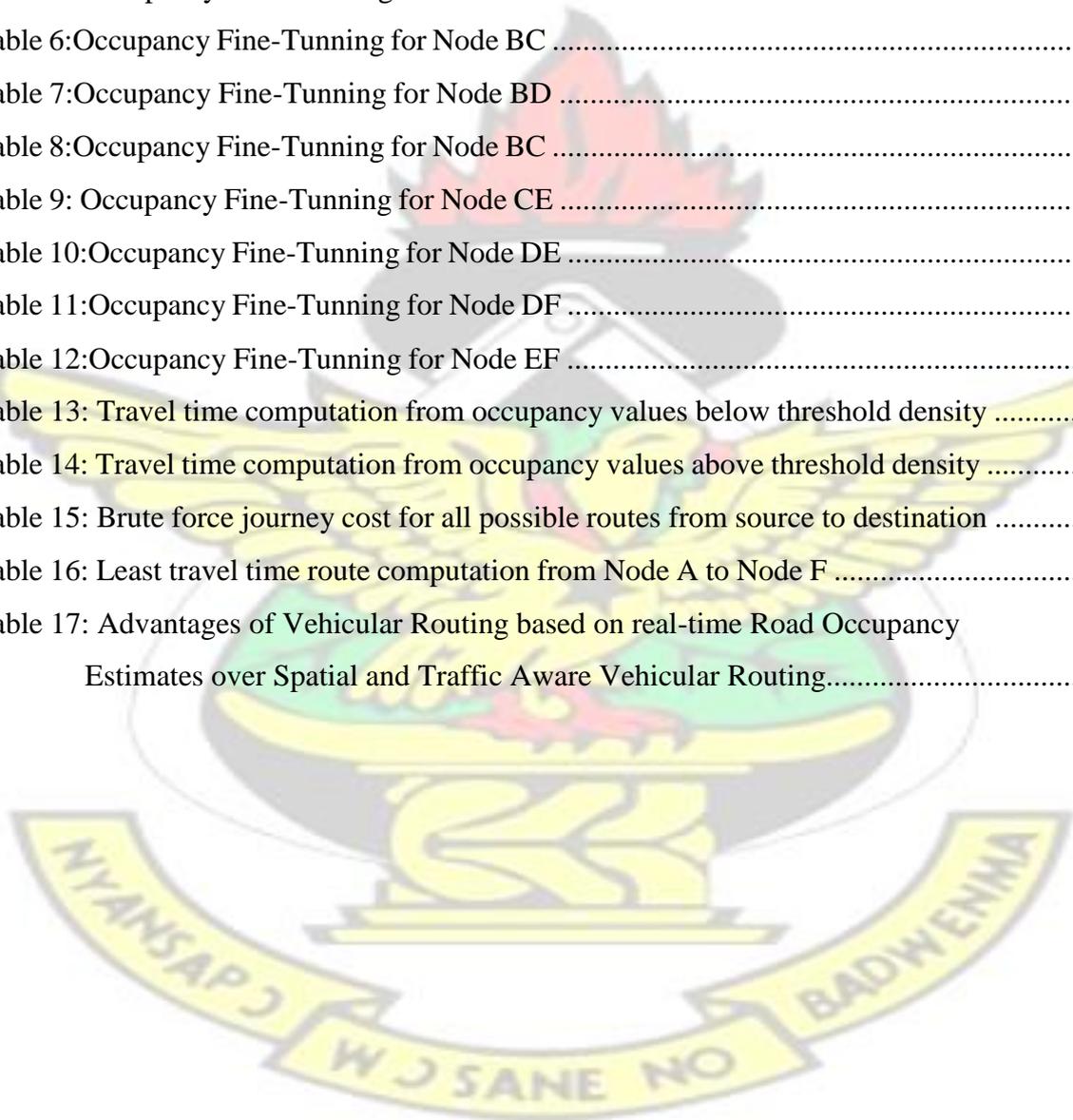
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# CHAPTER ONE

## 1.1. INTRODUCTION

Tremendous growth and development in the world has been buttressed mostly by growth in data and road networks. Data networks mostly the internet and GSM networks have been the bolstering force behind data communication and transfer from one place to another whereas Road networks on the other hand have been the driving force for movement of people and goods from one place to another.

Transfer of data on data networks has however attained a state of better traffic management, better transfer protocols (e.g. Link State Routing, Distance vector Routing, Shortest Path First, etc.), proper control algorithms (TCP/IP, UDP), optimized routing and better traffic decongestion strategies relative to our road networks. This has caused the world to see an exponential growth in patronage of the use of data networks mostly the internet over the past decade.

Data networks have however not been able to take over completely the relevance of vehicular networks as they are unable to perform the vehicular network's core mandates of transporting people and goods in time and space. It is however quite unfortunate that the performance of vehicular networks almost globally has experienced almost constant deterioration due to its inability to commensurate its routing capabilities to the burgeoning demand for vehicular routing as a result of the exponential growth in the number of vehicles. The resultant is the massive traffic congestion that plaques our major cities.

Traffic congestion on vehicular networks occurs when the number of vehicles per unit distance of a road segment or all over the road-network exceeds the routing capabilities of that road

segment or road network. In extreme situations, the road usage increases beyond a point where the volume of traffic on a particular road segment demands for space greater than the available road capacity.

Traffic congestion can be characterized by slow speed, longer trip time and increased vehicular queuing. Traffic congestion plagues the roads of most cities globally and is one of the prevalent problems associated with most cities in the world especially in developing countries where the road networks are inadequate.

There is the need to address the problem [1] by the provision of real time data from which one can determine the least congested route for any departure destination pair on road networks and minimizing the overall traffic congestion on road networks. The solution should aim at balancing the vehicular load evenly on all available sub routes based of their destination points with respect to their current position.

## **1.2. BACKGROUND STUDY**

Of all the problems that challenge cities globally, traffic congestion seems to be the one causing so much damage and it needs to be tackled with all seriousness. Lots of efforts have been made in different countries by different expertise in attempt to either eliminate, control or reduce traffic congestion.

The truth is, the number of cars in most countries keep increasing. Statistics released by the Ghana Driver Vehicle and Licensing Authority (DVLA) indicates that a total of 174, 234 vehicles were registered in 2012. This is about 22.86 percent more than the total number

registered in 2011. The number of cars will increase even exponentially as a country like Ghana is struggling to achieve middle level income. The DVLA estimates about 1.2 million vehicles in Ghana with an estimated 60% of these vehicles in the capital, with an entire road network stretching to about 1,632 kilometers out of which 1,310 kilometers is tarred.

With the current number of vehicles and the available vehicular network, statistics[2] made available by the Metropolitan Roads Department (MRD) of the Accra Metropolitan Assembly (AMA), indicates that the Winneba Road (Mallam-Kasoa Highway) registers about 4,000 vehicles every hour during peak periods, the Achimota (Nsawam) road also records 4,100 vehicles every hour during peak hours, followed by Adenta with 3,500 vehicles per hour, the Spintex Road registers a vehicle population of 1,500 per hour followed closely by the High Street, located in the central business district of Accra, with 600 vehicles per hour. Traffic situations on some streets in Ghana are becoming comparable to São Paulo in Brazil which is known globally to be amongst the most congested cities in the world [3].

ROAD SUB-SECTION	REGISTERED AVERAGE VEHICULAR INTAKE AT PEAK HOUR (VEHICLES/HOUR)	AVERAGE TRAFFIC FLOW RATE (VEHICLES/HOUR)
Winneba Road	4,000	N/A
Achimota Road	4,100	504
Adenta Road	3,500	582
Spintex Road	1,500	N/A

Figure 1 Report by Accra Metropolitan Department – 2014

Traffic congestions result in massive delays, reduced travel reliability, increases effort needed to drive, increased fuel wastage and imposes other monetary cost on motorists and the economy.

An interview with the Assistant Commissioner of Police; ACP Awuni by the daily graphic revealed that currently there are 312 MTTU personnel managing the traffic flow, adding that the Inspector General of Police (IGP) had promised to release 300 more personnel to augment its number to reach more traffic-prone intersections. The problem in Accra keeps getting worst to the point where statements were made in May, 2015 by the National Service Secretariat considering the possibility of engaging some university graduates in directing traffic on the streets as their service to the nation.

A study conducted over 85 areas in the United States [4] reveals a total congestion cost of \$6.3 billion. The study relates 3.5 billion of this cost to hours of delay and 2.8 billion of this cost is related to burnt fuel for no productive work. It is evident that this study only considers these two parameters as they were the only easy and measurable parameters. Other congestion costs related to longer goods delivery times, missed and rescheduled meetings, business collapses and relocations, deaths and other indirect costs are not included.

The United States department of Transportation estimates in [4] an annual indirect cost associated with traffic as follows

- Wasted Man Hours/ Productivity losses \$38 billion
- Unreliability of road usage \$38 billion
- Cargo and Goods delay costs \$4.7 billion
- Environmental Safety \$12,6 billion

Combining both the direct and indirect costs, the department estimates a total congestion invoice of more than \$200 billion (\$213.4 billion) in congestion costs annually. With this, I should have a fair idea of how much traffic congestions costs us and hinders the development of a nation [4].

Not only do traffic congestions hamper economic activities and creates hindrances for development but also contributes greatly to environmental degradation and threatens the health of inhabitants of the city. The total number of annual premature deaths caused by air pollution solely from vehicular fumes in the United States as a result of traffic congestion is pegged over 2000 by a research paper published by the Harvard school of Public Health. In most of the world's growing economies, where many of the vehicles are older and roads are quite in bad conditions compared to that in the United States, it becomes undeniable that damage to people's health from pollution is very likely to be much worse than that estimated above.

### **1.3. THE PROBLEM STATEMENT**

The demand for road networks beyond what is available keeps increasing as:

- I. Efficient operations on the economy and school systems require that people go to work, go to school and perform many other errands at about the same hours of the day so they can interact with each other resulting in Peak-Hour road congestion.
- II. Most people will keep to the mindset that private vehicles are more comfortable, faster, convenient and also more private which is obviously true.
- III. Wage disparities between rural and urban (formal) labor markets drives migration decision.

The three statements above coupled with the increasing number of vehicles and thus, the increasing demand for expanded road network has led to a state of traffic congestion which plagues the roads of most cities globally. Effects of this state of congestion are massive delays, reduced travel reliability, increased effort needed to drive, increased fuel wastage and monetary cost to motorists and the economy at large. There are other indirect costs, such as deaths caused by air pollution and costs incurred due to delay of goods, which are quite abstract and difficult to quantify.

In general, traffic congestion on road networks has become a global problem inhibiting economic productivity and the objective of this work is to address the problem by adopting and reengineering a data network algorithm for use in ensuring fair vehicular routing based on real time road occupancy estimates.

#### **1.4. RESEARCH QUESTIONS**

The research questions for this study were:

1. Are there enough similarities between the causes/parameters of traffic congestion on data networks and the causes/parameters of traffic congestion on road networks that warrant the study and reengineering of the data network algorithms for application to the enhancement of management of vehicular traffic on road networks?
2. If the answer to the above question is yes, then which aspects of data network algorithms will need reengineering in order to make it suitable for use in vehicular traffic decongestion on road networks?
3. How will the reengineered algorithm be usable or easy to implement as solutions to the problem of vehicular traffic congestion on road networks?

## **1.5. RESEARCH OBJECTIVES**

The general objective of this research work is to address the congestion problem on road networks by adopting and reengineering a data network algorithm for use to manage road traffic congestion through fair routing of vehicular traffic on road networks. This objective is set based on similarities identified between traffic behavior on road and data networks addressed later in this work under literature review. To achieve the objective the following specific objectives is set.

1. To select a suitable routing algorithm for modification and adoption
2. To determine a suitable metric for the application of the dynamic algorithm
3. To formulate the method of congestion-aware routing and illustrate its use based on an assumed sensor network infrastructure.
4. To implement the method as a mobile application and demonstrate its ease of use

## **1.6. JUSTIFICATION OF RESEARCH**

Performance of vehicular networks almost globally has experienced almost constant deterioration as a result of the exponential growth in the number of vehicles. This has led to massive traffic congestion that plaques our major cities.

Traditional attempts to mitigate the problem have focused on building new roads or expanding existing roads. Statistics by author in [5] however exposes how drastic these attempted solutions have failed to solve the problem. Reasons why these traditional methods will keep failing is explained by the principle of induced traffic explained by Todd Littman in [6]. According to the author in [6], traffic congestion on vehicular networks occurs when the number of vehicles per unit distance of a road segment or all over the road-network exceeds the routing capabilities or capacity of that road segment or road network.

Work by author in [7] suggests that vehicles be equipped with a network interface card (NIC) to enable them partake in a vehicular network infrastructure and taking routing decisions based on the vehicular network state coupled with the geographical layout of the road networks. This approach however, requires all vehicles to be connected to yield accurate results otherwise the performance of this solution will be capricious. The solution also is limited by the coverage area of the wireless technology to be used by the vehicles and it also does not factor the actual flow rate of vehicles on each link of the road network in its routing decision but rather bases decision on the speed of the vehicles—a factor which is human dependent.

This thesis work proposes a strategy to address the problem of decongesting vehicular traffic on road networks using transport telematics to compute the instantaneous least cost path with regards to real-time congestion state and travel time for departure-destination nodes (junctions) of a journey. In this work I devise a fair routing of vehicular routing in order to manage congestion on road networks and ensures balancing of vehicular load evenly on all available sub routes.

## **1.7. METHODOLOGY**

The proposed work seeks to combat traffic congestion on road networks using routing algorithms and techniques modeled around the SPF algorithm, the principle of PID controllers and the Eddie model of traffic modeling.

In line with my first research question, the congestion situation on data networks are examined with keen interest in the parameters that act as catalyst of data traffic. The identified parameters and cases of traffic congestion from the examination of data networks is then related to identified traffic congestion causes/parameters on road for similarities. If the parameters are

similar in behavior, then it is likely algorithms used to handle congestion on data networks could be reengineered for use in road networks as raised in my second research question. The third research question is affirmed by a prototype mobile application implemented as a proposed solution based on the findings of this work.

## **1.8. ORGANIZATION OF THESIS**

Chapter two reviews existing work in the scope of traffic management on both road and data networks. It also examines some similarities between data and vehicular traffic congestion and some data network routing techniques with the view to establishing what aspects of routing and congestion control in data networks could be adopted or reengineered for decongestion of traffic on road networks. Chapter three outlines my strategy to address the problem of decongesting vehicular traffic on road networks using transport telematics to compute the instantaneous least cost path with regards to congestion state and travel time for departedestination nodes (junctions) of a journey. It details how instantaneous occupancy data is acquired from a sensor network superimposed on the target road network and adjusted by estimating the error based on the classical PID controller model. The chapter ends with how Dijkstra's algorithm is adopted and re-engineered for use in vehicular routing using an estimated travel time as the only metric. In chapter four I use simulated data to discuss and justify the speed-relation model used in the generation of travel time as a routing metric. Also the CAR method is evaluated against a similar research work (STAR) in this chapter. This research work is finally summarized and concluded in chapter five.

## **CHAPTER TWO**

### **LITERATURE REVIEW**

## 2.1. INTRODUCTION

The literature review will discuss some previous works done in this field including one which considers equipping vehicles with network interface cards enabling them to partake in a vehicular network infrastructure and taking routing decisions based on the vehicular network state coupled with the geographical layout of the road networks [7][8].

## 2.2. TRADITIONAL TRAFFIC DECONGESTION METHODS

Many traditional mechanisms are being adapted in an attempt to solve the problems of traffic congestion but they keep failing as long as the inevitable conditions discussed in Section 1.3 prevail. Traditional attempts to solve the problem of road traffic congestion in Ghana have concentrated on either building more roads or expanding existing road networks.

Available statistics (National Transport Policy, 2008: 28) analyzed by author in [5] exposes the following details concerning vehicular population and road status across a selected section of Ghana:

- Expenditure on road subsector : 99% road Ministry investment
- Investment growth in road Ministry : 30% growth rate every 3 years
- Road quality Evaluation : 36% poor, 26% average, 28% good
- Expected Quality Level(2008 Policy) : 10% poor, 20% average, 70% good

In spite the above analyzed investment into road construction by the road industry, traffic congestion seems not to be getting any better than before. This is mostly associated with the rate at which the economy is growing and is partly explained by the principle of induced traffic[6].

The traditional method of road construction and enlarging aim mostly at increasing the resource available in an attempt to avoid congestion. However in developing countries and even most

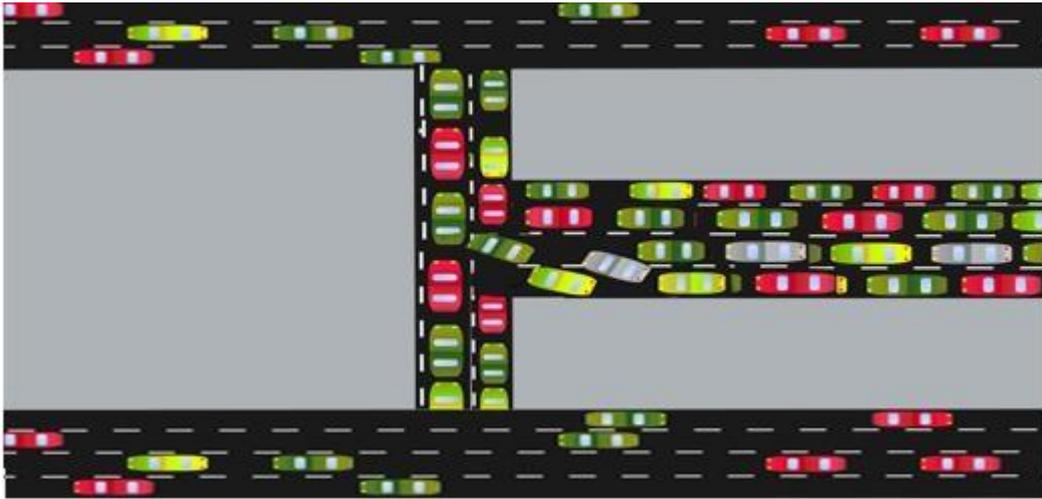
developed countries the ability to build enough roads to avoid traffic congestion is either politically, geographically or financially impossible. It thus becomes evident that other methods need to be adopted to augment the traditional methods currently being used.

### **2.2.1 DRAWBACKS TO ROAD CONSTRUCTION AND EXPANSION AS TRAFFIC DECONGESTION STRATEGY**

From the statistics drawn from the work in [5], I could conclude that though the motive of these traditional attempts of road building and expansions are to reduce traffic congestion on roads, the problem of traffic congestion seem to have rather worsened on our road networks. This controversial situation is explained and termed **Induced Traffic** [6] by Todd Littman; an expert in Transportation systems.

The concept of induced traffic is explained as a situation where the reduction of the cost of traversing certain routes (usually by improving or enlarging those routes in an attempt to reduce traffic congestion) within the entire road network induces more vehicles to route through that section. Littman's work further explains this increase in vehicular trips on these improved road segments by associating them to new economic activities that are likely to be established along these routes attracting the trips on those roads.

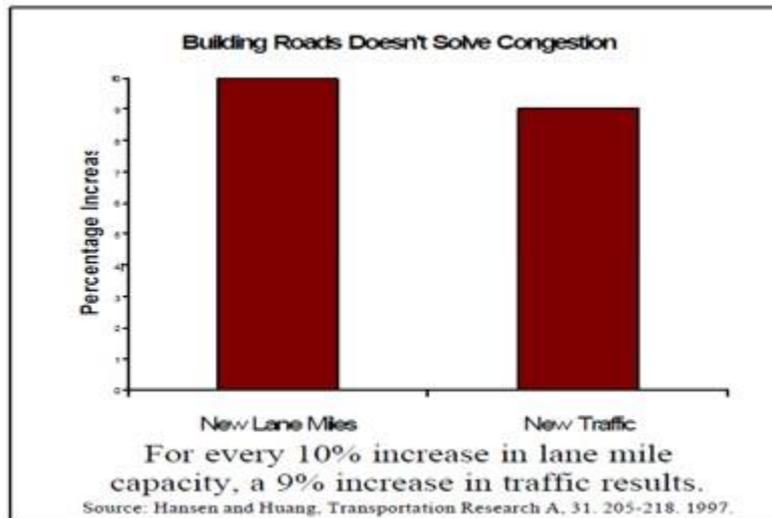
The situation often gets worse when development or improvement of a subsection of our road network is not well planned resulting in drastic mismatch between road segments. When this happens we experience the bottleneck problem where unimproved road segments are usually unable to forward traffic at same or better speed as the arriving speed of the vehicles from improved segments of road networks causing severe traffic congestion at those portions or nodes. Figure 2 depicts an example of a very common situation on our road network.



*Figure 2: Traffic bottle neck due to road mismatch*

Experts in the field of transportation planning are of the view that the development and use of a piece of land as settlements and for economic activities increase trips to the place. In response to these, they plan areas where road capacity require expansion and even where there is demand for new roads to be constructed barely paying adequate attention to the effect of these expansions and improvements on the existing road network.

On the contrary I brainstorm on the reverse possibility where the improvement or construction of new roads rather become a trigger for more economic activities getting created in those settlements and more people migrate to settle in such areas increasing the demand for roads and worsening traffic conditions after a few years. Below is a graphical view showing the effect of induced traffic by work in [9] using data from the freeway system in California.



*Figure 3: Implications of Induced Traffic[9]*

From this work it was concluded that about 60% to a little over 90% of improved road capacity in urban areas is consumed with new traffic in less than six years [9].

### **2.2.2 REVIEW OF FRANCOIS MAHAMA'S THESIS**

In Francois Mahama's thesis[8] for MSc Industrial Mathematics at KNUST, he proposed that to be able to overcome the limitation of transport solutions lagging behind the estimated demand, transport solution planners will need advanced computer aided software tools. These tools were to incorporate intelligence that will allow transportation planners have a fair idea of the dynamic changes in road resource demands. In his work, he proposes some transport models which are able to give insight beyond the obvious trends seen by lay minds. He devoted to study the Vehicular Traffic Congestion in the Sekondi-Takoradi Metropolis and evaluated some planning options to ease the Traffic Congestion in the Metropolis.

### **2.2.3 SETBACKS AND LOOPHOLES TO MAHAMA'S THESIS**

Planning road networks carefully is indisputably a good thing to do before construction but transport planning will always lag behind demands due to the rapid and versatile nature of demand for road usage especially in developing cities like Accra. A report by the World Bank

Group in 2006 (quoted in chapter 1 of the article: Urbanization and Growth: Setting the Context Patricia Clarke Annez and Robert M. Buckley and by work in [8]) stated that transport planning in cities of developing countries is extremely difficult because of the rapid pace of change.

The question is; how perfect can we be in our planning such that the elements of roads improvement and development lagging behind the demand can be resolved vis-a-vis the dynamic nature of communities and lack of adequate financial resources in developing countries? This is not possible because there is always that element of assumption in our planning. At best we will have to predict the future based on the past and the present. This school of thought has been used in several areas because the future has constantly become the past. However, there is no guarantee that the future's future will be exactly like the past's future.

Planning will not eradicate the problem completely but is quite very expensive if it has to be done properly.

Other methods like charging extra tolls on selected roads at peak-hours, expanding road capacity to accommodate all vehicles or expanding public transit capacity could be tried to reduce road traffic congestion. However these methods are either politically, financially or physically infeasible in most countries.

In such cases, where cause of problems are inevitable, one can resort to strategically coupling road management systems that will manage the use of available resources (in this case the road) with gradual road network improvement (construction and expansion) policies.

The road management system will seek to ensure better/even distribution of traffic on the available road network connections thus bringing traffic conditions to the best state we could have subject to a ratio of demand per available road network for a given locality.

## **2.3 SPATIAL AND TRAFFIC-AWARE ROUTING (STAR) FOR VEHICULAR SYSTEMS**

Francesco Giudici, Elena Pagani of the Information and Communication Department of the Università degli Studi di Milano, Italy, address the issue by suggesting that vehicles be equipped with a network interface card (NIC) and Global Positioning System (GPS) devices. The NIC and GPS devices will enable them partake in a vehicular network infrastructure for taking routing decisions based on the vehicular network state coupled with the geographical layout of the road networks [7]. I see this method however, to be hit by the drawback of having to depend directly on vehicles actively connected to the routing network for routing decisions. This approach requires all vehicles to be connected to yield accurate results otherwise the performance of this solution will be capricious. This solution is limited by the coverage area of the wireless technology used by the vehicles. It also does not factor the actual flow rate of vehicles on each link of the road network in its routing decision but rather bases decision on the speed of the vehicles—a factor which is human dependent.

## **2.4 CONGESTION HANDLING IN DATA NETWORKS**

Similar to road networks, computer data networks encounter data traffic congestion usually as a result of data packets from multiple sources needing to go through the same path to their destination and mismatch between system parts where low bandwidth lines are unable to forward packets at the same or better speed than the arriving speed of packets. Traffic congestion in data networks is characterized by a very large number of packets being sent through some portions or all of a subnet that exceeds its routing capabilities resulting in performance slowdown.

When decongestion strategies are not employed quickly in such situations the network may encounter congestion collapse (when the data load exceeds the channels capacity).

Vehicular networks are plagued with massive traffic congestions for similar reasons such as:

1. Economic activities being centered on specific locations in our township requiring that a majority of the population go through the same road networks to these locations daily.
2. Improving a sub-section of our road networks in an attempt to reduce congestion results in a drastic mismatch between road sections resulting in a shift of bottleneck. When this happens, unimproved sub-sections of roads are usually unable to forward traffic at same or better speed as the arriving speed of the vehicles from improved sections of causing severe traffic congestion in these portions of our road network.

Though both data and road networks are plaque with congestion, the former has advanced relatively in handling the problem through flow control and congestion control algorithms [10][11] which ensures more stability, fairness and optimization of resource usage as compared to the later which seeks to solve the problem mostly by increasing resources (road networks) with less concern to management and control of resource usage.

Congestion handling in data networks has had flow control and congestion control strategies as driving forces with flow control seeking to ensure:

- the control of flow rate between a given sender and a receiver on transmission links.
- that fast sender devices (routers, switches, etc.) not overwhelm slow receiver devices (routers, switches, etc.).
- the incorporation of a feedback mechanism on transmission (eg. TCP protocol) mostly used for routing decisions and further flow control decisions.

Congestion control strategies on the other hand focus on:

- Ensuring that all subnets are not overwhelmed with data flow rate beyond their capacity
- factors that diminish carrying capacity

- the behavior of all hosts that affect or are affected by the congestion

It is undeniably true that the two major factors that control the congestion level on both data and road networks are the resources (roads or network links) and the load (vehicles/data packets) that needs access to the later (resources).

$$\text{Congestion } \alpha = \frac{\text{LOAD DEMANDING USE OF RESOURCE(ROAD OR NETWORK LINK)}}{\text{RESOURCES AVAILABLE}}$$

Analyzing the above variation on the grounds of natural laws, proportionality and first principles suggests two major approaches to handling the problem of congestion being:

i. Increase resources(**Congestion Avoidance**) ii. Decrease/Regulate Load (**Congestion control or congestion detection and correction**) Computer data network congestion control mechanisms apply a mixture of congestion avoidance techniques (redundant links), congestion control techniques (traffic aware routing protocols [12][13]) and congestion detection & correction techniques [13] as remedies for handling data congestion. Aside the complexities and cost overhead introduced by these solutions to congestion, the trade-off has been analyzed to be worth implementing [13].

## 2.5 TECHNICAL DEFINITION OF THE PROBLEM OF CONGESTION

Traffic flow ( $q$ ) is traditionally defined as the number of vehicles ( $n$ ) passing through a given cross-section of a road network per unit time ( $T$ ). I can thus, mathematically define traffic flow as a local variable (as it is defined for cross-section of the road network) as shown below[14]:

$$q = \frac{n}{T} = \frac{n}{\sum_{i=1}^n h_i} = \frac{1}{h} \dots\dots\dots (1)$$

From the above expression, I can deduce that the flow rate on any road link can be measured easily by counting the number of vehicles that drive pass a specified/selected cross-section over a period of time. The expression also shows an inverse relationship between flow rate and the average headway  $h$ .

The occupancy  $k$  of a road subsection can be defined as the average number of vehicles occupying a unit distance of that road subsection. The instantaneous road occupancy can be defined mathematically as shown below[14]:

$$q = \frac{m}{X} = \frac{m}{\sum_{i=1}^m s_i} = \frac{1}{s} \dots\dots\dots (2)$$

Simply put, if a snapshot of any length  $X$ , is captured from a road subsection and the number of vehicles  $m$ , within the snapshot is counted then dividing  $m$  by  $X$  becomes the occupancy per unit length. From the mathematical expression I can also find the relationship between occupancy and average distance headways,  $s$ .

Unlike vehicular flow rate which is relatively easy to measure at a single cross section of the road network, the occupancy of a section of the road is more complex to measure as it requires monitoring at multiple sections of the road(probably from node to node). In a later part of this work, I show how I employ circuitry embedded with ultrasonic sensors to measure instantaneous occupancy of road sub-sections.

Capacity of a road link is defined to be the maximum hourly rate at which vehicles can reasonably traverse a point or uniform sub-section of the road link at a given time period subjected to prevailing roadway, traffic and control conditions.

Traffic congestion on vehicular networks occur when the number of vehicles journeying through sub-sections(occupancy) or all over the road-network exceeds the routing capabilities of the road sub-section or road network. If decongestion strategies are not employed quickly to

control the flow in such situations the network may encounter **congestion collapse** where the vehicular load exceeds the road's capacity. Figure 4 shows a graphical representation of the situation.

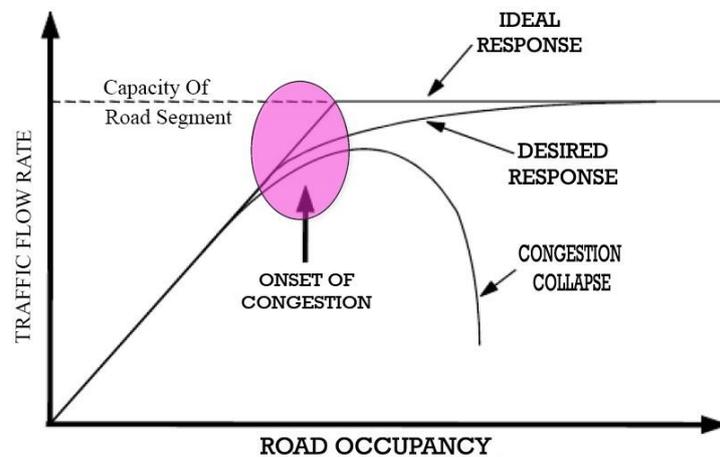


Figure 4: Ideal flow-rate at different occupancy levels.

During congestion collapse there is performance slowdown even when the load below the data/road network's capacity

Figure 5 is an example quadratic, inverse, cubic and linear representations drawn from data gathered on the Liberation Street in Accra. The graph shows the relationship between vehicular flow rate and road occupancy.

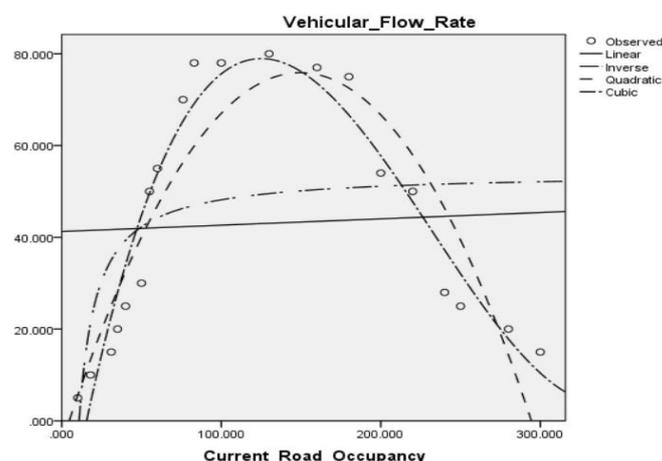


Figure 5: Sample flow-rate at different occupancy levels.

After congestion collapse, one or more segments of the road network is more likely to experience a situation termed **capacity drop**. Capacity drop describes the situation once congestion has formed and drivers are not maintaining a headway that is as close as it was before the congestion collapse. In this situation the capacity of the road network may seem to be lower. This effect is considerable, and values of a reduction up to 30 percent are quoted (Hall and Agyemang-Duah, 1991; Cassidy and Bertini, 1999; Chung et al., 2007) by author in [14] as illustrated in the figure below.

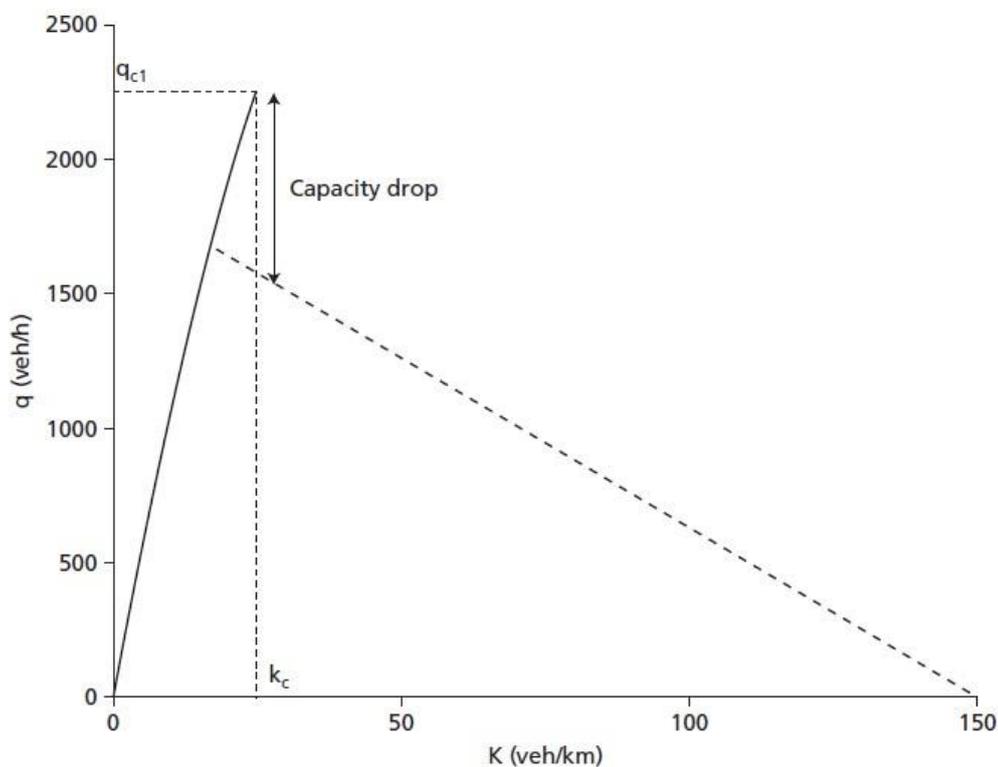


Figure 6: capacity drop during congestion collapse[14].

### 2.5.1 OVERVIEW OF DIJKSTRA'S SHORTEST PATH FIRST ROUTING ALGORITHM

Dijkstra's algorithm [10] is one of the most common and most used approach in solving the shortest path first (SPF) problem in graph theory. The SPF problem is defined as finding the

path between two nodes or vertices in a graph such that the path cost of traversing from one node to the other is the minimum among all the possible routes between the two nodes in question. The SPF problem is no different from finding the least cost path between any two intersections on a road map/network where the intersections on the road network serve as vertices of the road map and the road links serve as the edges of the graph. The weight(s)/parameter(s) for computing the least cost path need not necessarily be the distance between nodes but could be any arbitrary metric or combination of metrics.

Dijkstra's Shortest Path algorithm which was conceived somewhere in 1956 seems to be an increment or a patch up of the Breadth First Search(BFS) algorithm invented by Moore in the 1950s. Moore's BFS algorithm traverses a tree or graph data structure starting at a node (root/search key) and visit neighboring nodes first before moving to other levels of the tree or graph until a target node is reached. A limitation of this algorithm is that it does not employ any form of weight or cost of traversing any of the edges within the graph. In this case the shortest path considered by this algorithm is merely the path with the least number of edges irrespective of the cost of traversing the edges.

The SPF algorithm is able to factor the cost of traversing each path in computing the shortest path for any source-destination node pair. In Dijkstra's SPF algorithm, each edge is assigned a positive metric. For bidirectional graphs, the algorithm allows each link to have different metric in each direction. The simplest possibility that could occur would be a situation where all routes under consideration are exactly one unit length in which case the algorithm reduces to be the same as the BFS algorithm discussed earlier.

Probably, the worst case scenario to be encountered will be a situation where the weight or metric for the individual routes keep changing as in this situation depending on the prevailing traffic congestion and flow rate on the individual links which is usually the case to be dealt with on vehicular road networks. In cases like this where the routing metric keeps changing, there exist the need for an extra overhead of introducing an incorporated feedback mechanism for whatever solution is assumed.

A limitation of Dijkstra's SPF algorithm is its inability to handle edges with negative metric values. Running the SPF algorithm over graphs with negative weighted edges may result in incorrect routes. Though the Bell-Man Ford algorithm is able to detect edges with negative weights, it is still unable to compute the shortest path when such edges exist. Dijkstra's algorithm thus, still stands a better choice for situations like finding least congested route on vehicular networks as road networks do not have links with negative weights coupled with the ease and computational time (time complexity of  $O(m \cdot \log(n))$  when running with the heap data structure) advantage of the SPF algorithm over the Bell-Man Ford algorithm. In simple terms, Dijkstra's algorithm visits each node in the graph only once while the Bellman-Ford algorithm visits each node  $|V| - 1$  times.

Implantation of the SPF algorithm is based on the mathematical principle of relaxation that makes changes that reduces constraints surrounding a given scenario. In the SPF algorithm principle of relaxation is employed in updating the cost of all vertices connected to a visiting vertex 'v' if the overall path cost will be improved by including the path via v. Relaxing an edge is the process of trying to reduce the cost of getting to one node by using another node. Find pseudo code of the algorithm below

1. INITIALIZE-SINGLE-SOURCE( $G, s$ )
2.  $S \leftarrow \Phi$
3.  $Q \leftarrow V[G]$
4. **while**  $Q \neq \Phi$
5.   **do**  $u \leftarrow \text{EXTRACT-MIN}(Q)$
6.    $S \leftarrow S \cup \{u\}$
7.   **for** each vertex  $v \in \text{Adj}[u]$
8.     **do** RELAX( $u, v, w$ )
9.    RELAX( $u, v, w$ )
10.   **if**  $d[v] > d[u] + w(u, v)$
11.     **then**  $d[v] \leftarrow d[u] + w(u, v)$
12.  $\pi[v] \leftarrow u$

Dijkstra's algorithm maintains a set  $S$  of vertices whose final shortest-path weights from the source  $s$  have already been determined. The algorithm repeatedly selects the vertex  $u \in V - S$  with the minimum shortest-path estimate, adds  $u$  to  $S$ , and relaxes all edges leaving  $u$ . In the following implementation, I use a min-priority queue  $Q$  of vertices, keyed by their  $d$  values.

Dijkstra's algorithm, run on a weighted, directed graph  $G = (V, E)$  with non-negative weight function  $w$  and source  $s$ , terminates with  $d[u] = \delta(s, u)$  for all vertices  $u \in V$ . The simplest implementation of the Dijkstra's algorithm stores vertices of set  $Q$  in an ordinary linked list or array, and extract minimum from  $Q$  is simply a linear search through all vertices in  $Q$ . In this case, the running time is  $O(|V|^2 + |E|) = O(|V|^2)$ . Dijkstra's algorithm can be implemented more efficiently by storing the graph in the form of adjacency lists and using a binary heap, pairing heap, or Fibonacci heap as a priority queue to implement extracting minimum

efficiently. With a binary heap, the algorithm requires  $O((|E| + |V|)\log|V|)$  time (which is dominated by  $O(|E|\log|V|)$ ), assuming the graph is connected).

## 2.6.SPEED-OCCUPANCY RELATIONSHIP

In accordance with Greenshield's postulate [15] of a linear relationship between speed and occupancy, speed–occupancy relationship is modeled as  $v = f(d)$  and is estimated from paired observations of speed and occupancy as [15]:

$$v_i = f(d_i) + e_i \dots\dots\dots (3)$$

where  $e_i$  is an error term for the estimated speed. Statistical procedures can be applied to estimate parameters of a given model form for  $f(\cdot)$ , and these generally depend on the statistical distribution that is adopted for the error term  $e$ . This formulation supports the hypothesis that traffic speed is determined by traffic density/occupancy.

An alternative view is that the traffic assumes a certain density and hence occupancy depending on the prevailing speed. Thus, for example, in slow traffic conditions, drivers could choose to follow at a headway that is comfortable for them given the prevailing speed. This leads to a statistical model formulation

$$d_i = g(v_i) + \epsilon_i \dots\dots\dots (4)$$

where  $\epsilon_i$  is an error term for the estimated occupancy. In this case, the form of the function  $g(\cdot)$  is inverse to that of  $f(\cdot)$ .

Various forms have been proposed in literature for the function  $f(d_i)$  of Equation 3. A detailed version of Greenshield's postulate of a linear relationship is as mathematically stated in

Equation 5.

$$f(d) = v_0 (1 - d/d_j) \dots\dots\dots (5)$$

$d$  = density/occupancy (measured in vehicles per length of road);  $v_0$ = free-flow speed; and  $d_j$ = jam density

Though this linear model is simple and useful, other non-linear models in works [15] have shown better results. Among these includes Greenburg's model (1959) relationship between speed and occupancy which was intended for use at high densities. This model is stated mathematically as

$$f(d) = v_m \log_e (d_j/d) \dots\dots\dots (6)$$

where  $d$  = density/occupancy (measured in vehicles per length of road);  $v_m$ = free-flow speed and  $d_j$ = jam density. Results from this model was proven to be better than the linear model by work in [15] but this model will not fit the purpose of computing travel time from this relationship without imposing certain constraints especially when dealing with lower occupancy values because the speed in theory approaches infinity as the occupancy approaches zero.

Underwood's (1961) model relationship between speed and density is another model but was intended primarily for use in free-flow conditions. Underwood's model is expressed as an exponential decay curve mathematically shown below and is most effective for non-congested traffic:

$$f(d) = v_0 \exp (-d/d_j) \dots\dots\dots (7)$$

Where  $d_j$  is the jam density. This model has an explicit free-flow speed  $v_0$ , but there is no value of occupancy that will cause the speed to be 0 so that it is consistent with the possibility that traffic can travel at a non-zero speed even when it is at jam density.

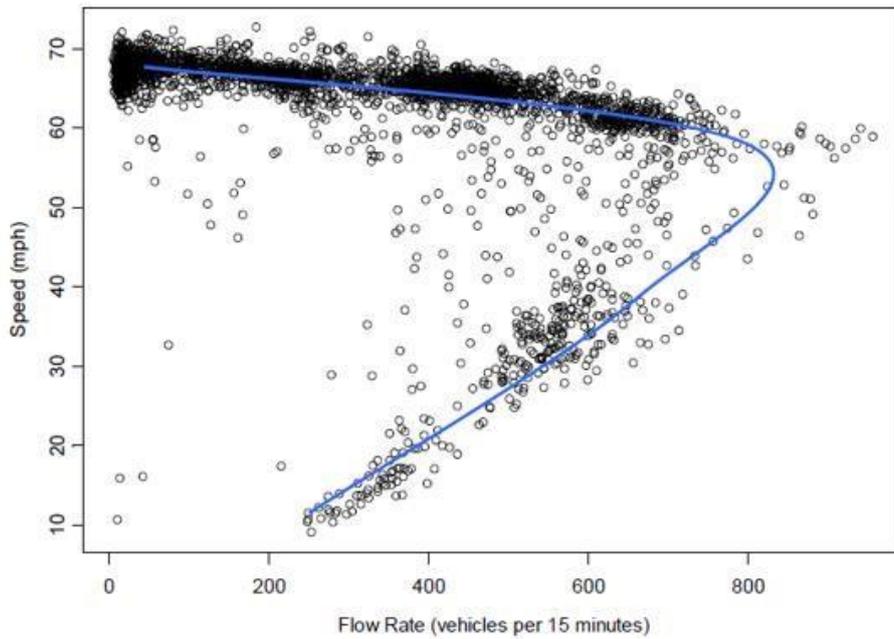
The Eddie model(1961)[15] employs two equations, an exponential equation (Underwood’s model) used when occupancy values are below the threshold value that marks the onset of congestion and a logarithmic equation(Greenburg’s model) used for occupancy values greater than the threshold occupancy value. These two equations are as follows

$$\text{Speed } (v) = V_m * \exp(-d/d_j), \text{ for } d \leq d_t \dots\dots\dots (8)$$

$$\text{Speed } (v) = V_m * \ln (d_j/d), \text{ for } d > d_t \dots\dots\dots (9)$$

Where  $d_j$  is the jam density which in this case is same as the capacity of the road segment and  $d_t$  is threshold density, which refers to the occupancy or density value that marks the onset of congestion.

An alternative to modeling the relation between speed and occupancy would be the use of data collected directly from the road network. In such a situation I could consider the fundamental relation of  $v = S * D$  where “v” is the flow rate, “S” being the corresponding average speed of vehicles and “D” being the vehicular density/occupancy on the road segment under study. The relation above suggests zero flow rate when there is zero occupancy and also will result in a flow rate of zero for jam density assuming that the speed at absolute jam density is zero. An example simplified of such relation plot with sample data from the Atlanta intersection from work by author in [15] is as shown below:



*Figure 7: Speed-Flow Data and Model [15].*

Using data provided from four detectors, the first attempt was to fit a speed-flow relation from the raw data. The fundamental relation is then used to calculate density and attempt is made to fit one of the speed-density models to the data. By using both the speed and the volume data provided by the detectors, this work accepts that the method they used to calculate speed (using an artificial zone and measuring entry to exit time for the zone) is accurate and consistent.

The data provided for the Atlanta interstates gave both speed and volume data. By plotting the raw data for the four detectors, a conclusion can be drawn that the empirical representation of the speed-flow relation is not as clearly defined as theory suggests. The empirical data do not easily lend to an obvious regression. It can also be noticed that there are several errant points in the data that would probably need to be cleaned.

This model indicates a capacity, or congestion collapse point, at around 800 vehicles per 15 minutes where the speed-flow model breaks down and speeds drop significantly.

Next, the density is calculated to define the speed-density relationship for the data. Of the several theoretical models described in the earlier, a three-part linear model was chosen for the study by the author in [15] resulting in the characteristics shown in the graph below:

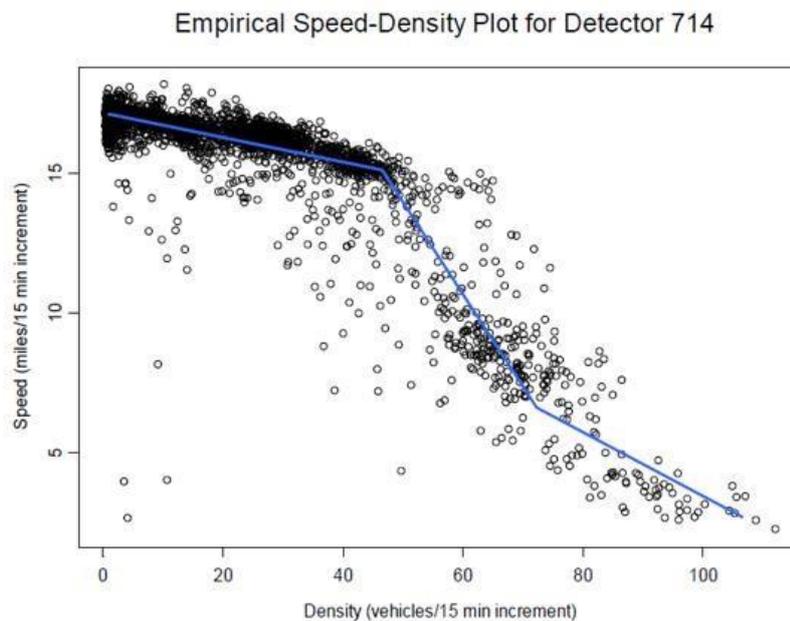


Figure 8: Speed-Density Model for one detector[15].

## 2.7 PROPORTIONAL-INTEGRAL-DERIVATIVE (PID) CONTROL THEORY

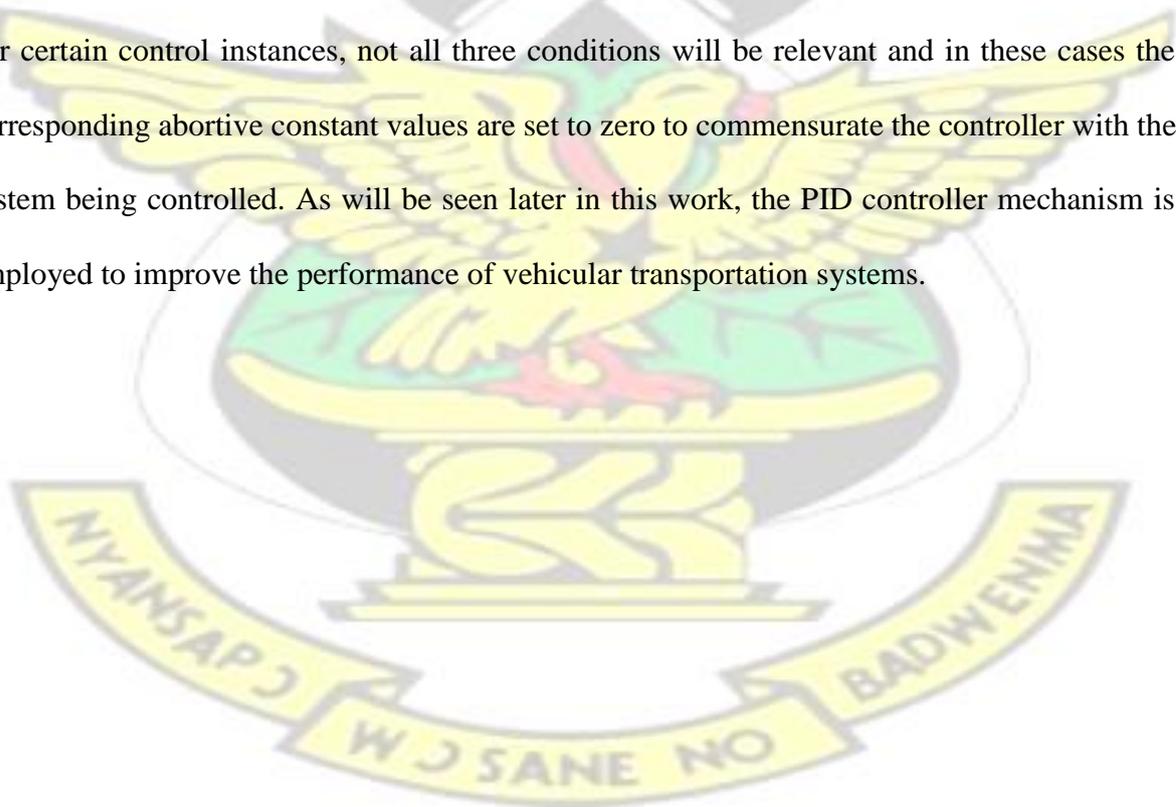
The PID controller mechanism widely used in the field of industrial control system is a feedback loop control technique system. Generally, PID controllers compute an error value/figure as the difference between an instantaneous measured industrial process variable and a required threshold value. The major task of the PID control mechanism is to reduce this error value by adjusting parameters of the process in an attempt to have a zero difference between the instantaneous process value and the desired threshold value.

The PID controller does this parameter manipulation via three constant figures (Proportional gain, Integral gain and Derivative gain) and the measured error values. The proportional gain

constant is used to scale the computed instantaneous error to an appreciable level for error correction. The Derivative gain takes charge of a predictive error based on the rate of change of previously computed error values and the Integral gain is a forgetful factor used by a portion of the controller that accumulates all past errors as a parameter for error correction.

A cumulative sum of these three actions are used to alter the industrial process input parameters as a conciliatory value in an attempt to assuage and abate the previously measured error value. The PID controller's dependency on instantaneous measured values rather than the underlining process makes it a widely useful concept that can be adopted to ameliorate performance in diverse fields beyond industrial control systems. This is easily achieved by tuning the three controlling constants (PID) explained above.

For certain control instances, not all three conditions will be relevant and in these cases the corresponding abortive constant values are set to zero to commensurate the controller with the system being controlled. As will be seen later in this work, the PID controller mechanism is employed to improve the performance of vehicular transportation systems.



## CHAPTER 3

### METHODOLOGY

#### 3.1 OVERVIEW

Routing algorithms are required heavily in transportation system. Their main purpose is to give a fair idea of travel costs between nodes and sometimes to assist or select best routes from any departure node to any arrival node.

On the front, routing algorithms usually require convergence of the network (road sub section in this case) being considered. A network is said to have converged if enough information concerning all links within the network are known allowing routing decisions to be made on solid grounds with least amount of guess. Also, good routing algorithms should be able to handle situations of failure in links and finally the routing algorithm is better and usually has higher efficiency if it is adaptive. An adaptive routing algorithm is able to modify its routes when some links within the network become congested to an extent that will significantly affect a previously chosen path. A routing technique that is able to handle the final situation mentioned above is likely to require a feedback mechanism.

The main purpose of a routing algorithm is to select routes for departure destination pair. To this side of the problem I will adapt an algorithm based on Dijkstra's solutions to the shortest paths problem which is commonly used in traffic decongestion on data networks. However in this case, the metric to be used in determining the best path will rather be estimated travel-time based on prevailing traffic congestion measured on the road networks at any instance in time. Contrary to most existing routing algorithms where routing issues like link and node failures/repairs are broadcast to all routers resulting in a decentralized approach as a measure

to cope with link and node failures, I discuss how embedded systems fitted with ultrasonic sensors are mounted on road networks to dynamically collect and convey vehicular flow rates and road occupancy data on all road sub-sections to a central database (centralized approach single point of failure noted but kept to reduce cost and size of needed storage capacity and processing power of the mounted embedded system units).

In this solution I apply principles of graph theory to attain topological design of a sub-section of the road network as a data structure (A MAP) implemented in the JAVA programming language. This map serves as a routing table where nodes of a graph are represented by road intersections and the road networks themselves form the edges of the graph. Information about an edge stored in the data structure include distance of the road subsection, the grade of the road, the current road occupancy on that sub-section (updated continuously from the database mentioned above), source node, destination node, direction of edge (bidirectional or unidirectional) and the estimated travel time of that edge.

Information stored about a node include the node's id, connected edges, etc. Both nodes and edges information are stored in an oracle database. Any form of update can be performed on the nodes and edges information stored in the database from time to time including addition of new nodes or edges, blocked roads can be removed from the database, etc. A function in the data structure allows the map to be reconstructed dynamically from the current status of nodes and edges stored in the database. This is very necessary as attributes of the edges and nodes will not remain static. This also makes provision for scaling the solution in an incremental form without having to alter the underlining codes and algorithms.

I choose to use a dynamic routing algorithm for routing vehicles rather than a static algorithm as I target at a higher throughput on the road networks. For *Static* routing algorithms, a fixed and preconfigured route for all departure destination node pair regardless of traffic conditions are kept in a routing table. These type of algorithm hardly achieve high throughputs under broad variety of traffic input patterns. A good algorithm is expected to keep delays low while increasing throughput. An example of static routing systems is the current situation of unintelligent traffic lights used mostly for vehicular routing globally.

In my implementation, I employ a dynamic routing system modeled from principles of the SPF routing algorithm. Here, each edge of a graph data structure representing a route on the road network is dynamically assigned a positive numeric metric. This numeric metric is a modelled estimated travel time on that route. Bidirectional routes may have different metric values in each direction. This dynamically assigned value at any point in time for all routes are critically modeled (to be discussed later in this chapter) using real time vehicular flow and road occupancy values as parameters. The formulae are derived such that the lesser the metric (estimated travel time) value, the more optimum the route will be.

The succeeding sections give details of the proposed vehicular routing based on real-time road occupancy estimates.

### **3.2. THE PRIMARY METRIC AND ITS ESTIMATION**

To be able to apply the Shortest Path First algorithm to road networks, there is the need to derive a performance metric close to a true measure of traffic behavior on the road network.

The choice of parameters for this metric plays a vital role in the metric's performance. Major parameters chosen for the metric computation for traffic congestion are the flow rate of vehicle on the road and the average road occupancy. Keeping in mind the fact that there exist other

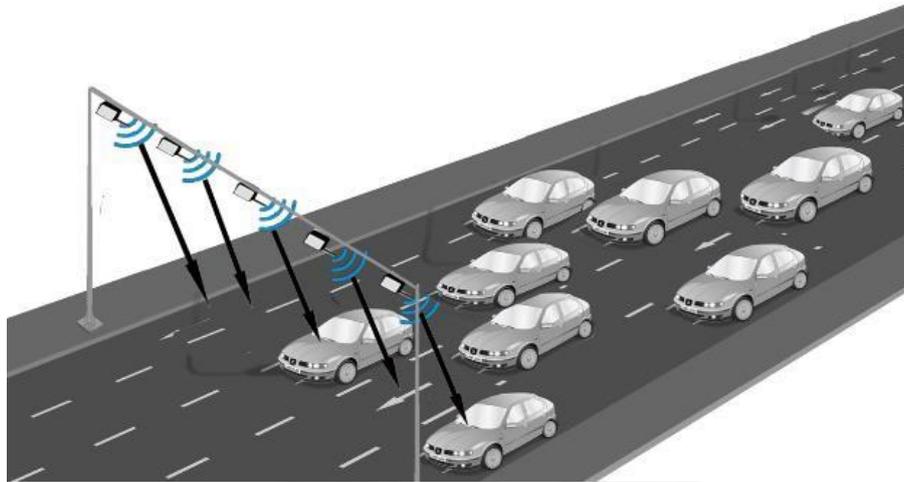
parameters that influence traffic congestion, there is still the likelihood to encounter the problem of measurement inversion. In this work, I try to reduce the effect of such factors on the metric through the well tested Proportional Integral Derivative (PID) controller corrective mechanisms for controlling and refining deviation likely to be in the measured values. I am mostly concerned with the measurement variations over the transmission period.

I then analyze relationships between occupancy, flow rate and speed of vehicles on a road network. A major factor that influences flow rate and speed of vehicles on a road network is the state of occupancy of the road network. I use the study of speed-occupancy, speed-flow relationship to compute the estimated speed of vehicles on a road link based on refined occupancy values measured. Travel time of vehicles on the road network based on the degree of deviation of occupancy is then determined using the fundamental relation between distance, speed and time. One very early research into the relationship between occupancy and flow rate is Greenshield's postulated [15][16] of a linear relationship between speed and occupancy in 1934.

In this work I first consider a way in which a value (density/occupancy) that relates to the fundamental equation of speed-occupancy relation used can be measured practically on road segments using ultrasonic sensors. I then analyze different functional forms that could be used to represent the fundamental relationship between the measured occupancy value and average speed of vehicles. As mentioned earlier, the direct and inverse relationship between the speed, distance and time thus, gives us a way of predicting estimated travel time for any subsection of the road network. This estimated travel time is what I substitute for the routing metric in SPF algorithm.

### 3.2.1. OCCUPANCY/DENSITY MEASUREMENT

Road occupancy data for the various road sub sections is obtained from electronic devices fitted with ultrasonic sensors and mounted at strategic entry and exit points on road networks as shown below.



*Figure 9: Integrated traffic data gathering setup with ultrasonic sensors.*

These devices count the inflow and outflow of vehicles on a road sub-sections and computes the road subsection occupancy as the difference between the inflow count and outflow count. In this work, I stay with models in line with *Equation 3* of the contention that traffic speed is determined by traffic density/occupancy. However, for occupancy values below jam density/occupancy, flow-rate is high and the occupancy values reported by the sensors in the previous section lags behind the actual value due to transmission delays as a few more vehicles join the road segment over the transmission period. On the contrary, for occupancy values above jam density, flow-rate is very slow and vehicles which are only partly within the segment are counted by the sensors as vehicles within the road segment. These vehicles however take quite some time to actually join the road segment in full. The instantaneous occupancies in this case are therefore, likely to be different from the actual occupancy.

The error term introduced into the speed/occupancy relation is to make up for the dynamic and capricious changes in occupancy values over time. In literature, statistical procedures have been applied to estimate parameters of a given model form for function  $f$  with corresponding statistical distribution that is adopted for the error term  $e$  in *Equation 3*.

In this work however, I intend to adopt the same postulate but to incorporate a real time and reactive component into the function  $f(d_i)$  that takes care of the error term  $e$  at any point in time based on real time data rather than predefined statistical data.

In the following section I present how error term  $e_i$  is compensated for by a PID compensator output used to refine the measured instantaneous occupancy value before it is used to model the vehicular speed on the road link. Thus, if the refined occupancy values accurately compensate for the errors due to transmission delays then the modeled speed values will need no error term reducing *Equation 3* to:

$$v_i = f(d_i') \dots\dots\dots(10)$$

where  $d_i'$  is the adjusted instantaneous occupancy

### 3.3. ADJUSTING INSTANTANEOUS OCCUPANCY FOR ERROR CORRECIION

In refining the measured road occupancy/density values, I model the traffic flow on vehicular networks as a classic Proportional Integral Derivative (**PID**) control system considering the current vehicular flow rate (inflow and outflow), road capacity, threshold occupancy level of the road subsection and the current/instantaneous occupancy of the road as factors for computing the likelihood degree of congestion on any road subsection. A PID compensator

computes an error value as the difference between the measured traffic flow rate and a desired/ideal flow rate on the road subsection.

The PID compensator mechanism widely used in the field of industrial control system is a feedback loop control technique system. Generally, PID controllers compute an error value as the difference between an instantaneous measured industrial process variable and a required threshold value. The major task of the PID control mechanism is to reduce this error value by adjusting parameters of the process in an attempt to have a zero difference between the instantaneous process value and the desired threshold value.

In this work I use road occupancy as the process variable and the jam density as the required threshold value. The idea is to direct more vehicles to road segments with occupancy below the required threshold and at the same time divert vehicular flow away from road segments with occupancy above the threshold. The threshold value termed jam density in this case is that occupancy value that marks the onset of traffic congestion. The final result is to have the best load balance possible based on the current vehicular trip demands with respect to the available routes.

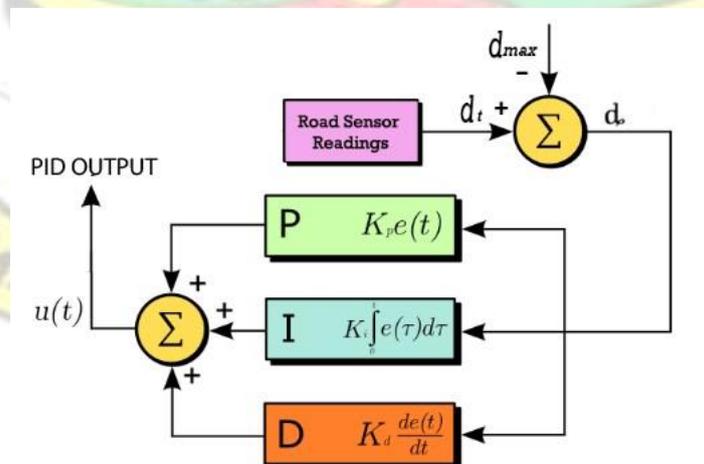


Figure 10: The PID compensator.

In summary, the PID compensator in Figure10 receives instantaneous occupancy ( $d_t$ ) and the threshold occupancy ( $d_{max}$ ) as input and computes the deviation( $d_t - d_{max}$ ) of the current occupancy value from the threshold value as the error ( $d$ ). This deviation (error) value(s) is used by the Proportional Congestion Deviation unit ( $P_{cd}$ ), Derivative Congestion Deviation unit( $D_{cd}$ ) and Integral Congestion Deviation unit( $I_{cd}$ ) units to compute the proportional, derivative and integral deviations of the measured occupancy value. A summation of the respective deviations mentioned above is a deviation value ( $U(t)$ ) that factors in both deviation history and a predictive measure of deviation.

As input, the first stage of the metric computation process subtracts the instantaneous occupancy level from the threshold value of occupancy that marks the onset of congestion. This value is the occupancy deviation ( $d$ ).

The value  $d$  is used as inputs to the Proportional Congestion Deviation (**PCD**) unit, Integral Congestion Deviation (**ICD**) unit and the Derivative Congestion Deviation (**DCD**) unit. The **DCD** unit also keeps the previous  $d$  value as additional input and the **ICD** unit keeps a history of the previous  $d$  values as input.

### 3.3.1. PROPORTIONAL CONGESTION DEVIATION

The computed deviation value is used as input to the proportional congestion deviation (PCD) unit. In the PCD unit, the occupancy deviation ( $d$ ) is scaled using a Proportional gain (**Kp**) whose value range from 0 – 1. The value of **Kp** for any road sub section is carefully chosen to either intensify or relax the  $d$  value based on the relative impact of traffic congestion of that road subsection on other road sub sections. Thus proportional congestion deviation (**Pcd**) is computed as shown below

$$\text{Pcd output} = K_p * d \dots\dots\dots (11)$$

Where  $d$  is the occupancy deviation value computed as the error, which is the difference between the instantaneous occupancy value measured and the threshold occupancy value that marks the onset of congestion for the road segment.

### 3.3.2. DERIVATIVE CONGESTION DEVIATION

The DCD unit computes the rate of change of deviation of the  $d$  value from the threshold value as the derivative deviation and is scaled using a Derivative gain ( $K_d$ ). In this case, derivative **deviation** is the difference between the two preceding **deviations**, i.e.  $d(t)$  and  $d(t-1)$  where  $d(t)$  is the current computed **deviation**. The derivative congestion deviation (**Dcd**) is computed as shown below

$$\text{Dcd output} = K_d * \frac{d}{dt}(d) \dots\dots\dots (12)$$

The derivative deviation is a predictive measure being used to predict future congestion because I know the slope (gradient of a line, the rate of change of deviation). This allows the metric a way to factor in a very likely future traffic congestion expectancy measurement and this measure is incorporated as a congestion avoidance mechanism. The  $K_d$  value is adjusted in multiples of tens into thousands depending on how predictive I intend the metric to be.

### 3.3.3. INTEGRAL CONGESTION DEVIATION

The ICD unit accumulates instantaneous past errors over a period of time. It factors in both the magnitude and duration of congestion deviation into the value of the generated metric giving the controller an accumulated offset of deviation that should have been corrected in the past. The Integral congestion deviation (**Icd**) is thus computed as shown below

$$\text{Icd output} = Ki * \int_0^t d_b(\tau) d\tau \dots\dots\dots (13)$$

The constant **Ki** can be seen as the forgetful factor which is kept as a fraction of a whole. It is used to forget a bit of the past or weight the current deviation more than the previous integral deviations. Another way to think of it is that I am forcing integral to be forgetful of things that happened in the past or a "long" time ago.

### 3.3.4. FINAL PID CONTROLLER OUTPUT

The final output of the PID model is a summation of the proportional, integral and derivative deviations from the desired congestion value as shown below:

$$U(t) = Kp * error(t) + Kp * \frac{d}{dt}(error(t)) + Ki * \int_0^t error(\tau) d\tau \dots\dots\dots (14)$$

The resulting  $U(t)$  is either positive or negative depending on whether the road occupancy fall above or below the threshold value and also on the trends of variation of occupancy values over a monitored period of time.

In this work, the aberrancy in the instantaneous occupancy value is handled by subtracting the PID output from the reported instantaneous occupancy as a conciliatory value for transmission delays and vehicular behavior at different occupancy levels. The refined occupancy value is thus computed as

$$d_i' = d_i - U(t) \dots\dots\dots(15)$$

where  $d_i'$  = refined occupancy,  $d_i$  = instantaneous occupancy and  $U(t)$  = PID Output as shown in *Figure 10*.

### 3.3.5 FORMULATION OF SPEED RELATIONSHIPS

Throughout this work, the occupancy values used are the refined instantaneous occupancies  $d_i'$  computed from *Equation 15*. To begin review of the formulation of  $f(d_i')$  in *Equation 10*, I adopt and refine *Equation 8* and *Equation 9* for as they are most effective for situations of

occupancy values being either below or above threshold value respectively. However to tune the model in line with this solution, I replace the occupancy value “d” with the refined occupancy “d<sub>i</sub>’”. Note that the Eddie model adopted had no way of compensating for the error due to transmission delays but with the substitution made, this error component as postulated by fundamental relationship is taken care of.

Thus, the adopted and refined model can be stated as in Equations 16 and 17.

$$\text{Speed } (v) = V_0 * \exp(-d_i' / d_j), \text{ for } d_i' \leq d_t \dots\dots\dots(16)$$

$$\text{Speed } (v) = V_0 * \ln (d_j/d_i'), \text{ for } d_i' > d_t \dots\dots\dots (17)$$

I exploit the fundamental relationship between speed, distance and time to estimate the travel time on a road link. The travel time is computed from the predicted speed using the fundamental relation:

$$\text{Travel Time } \alpha \frac{\text{distance}}{\text{Speed}}$$

Thus

$$\text{Travel Time} = \begin{cases} \frac{\text{distance}}{V_0 * \exp(-d_i' / d_j)} & \text{for } d_i' \leq d_t \\ \frac{\text{distance}}{V_0 * \ln(d_j / d_i')} & \text{for } d_i' > d_t \end{cases} \dots\dots\dots(18)$$

This travel time is used as a routing metric for the SPF algorithm.

## CHAPTER 4

### RESULTS AND DISCUSSION

## 4.1. INTRODUCTION

In the following section I discuss and justify the speed-relation model used in the generation of travel time as a routing metric. I also discuss how the computed travel time metric is used together with the SPF algorithm for traffic management on vehicular networks.

I later compare and discuss results of the proposed solution with the STAR reference solution discussed in my literature review as I find that to be the closest implementation to my proposed solution. Finally I discuss a briefing of a prototype mobile application of this work to be used by drivers for routing.

## 4.2. SIMULATION AND DISCUSSION OF THE SELECTED EDDIE MODEL

I confirm the behavior of this routing metric by simulating varying occupancy values for a 5km stretch of road segment with a capacity of 1200 vehicles and a congestion threshold value of 1000. Find below the simulated data captured at five minutes interval for this study. The first part of the simulation as shown in the table below shows how the PID controller principle is applied to refine the instantaneous occupancies being captured before fed as input to the second table that simulates the speed-occupancy relationship in line with *Equations 16 and 17*. The second table goes further to simulate the travel time speed relationship resulting in the desired occupancy-travel time relationship.

### 4.2.1. PID SIMULATION

Table 1 shows simulation data of a PID controller with a Proportional gain of 0.0009 a derivative gain of 10 and an integral gain (which could also be termed the forgetful factor) of 0.0005. The controller in this simulation is being used as explained earlier to refine instantaneous occupancy

values  $d_i$ , measured by road sensors. Under normal circumstances the Derivative output from the controller is taken as the refined occupancy value for each corresponding instantaneous occupancy. Under special conditions the cumulative PID output is taken as the refined occupancy—here the gains are adjusted to achieve the targeted objective such as intentionally setting the occupancy of a certain road segment to a large value to repel traffic.

Table 1: PID Simulation

$d_i$	$d_i$	$\frac{d}{dt}(d_i)$	$\int_0^t d_i(\tau) d\tau$	$P_{out}$	$D_{out}$	$I_{out}$	$PID_{out}$	Derivative Occupancy, $d_i'$	PID Occupancy
3	-997	0	0	-0.8973	0	0	-0.8973	3	3.8973
4	-996	-1	-997	-0.8964	-1	-0.4985	-2.3949	5	6.3949
8	-992	-4	-1993	-0.8928	-4	-0.9965	-5.8893	12	13.8893
10	-990	-2	-2985	-0.891	-2	-1.4925	-4.3835	12	14.3835
...	...	...	...	...	...	...	...	...	...
877	-123	29	-345	-0.1107	29	-0.1725	28.7168	848	848.2832
891	-109	-14	-420	-0.0981	-14	-0.21	-14.3081	905	905.3081
901	-99	-10	-477	-0.0891	-10	-0.2385	-10.3276	911	911.3276
904	-96	-3	-528	-0.0864	-3	-0.264	-3.3504	907	907.3504
903	-97	1	-521	-0.0873	1	-0.2605	0.6522	902	902.3478
909	-91	-6	-524	-0.0819	-6	-0.262	-6.3439	915	915.3439
919	-81	-10	-492	-0.0729	-10	-0.246	-10.3189	929	929.3189
924	-76	-5	-464	-0.0684	-5	-0.232	-5.3004	929	929.3004
913	-87	11	-441	-0.0783	11	-0.2205	10.7012	902	902.2988
918	-82	-5	-432	-0.0738	-5	-0.216	-5.2898	923	923.2898
915	-85	3	-417	-0.0765	3	-0.2085	2.715	912	912.285
917	-83	-2	-411	-0.0747	-2	-0.2055	-2.2802	919	919.2802
955	-45	-3	-274	-0.0405	-3	-0.137	-3.1775	958	958.1775
958	-42	-3	-254	-0.0378	-3	-0.127	-3.1648	961	961.1648
948	-52	10	-235	-0.0468	10	-0.1175	9.8357	938	938.1643
959	-41	-11	-239	-0.0369	-11	-0.1195	-11.1564	970	970.1564

979	-21	-20	-228	-0.0189	-20	-0.114	-20.1329	999	999.1329
982	-18	-3	-201	-0.0162	-3	-0.1005	-3.1167	985	985.1167
986	-14	-4	-174	-0.0126	-4	-0.087	-4.0996	990	990.0996
993	-7	-7	-146	-0.0063	-7	-0.073	-7.0793	1000	1000.0793
996	-4	-3	-101	-0.0036	-3	-0.0505	-3.0541	999	999.0541
1000	0	-4	-64	0	-4	-0.032	-4.032	1004	1004.032
1003	3	-3	-43	0.0027	-3	-0.0215	-3.0188	1006	1006.0188
1008	8	-5	-22	0.0072	-5	-0.011	-5.0038	1013	1013.0038
1011	11	-3	0	0.0099	-3	0	-2.9901	1014	1013.9901
1012	12	-1	18	0.0108	-1	0.009	-0.9802	1013	1012.9802
1013	13	-1	34	0.0117	-1	0.017	-0.9713	1014	1013.9713
1015	15	-2	47	0.0135	-2	0.0235	-1.963	1017	1016.963
1017	17	-2	59	0.0153	-2	0.0295	-1.9552	1019	1018.9552
1028	28	-11	68	0.0252	-11	0.034	-10.9408	1039	1038.9408
1011	11	17	85	0.0099	17	0.0425	17.0524	994	993.9476

1012	12	-1	84	0.0108	-1	0.042	-0.9472	1013	1012.9472
1037	37	-25	83	0.0333	-25	0.0415	-24.9252	1062	1061.9252
1028	28	9	105	0.0252	9	0.0525	9.0777	1019	1018.9223
1029	29	-1	116	0.0261	-1	0.058	-0.9159	1030	1029.9159
1030	30	-1	117	0.027	-1	0.0585	-0.9145	1031	1030.9145
1027	27	3	136	0.0243	3	0.068	3.0923	1024	1023.9077
1053	53	-26	151	0.0477	-26	0.0755	-25.8768	1079	1078.8768
1050	50	3	167	0.045	3	0.0835	3.1285	1047	1046.8715
1049	49	-32	68	0.0441	-32	0.034	-31.9219	1081	1080.9219
1048	48	1	106	0.0432	1	0.053	1.0962	1047	1046.9038
1047	47	1	142	0.0423	1	0.071	1.1133	1046	1045.8867
1042	42	5	176	0.0378	5	0.088	5.1258	1037	1036.8742
1042	42	0	203	0.0378	0	0.1015	0.1393	1042	1041.8607
1041	41	1	228	0.0369	1	0.114	1.1509	1040	1039.8491
1041	41	0	220	0.0369	0	0.11	0.1469	1041	1040.8531
1038	38	3	213	0.0342	3	0.1065	3.1407	1035	1034.8593
1037	37	1	204	0.0333	1	0.102	1.1353	1036	1035.8647
1037	37	0	199	0.0333	0	0.0995	0.1328	1037	1036.8672
1037	37	0	194	0.0333	0	0.097	0.1303	1037	1036.8697
1036	36	1	190	0.0324	1	0.095	1.1274	1035	1034.8726
1034	34	2	185	0.0306	2	0.0925	2.1231	1032	1031.8769
1032	32	2	181	0.0288	2	0.0905	2.1193	1030	1029.8807
1032	32	0	176	0.0288	0	0.088	0.1168	1032	1031.8832
1031	31	1	171	0.0279	1	0.0855	1.1134	1030	1029.8866
1030	30	1	165	0.027	1	0.0825	1.1095	1029	1028.8905
1030	30	0	159	0.027	0	0.0795	0.1065	1030	1029.8935
1029	29	1	155	0.0261	1	0.0775	1.1036	1028	1027.8964

1029	29	0	152	0.0261	0	0.076	0.1021	1029	1028.8979
1029	29	0	149	0.0261	0	0.0745	0.1006	1029	1028.8994
1028	28	1	147	0.0252	1	0.0735	1.0987	1027	1026.9013
1028	28	0	145	0.0252	0	0.0725	0.0977	1028	1027.9023
1027	27	1	143	0.0243	1	0.0715	1.0958	1026	1025.9042
1026	26	1	141	0.0234	1	0.0705	1.0939	1025	1024.9061
1025	25	1	138	0.0225	1	0.069	1.0915	1024	1023.9085
1022	22	3	134	0.0198	3	0.067	3.0868	1019	1018.9132
1017	17	5	128	0.0153	5	0.064	5.0793	1012	1011.9207
1015	15	2	117	0.0135	2	0.0585	2.072	1013	1012.928
1013	13	2	105	0.0117	2	0.0525	2.0642	1011	1010.9358
1012	12	1	92	0.0108	1	0.046	1.0568	1011	1010.9432
1012	12	0	79	0.0108	0	0.0395	0.0503	1012	1011.9497
1011	11	1	69	0.0099	1	0.0345	1.0444	1010	1009.9556
1011	11	0	63	0.0099	0	0.0315	0.0414	1011	1010.9586
1008	8	3	59	0.0072	3	0.0295	3.0367	1005	1004.9633
1003	3	5	54	0.0027	5	0.027	5.0297	998	997.9703
1000	0	3	45	0	3	0.0225	3.0225	997	996.9775
996	-4	4	33	-0.0036	4	0.0165	4.0129	992	991.9871
993	-7	3	18	-0.0063	3	0.009	3.0027	990	989.9973
986	-14	7	0	-0.0126	7	0	6.9874	979	979.0126
982	-18	4	-22	-0.0162	4	-0.011	3.9728	978	978.0272
979	-21	3	-43	-0.0189	3	-0.0215	2.9596	976	976.0404
959	-41	20	-64	-0.0369	20	-0.032	19.9311	939	939.0689
958	-42	1	-101	-0.0378	1	-0.0505	0.9117	957	957.0883
955	-45	3	-136	-0.0405	3	-0.068	2.8915	952	952.1085
952	-48	3	-167	-0.0432	3	-0.0835	2.8733	949	949.1267
952	-48	0	-197	-0.0432	0	-0.0985	-0.1417	952	952.1417
948	-52	4	-224	-0.0468	4	-0.112	3.8412	944	944.1588
948	-52	0	-235	-0.0468	0	-0.1175	-0.1643	948	948.1643
939	-61	9	-245	-0.0549	9	-0.1225	8.8226	930	930.1774
935	-65	4	-261	-0.0585	4	-0.1305	3.811	931	931.189
934	-66	1	-278	-0.0594	1	-0.139	0.8016	933	933.1984
934	-66	0	-296	-0.0594	0	-0.148	-0.2074	934	934.2074
933	-67	1	-310	-0.0603	1	-0.155	0.7847	932	932.2153
932	-68	1	-325	-0.0612	1	-0.1625	0.7763	931	931.2237
931	-69	1	-332	-0.0621	1	-0.166	0.7719	930	930.2281
930	-70	1	-336	-0.063	1	-0.168	0.769	929	929.231
924	-76	6	-340	-0.0684	6	-0.17	5.7616	918	918.2384
919	-81	5	-350	-0.0729	5	-0.175	4.7521	914	914.2479
918	-82	1	-364	-0.0738	1	-0.182	0.7442	917	917.2558
917	-83	1	-378	-0.0747	1	-0.189	0.7363	916	916.2637
917	-83	0	-392	-0.0747	0	-0.196	-0.2707	917	917.2707
915	-85	2	-405	-0.0765	2	-0.2025	1.721	913	913.279
915	-85	0	-414	-0.0765	0	-0.207	-0.2835	915	915.2835
913	-87	2	-418	-0.0783	2	-0.209	1.7127	911	911.2873
913	-87	0	-423	-0.0783	0	-0.2115	-0.2898	913	913.2898
913	-87	0	-427	-0.0783	0	-0.2135	-0.2918	913	913.2918
909	-91	4	-431	-0.0819	4	-0.2155	3.7026	905	905.2974
909	-91	0	-437	-0.0819	0	-0.2185	-0.3004	909	909.3004
906	-94	3	-443	-0.0846	3	-0.2215	2.6939	903	903.3061
904	-96	2	-450	-0.0864	2	-0.225	1.6886	902	902.3114
903	-97	1	-459	-0.0873	1	-0.2295	0.6832	902	902.3168
901	-99	2	-469	-0.0891	2	-0.2345	1.6764	899	899.3236
897	-103	4	-477	-0.0927	4	-0.2385	3.6688	893	893.3312
891	-109	6	-489	-0.0981	6	-0.2445	5.6574	885	885.3426
877	-123	14	-504	-0.1107	14	-0.252	13.6373	863	863.3627

The output from the PID computation are refined occupancy values that have factored in an error in the captured or instantaneous occupancy value mainly due to delays in the transmission of these values. The refined value computed this way uses the rate of change of occupancy value to be able to predict the next expected value of occupancy. This rate is a positive or negative corrective value which is subtracted from the instantaneous value to refine it. The controller also keeps track of previous uncorrected errors accumulated over a period of time and this again is multiplied by an integral gain (forgetful factor). The result from this is also applied in a similar manner as the derivative output to deliberately assign fictitious occupancy values to selected road segments of the road network as a form of prioritization as explained earlier.

The simulation goes further to show the output of the controller during decongestion. During decongestion there is likely to be a monotonic decrement in road occupancy. This means the behavior of traffic data will be the reverse of what it is during occupancy growth for values below the threshold in which case the actual occupancy value will continue to lag behind the transmitted value as a few more vehicles exit the road segment over the transmission period. This however is the case for values below threshold during decongestion characterized by a monotonic decrement in occupancy data.

Find below a linear, quadratic and cubic analyses of the simulated PID controller output from SPSS.

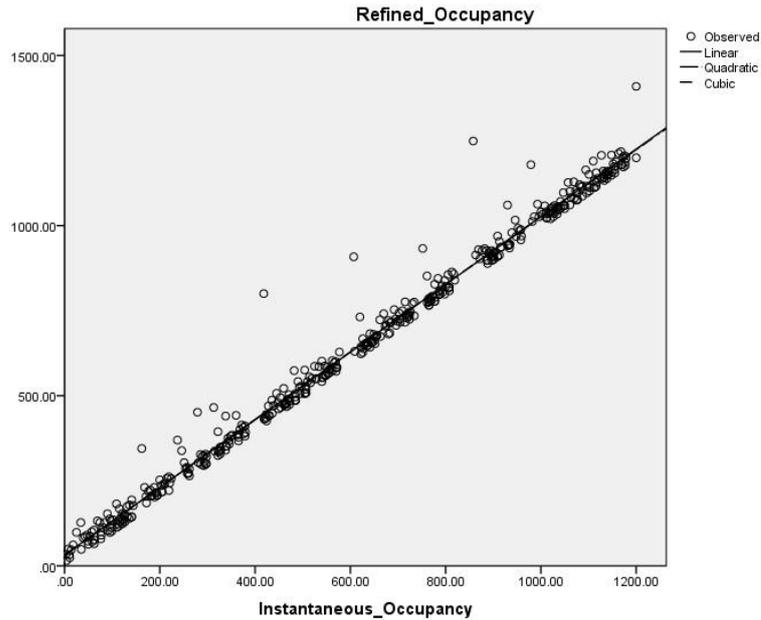


Figure 11: Instantaneous occupancy VRS Refined occupancy.

Model Summary and Parameter Estimates									
Dependent Variable: Refined_Occupancy									
Equation	Model Summary					Parameter Estimates			
	R Square	F	df1	df2	Sig.	Constant	b1	b2	b3
Linear	.987	34842.070	1	443	.000	32.036	.994		
Quadratic	.987	17384.972	2	442	.000	30.806	1.000	-4.929E-6	
Cubic	.987	11564.386	3	441	.000	31.612	.992	1.169E-5	-9.199E-9

The independent variable is Instantaneous\_Occupancy.

Figure 12: SPSS analytics on Instantaneous occupancy VRS Refined occupancy.

The analysis reveals a correlation coefficient of about 98.7% implying a very strong relationship between the instantaneous occupancy values captured and the refined value computed.

#### 4.2.2. OCCUPANCY-SPEED-TRAVEL TIME SIMULATION

Table 2 presents simulation data showing the occupancy-speed-travel time relationship using some of the refined occupancy values from Table 1.

In conformance with the congestion model from *Equations 16 and 17* being used, the simulation is in two sections. The first part simulates data for travel-time/occupancy relationship when occupancy values are below the threshold value. The second part of the simulation deals with occupancy values above the threshold value that marks the onset of congestion. Data for this part is shown in Table 3.



Table 2: Occupancy-Speed-Travel Time for Adjusted Occupancies below the Threshold Value

$di'$	$-di' / dj$	$\exp(-di' / dj)$	$V_0 * \exp(-di' / dj)$	TravelTime
3	-0.003	0.998	79.800	0.0627
5	-4166667.000	0.996	79.667	0.0628
12	-0.010	0.990	79.204	0.0631
...	...	...	...	...
902	-751666667.000	0.472	37.726	0.1325
905	-754166667.000	0.470	37.632	0.1329
909	-0.758	0.469	37.507	0.1333
915	-0.763	0.466	37.320	0.1340
917	-764166667.000	0.466	37.258	0.1342
919	-765833333.000	0.465	37.196	0.1344
913	-760833333.000	0.467	37.382	0.1338
917	-764166667.000	0.466	37.258	0.1342
932	-776666667.000	0.460	36.795	0.1359
933	-0.778	0.460	36.764	0.1360
934	-778333333.000	0.459	36.734	0.1361
935	-779166667.000	0.459	36.703	0.1362
936	-0.780	0.458	36.672	0.1363
943	-785833333.000	0.456	36.459	0.1371
944	-786666667.000	0.455	36.429	0.1373
956	-796666667.000	0.451	36.066	0.1386
965	-804166667.000	0.447	35.797	0.1397
970	-808333333.000	0.446	35.648	0.1403
985	-820833333.000	0.440	35.205	0.1420
990	-0.825	0.438	35.059	0.1426
999	-0.833	0.435	34.797	0.1437
<b>DISCONTINUITY</b>				
<b>(ADJUSTED OCCUPANCIES THAT ARE EACH GREATER THAN 1000)</b>				
999	-0.833	0.435	34.797	0.1437
998	-831666667.000	0.435	34.826	0.1436
993	-0.828	0.437	34.971	0.1430
989	-824166667.000	0.439	35.088	0.1425
984	-0.820	0.440	35.235	0.1419
969	-0.808	0.446	35.678	0.1401
964	-803333333.000	0.448	35.827	0.1396
960	-0.800	0.449	35.946	0.1391
957	-0.798	0.450	36.036	0.1387
955	-795833333.000	0.451	36.096	0.1385
943	-785833333.000	0.456	36.459	0.1371

The portion of the data in Table 2 shows a steady rise of travel time as occupancy increases from a small value to some value just under the threshold of congestion onset. Values in the lower part of Table 2 shows the travel time drops as adjusted occupancy falls. Table 3 reveals the exponential increase in travel time as the occupancy grows beyond the threshold value of

1000 which marks the onset of congestion in accordance with the Eddie model of speed-density relation.

*Table 3: Occupancy-Speed-travel Time for Adjusted Occupancies above the Threshold Value*

$di'$	$dj/di'$	$\ln(dj/di')$	$V_m * \ln(dj/di')$	$TravelTime$
1000.165	1.200	0.182	14.572	0.3431
1003.119	1.196	0.179	14.337	0.3488
1008.170	1.190	0.174	13.935	0.3588
1011.090	1.187	0.171	13.703	0.3649
1012.014	1.186	0.170	13.630	0.3668
1013.005	1.185	0.169	13.552	0.3689
1015.030	1.182	0.167	13.392	0.3733
1017.022	1.180	0.165	13.235	0.3778
1020.048	1.176	0.162	12.998	0.3847
1022.004	1.174	0.161	12.844	0.3893
1025.031	1.171	0.158	12.608	0.3966
1029.014	1.166	0.154	12.298	0.4066
1030.975	1.164	0.152	12.145	0.4117
1031.936	1.163	0.151	12.071	0.4142
1033.964	1.161	0.149	11.914	0.4197
1035.954	1.158	0.147	11.760	0.4252
1036.917	1.157	0.146	11.686	0.4279
...	...	...	...	...
1181	1.016	0.016	1.277	3.9160
1200	1.000	0	0	$\infty$
1221	0.983	-0.017	-1.388	-3.6026

The simulated data revealed an abnormal/infinite travel time if the road segment network is allowed to hit its full capacity. This confirms and coincides with the point of congestion collapse described by Todd Littman in my literature review. Analyzing the simulation data with the SPSS analytic tool results in the graphs shown in Figure 13 and Figure 14.

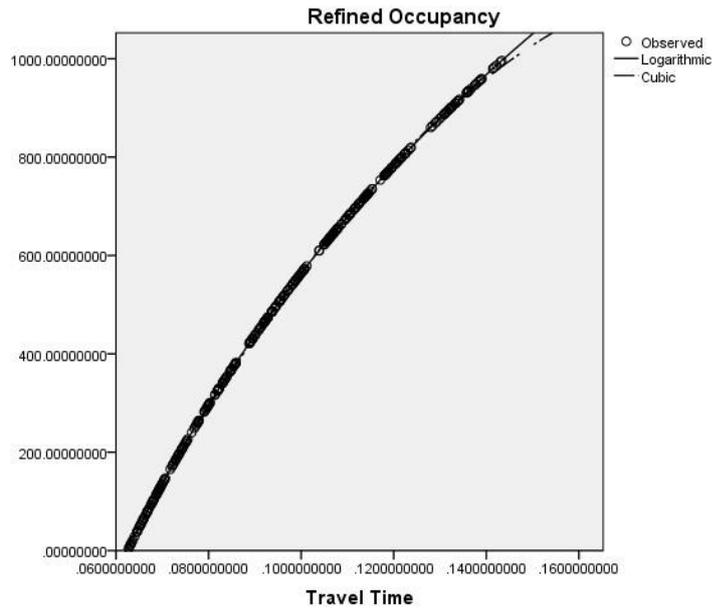


Figure 13: Occupancy Vs Travel-Time before threshold Occupancy

Figure 13 confirms the gradual but steady rise in travel time as occupancy increases up to the onset of congestion.

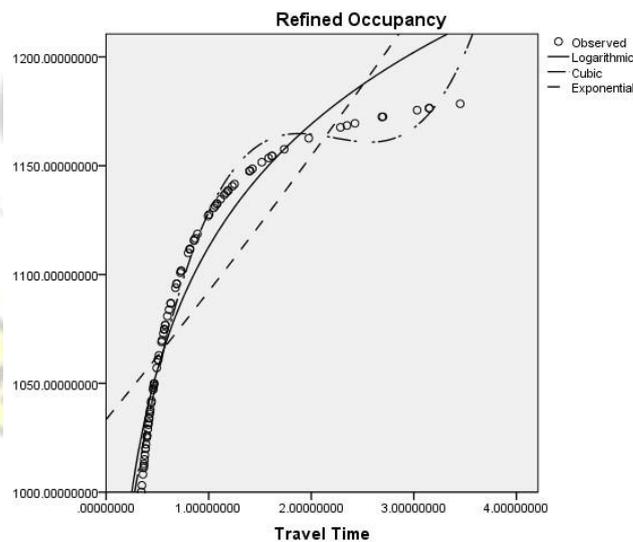


Figure 14: Occupancy Vs Travel-Time after threshold Occupancy

Figure 14 shows the rapid exponential growth in travel time for occupancy values above the value of congestion onset. It shows the rapid hopping of travel time for very small variations

in occupancy. Note that a value of occupancy just 0.079 above the road capacity will distort the behavior as it results in an abnormal spike value of -949.39833 travel time.

Note from Table 3, that an occupancy value equal to the capacity of the road results in an infinite travel time depicting the case of congestion collapse where there could be a stand still for even days if no drastic action is taken. This is because the road network cannot accommodate vehicles beyond its capacity (keep in mind that the capacity is different from the threshold value). Occupancy values greater than the road capacity will result in a negative travel time and can easily be detected and treated as errors in transmission or computation as this should not happen.

#### **4.3. TRAFFIC DECONGESTION ROUTING FOR VEHICULAR NETWORKS**

To route vehicles along least congested sections of the vehicular network, I modeled vehicular routing as a shortest path problem with constraints on computational metrics like traffic congestion and travel time. Travel time information for all road links are modeled as explained in above sections and stored in an oracle database. These travel time values are being constantly updated as real time occupancy data received from the mounted road sensors are remotely supplied to a Java Enterprise web service implementing the defined model. This setup greatly relinquishes the SPF algorithm of its numerous overheads in terms of its metric computation thus improving its response time.

In this work, the 'shortest' route computation for a departure destination pair employs a very simplified and scaled down version of the SPF algorithm since the route cost in terms of travel time for all road links are readily computed and available for substituting as routing metric.

Just like the standard SPF algorithm this solution employs the principle of relaxation in updating the travel time cost of all vertices connected to a visiting vertex 'v' if the overall path cost will be improved by including the path via v. Relaxing an edge is the process of trying to reduce the cost of getting to one node by using another node. The algorithm is as explained in the following pseudo code.

function SPF\_TRAVEL\_TIME(Graph, source):

```

    for each vertex v in Graph:
        dist[v] := infinity
        previous[v] := undefined
    dist[source] := 0
    Q := the set of all nodes in Graph
    while Q is not empty:
        u := node in Q with smallest dist[ ]
        remove u from Q
        for each neighbor v of u:
            alt := dist[u] + dist_between(u, v)
            if alt < dist[v]
                dist[v] := alt
                previous[v] := u
    return previous[ ]

```

The algorithm determines the shortest travel-time between a start node and any other node in a graph. The idea of the algorithm is to continuously calculate the shortest travel-time beginning from a starting point, and to exclude longer travel-times when making an update. It consists of

the following steps:

1. Initialization of all nodes with "infinite travel time"; initialization of the starting node with 0
2. Marking of the travel-time of the starting node as permanent, all other travel-times as temporarily.
3. Setting of starting node as active.
4. Calculation of the temporary travel-time of all neighbor nodes of the active node by summing up its travel-time with the weights (travel-time) of the edges.
5. If such a calculated travel-time of a node is smaller as the current one, update the traveltime and set the current node as antecessor.
6. Setting of the node with the minimal temporary travel-time as active. Mark its traveltime as permanent.
7. Repeating of steps 4 to 7 until there are no nodes left with a permanent travel-time, which neighbors still have temporary distances.

This implementation revolves around work cited in [17] for routing electric vehicles through appropriate charging stations. In my work, the least congested path computation for a departure destination pair employs Dijkstra's SPF algorithm substituting the routing metric with the travel time based on occupancy and congestion as explained earlier.

I try to routes each vehicle along a **minimum travel time metric** (least congested relative to distance of route) path between the chosen departure and destination nodes. The logic applied here is that the selected path should have an overall least travel time from the departure to the destination as compared to the travel time of any other possible route for the selected departure destination node pair.

I implement the famous Dijkstra's iterative algorithm for computing the shortest path to a given destination as follows:

$$D_i = \min_j [d_{ij} + D_j] \text{ ----- (19)}$$

Where  $D_i$  is the estimated shortest (least travel time) distance of node  $i$  to the destination and  $d_{ij}$  is the length of link  $(i, j)$  and  $D_j$  is the shortest distance to the previously selected node. Each node  $i$  periodically executes this iteration with the minimum taken over all of its neighbors  $j$ .

Thus  $d_{ij} + D_j$  may be considered as an estimate of shortest distance (in terms of travel time) from node  $i$  to the destination node  $j$  and  $\min_j [d_{ij} + D_j]$  may be viewed as the estimate of the route with the least travel time from  $i$  to the final chosen destination going through "best" neighboring nodes.

Complexity and sophistication now sets in as I try to accommodate time dependent variation of the route metrics depending on the prevailing conditions on our road network implying that the shortest path may keep changing for any chosen journey. It is in light of this that I introduce a feedback mechanism using an embedded system as real time data source for the routing algorithm. Details of this feedback mechanism are discussed later in this chapter.

Practically Dijkstra's iteration is implemented iteratively as a sequence of communications of the current value of  $D_j$  of nodes  $j$  to all their neighbors, followed by execution of the shortest distance estimate update of Equation (19)

It works correctly, finding the shortest distances in a finite number of steps, for an essentially arbitrary choice of initial conditions and for an arbitrary order of communications and updates.

This allows an asynchronous, real-time distributed implementation of the algorithm, which can tolerate changes of the metric value as the algorithm executes making the implementation adaptive.

In computing the least congested path for a journey, I treat the vehicular network as a directed graph  $G(V,E)$ . Vertices  $v \in V$  represents all junctions or nodes on the vehicular network and Edges  $e \in E$  represents connections between these junctions or nodes. The computed travel time metric for each edge is retrieved from the oracle database and used as the cost of traversing that edge  $c(E)$ . Also stored in this database for each edge is the corresponding road segment's effective capacity.

For each request of a departure-destination pair route, a Java web service dynamically generates a sub-map of all possible routes for the selected departure-destination nodes.

The application then computes the SPF algorithm over the generated map using the traffic congestion metrics on each edge as the routing metric of computation. The least congested path  $P$  is a sequence of  $n$  vertices  $(v_1, v_2, v_3 \dots, v_n)$  returned by the SPF algorithm after computation.

The Path Cost  $C(p)$  is a summation of the estimated **travel time** for each edge on the least congested path where travel time for each edge is the time required by a vehicle travelling at the maximum possible speed at that point in time but within the speed limits of the edge .

Note that with a system in place to provide the estimated travel time for each link of the road network, this database together with the web service become an open tool that could be used in line with any algorithm capable of finding least cost route over a map or graph and is not limited to just the SPF algorithm.

### 4.3.1. ILLUSTRATION OF IMPLEMENTATION

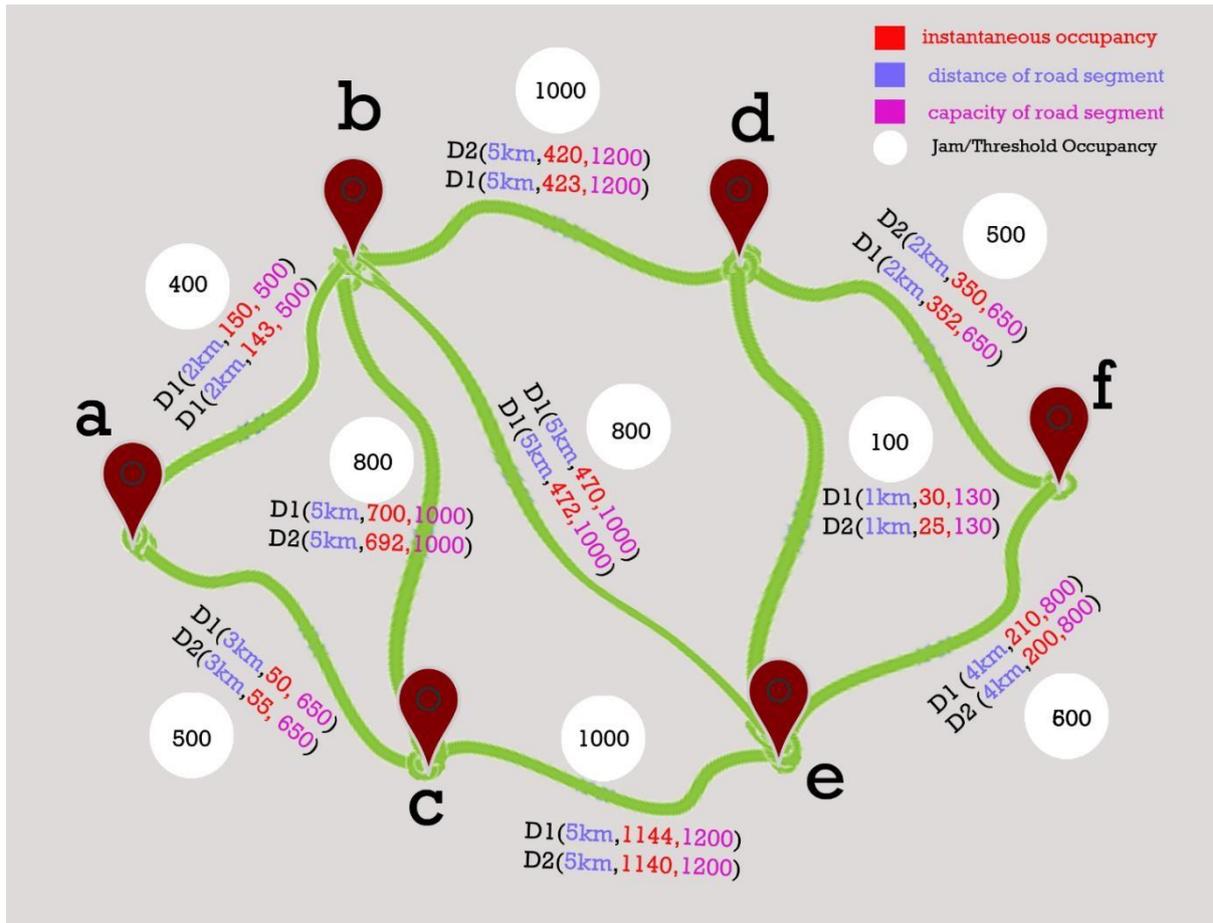


Figure 15: Sample Road Network For Illustration

Using the dummy road map shown in Figure 15, find in Table 4 through to Table 12 the derivative outputs computed for the various links.

#### NODE A-B

Table 4: Occupancy Fine-tuning for Route AB

Occupancy Differential error capture interval]	Dout	[d(e)/dt) *	Derivative Occupancy
143	0	0	143
150	-7	-7	157

#### NODE A-C

Table 5: Occupancy Fine-Tuning for Node AC

Occupancy Differential error capture interval]	Dout	[d(e)/dt) *	Derivative Occupancy
--	------	-------------	----------------------

50	0	0	50
55	-5	-5	<b>60</b>

**NODE B-C**

*Table 6: Occupancy Fine-Tuning for Node BC*

Occupancy	Dout	[d(e)/dt] *	Derivative Occupancy
700	0	0	700
692	8	8	<b>684</b>

**NODE B-D**

*Table 7: Occupancy Fine-Tuning for Node BD*

Occupancy	Dout	[d(e)/dt] *	Derivative Occupancy
423	0	0	423
420	3	3	<b>417</b>

**NODE B-E**

*Table 8: Occupancy Fine-Tuning for Node BC*

Occupancy	Dout	[d(e)/dt] *	Derivative Occupancy
472	0	0	472
470	2	2	<b>468</b>

**NODE C-E**

*Table 9: Occupancy Fine-Tuning for Node CE*

Occupancy	Dout	[d(e)/dt] *	Derivative Occupancy
-----------	------	-------------	----------------------

1144	0	0	1144
1140	4	4	<b>1136</b>

**NODE D-E**

*Table 10:Occupancy Fine-Tunning for Node DE*

Occupancy	Dout Differential error capture interval]	[d(e)/dt) *	Derivative Occupancy
30	0	0	30
25	5	5	<b>20</b>

**NODE D-F**

*Table 11:Occupancy Fine-Tunning for Node DF*

Occupancy	Dout Differential error capture interval]	[d(e)/dt) *	Derivative Occupancy
352	0	0	352
350	2	2	<b>348</b>

**NODE E-F**

*Table 12:Occupancy Fine-Tunning for Node EF*

Occupancy	Dout Differential error capture interval]	[d(e)/dt) *	Derivative Occupancy
210	0	0	210
200	10	10	<b>190</b>

Note that the implementation delineated here does not apply to proportional and integral deviation. It only consider the errors over the transmission period. Stage two is to model vehicular speeds corresponding to the refined occupancy values computed above. The speed

then translates to estimated travel time. Table 13 shows the result using a speed limit of 80km/h for all the links:

Table 13: Travel time computation from occupancy values below threshold density

					SpeedLimit * EXP (- (Road (-Occupancy/ Link Occupancy/ Capacity) Capacity) Capacity)	EXP Occupancy/ Occupancy/ Capacity) TravelTime
A – B	157		-0.3925	0.675366346	54.02930771	<b>0.03701</b>
A – C	60	-0.12	0.8869	70.953		<b>0.0423</b>
B – C	684	-0.855	0.4253	34.022		<b>0.1469</b>
B – D	417		-0.417	0.659	52.721	<b>0.0948</b>
B – E	468		-0.585	0.5571	44.568	<b>0.1121</b>
D – E	20		-0.2	0.8187	65.498	<b>0.0152</b>
D – F	348	-0.696	0.49856	39.886		<b>0.050143</b>
E – F	190	-0.31667	0.7286	58.2859		<b>0.068627</b>

Table 14: Travel time computation from occupancy values above threshold density

Road	(Occupancy/ Capacity)	ln (-Occupancy/ Capacity)	SpeedLimit * ln (- Occupancy/Capacity)	Travel Link Time	OCCUPANCY
C – E	1136	1.05634	0.05481	4.385	<b>1.14034</b>

The computed travel times then become a routing metric for the SPF routing algorithm used in this work. Find in Figure 16 the resulting pictorial view of the network with travel time metric for the various routes labeled.

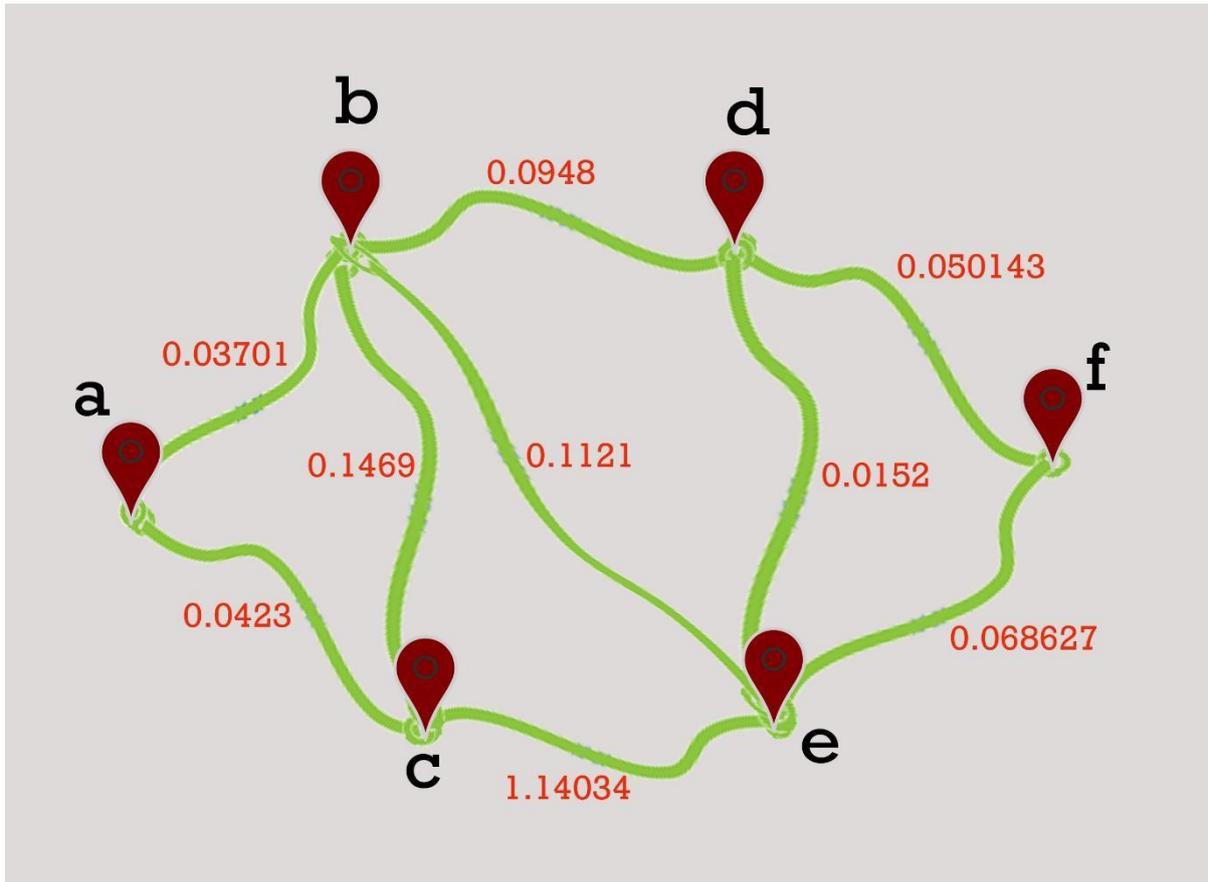


Figure 16: Road Network with Travel Time Metrics for routes

Using brute force, the travel times for all possible paths in from node 'a' to node 'f' is as shown in Table 15 indicate the best route to be {a, b, d, f} with a travel time of 0.181953 units.

Table 15: Brute force journey cost for all possible routes from source to destination

PATH	Route Cost (Travel Time)
{a, b, c, e, f}	1.392877
{a, b, d, f}	0.181953
{a, b, e, f}	0.217737
{a, b, d, e, f}	0.215637
{a, b, c, e, d, f}	1.389593
{a, b, e, d, f}	0.214453
{a, c, e, f}	1.251267
{a, c, b, e, f}	0.369927
{a, c, b, d, f}	0.334143
{a, c, b, d, e, f}	0.367827

The iterations through the algorithm used in the proposed routing system for the road network under discussion is as detailed in the Table 16

Table 16: Least travel time route computation from Node A to Node F

S	L(a)	L(b)	L(c)	L(d)	L(e)	L(f)
a	∞	∞	∞	∞	∞	∞
{a}		a 0.03701	a 0.0423	∞	∞	∞
{b}		a 0.03701	a 0.0423 B:0.1839	b 0.13181	b 0.14911	∞
{c}		a 0.03701	a 0.0423	b 0.13181	b 0.14911 C:1.18264	∞
{d}		a 0.03701	a 0.0423	b 0.13181	d 0.14701	d 0.181953
{e}		a 0.03701	a 0.0423	b 0.13181	d 0.14701	d 0.181953 E:0.215637
{f}						

After the iteration it is found that the least cost path in terms of travel time from node ‘a’ to node ‘f’ is by routing through {a, b, d, f} and has a path cost of 0.181953 time units. This path is confirmed by the brute force tables and is a proof that the algorithm used is able to compute the least cost path in terms of travel time.

#### 4.3.2. COMPARISON WITH SPATIAL AND TRAFFIC AWARE VEHICULAR ROUTING

This section compares the proposed solution with the spatial and traffic aware routing (STAR) for vehicular system by the author of [7]. The STAR solution exploits both street topology information achieved from geographic information systems and information about spatial distribution of vehicles along various streets. In order to perform accurate routing decisions the work by author of [7] suggests that vehicles be equipped with network interface cards enabling them to partake in a vehicular network infrastructure. In their solution these vehicles can share traffic data with each other. This solution however fails to distinctively provide a metric capable of being used by any algorithm to predict cost of a journey.

In this case however, captured data is not delivered to road users as raw traffic status but converted into a travel time cost and passed to the SPF algorithm making the solution more useful and usable.

The STAR solution also depends directly on vehicles actively connected to the road network requiring either all vehicles to have active Network Interface Cards to yield accurate results. Finally the solution is limited by the coverage area of the wireless technology used by the vehicles.

This solution overcomes these limitations as the detectors that capture the occupancy values are not attached to any particular vehicle but rather fitted to the road network system.

*Table 17: Advantages of Vehicular Routing based on real-time Road Occupancy Estimates over Spatial and Traffic Aware Vehicular Routing*

<b>Spatial And Traffic Aware Vehicular Routing</b>	<b>Vehicular Routing based on Real-Time Road Occupancy Estimates</b>
Does not provide a quantitative measure for congestion and route decision making	Provides a quantitative metric (travel time) and route decision making
Data (Individual vehicular speed) gathered from vehicles on road segments is delivered as raw data to road users.	Data (vehicular occupancy) gathered from various sections of the road is processed to generate complete routes for departure/destination node pair on request.
Requires all vehicles to be equipped with NICs to achieve network convergence.	Requires only mounted stationary ultrasonic sensors to be active to achieve convergence.
Data gathered (speed of vehicles) is human dependent	Data gathered (vehicular occupancy) for route computation is not human dependent
Limited by coverage area of wireless technology used by NICs.	Coverage is wider using the internet to transfer data gathered from sensors to centralized oracle database.

#### 4.4. USE CASE SCENARIO

In this section of this work, I present “KWANSO” as novel prototype mobile application which employs the concept (explained above) as a traffic decongestion mechanism. The App is designed to be piloted in a sub-section of Accra, the capital of Ghana.

#### 4.4.1. IMPLEMENTATION

The mobile app allows a user to request for the least cost (in terms of travel time) path from a departure node to a destination node within the domain of the road network under pilot.

Embedded systems as described in the theory above is to be mounted at entry and exit points of the nodes within the portion of the road network under pilot. These embedded systems are to be fitted with ultrasonic sensors, wireless internet connectivity and a programmable microprocessor. The function of these embedded systems are to count the number of vehicles moving pass each node and to feed these values remotely to a hosted oracle database. A difference between the inflow and outflow for two consecutive sensor grids will evaluate to the occupancy of the segment of road that interconnects these two nodes.

For this work I automate a simulation of inflows and outflows through the various nodes as it is very expensive to mount the road sensors on the streets. These simulated values change over time dynamically to mimic various possibilities and the values feed into the oracle database just as it would be if the values came from real sensor devices described above.

For each request, the application connects to an oracle database through a Java Enterprise web service which dynamically generates a sub-map of all possible routes for the selected departure and destination nodes. The application then runs the popular Djikstra's SPF algorithm over the generated map using the traffic congestion metric values computed from the PID process explained above on each route on the map as the routing metric.

#### 4.4.2. OUTPUT

The computed least congested route from the selected departure to destination is then presented to the user in two forms:

- i. A directional map of the route
- ii. A list of nodes/junctions to traverse with journey details (estimated travel time, journey distance, estimated fuel consumption)

#### 4.4.3. SUGGESTED DATA SOURCE OF TRAFFIC CONGESTION INFORMATION

Traffic congestion information feeds is obtained from two sources

- i. **Sensor Readings:** The major source of real-time traffic congestion feed is obtained from ultrasonic sensors to mounted on the streets to measure and submit their readings to an oracle database as explained in section **IV-A**.
- ii. **Crowd Source:** As a backup data source, “**App**” has a section that allows users to submit their travel times for routes they have traversed. These feeds from multiple users are subjected to statistical analysis to generate a fairly good estimate of traffic congestion on the various subsections of the road network. The computed traffic congestion values based on these feeds are used to update the route information in an oracle database to be used for incoming user requests for least congested routes.

#### 4.4.4. SNAPSHOTS OF MOBILE APP

Figure 17 shows the interface for placing a request whilst Figure 18 shows the output interface giving the shortest route link-by-link. Figure 19 and Figure 20 shows a geographical direct route in satellite and map views respectively whilst Figure 21 and Figure 22 shows the shortest route (path) in satellite and map views respectively.

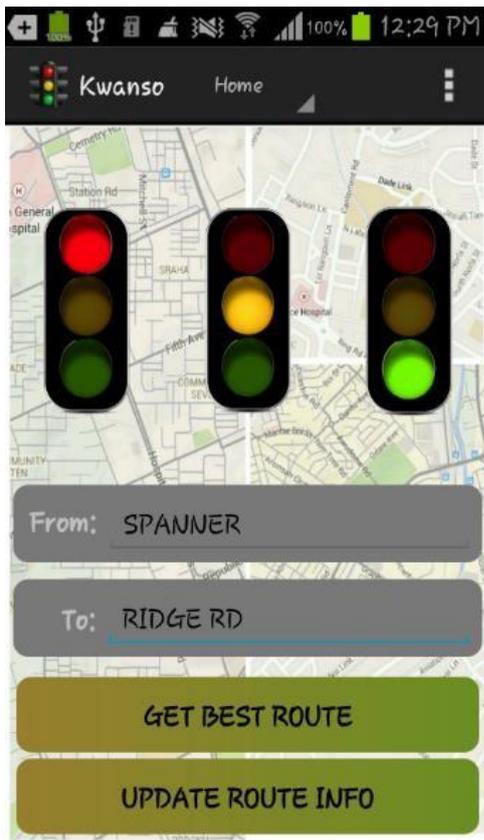


Figure 17: Rout Request Nodes

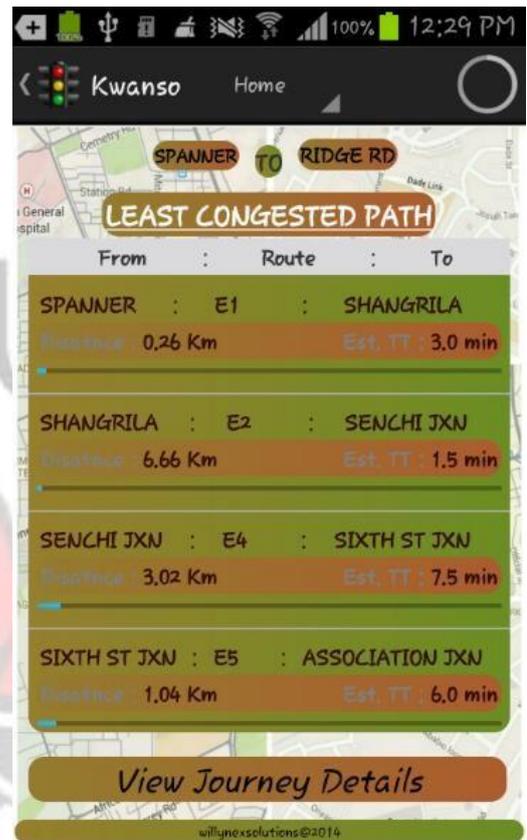
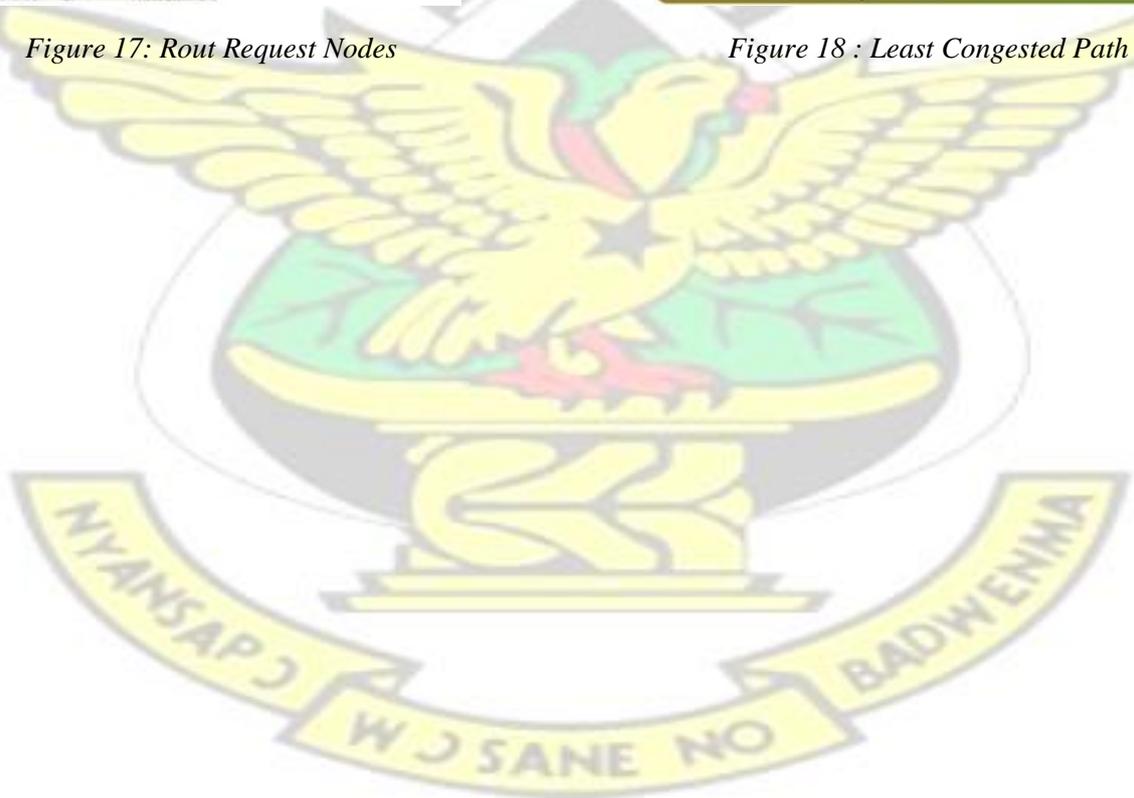


Figure 18 : Least Congested Path



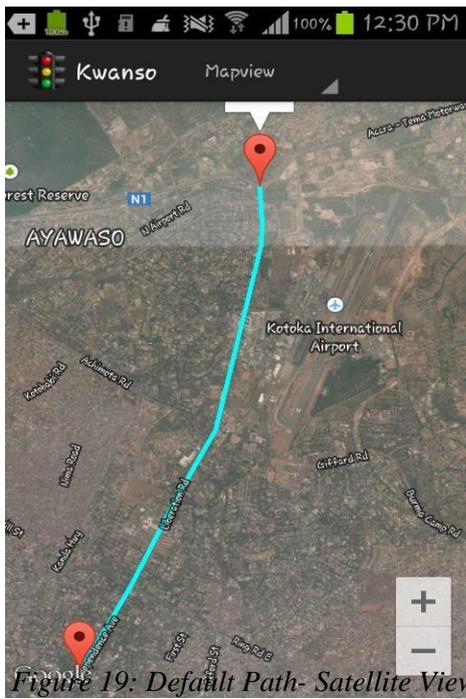


Figure 19: Default Path- Satellite View

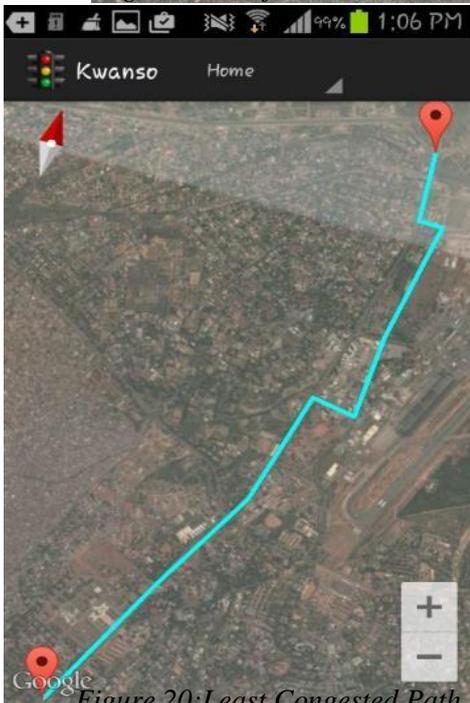
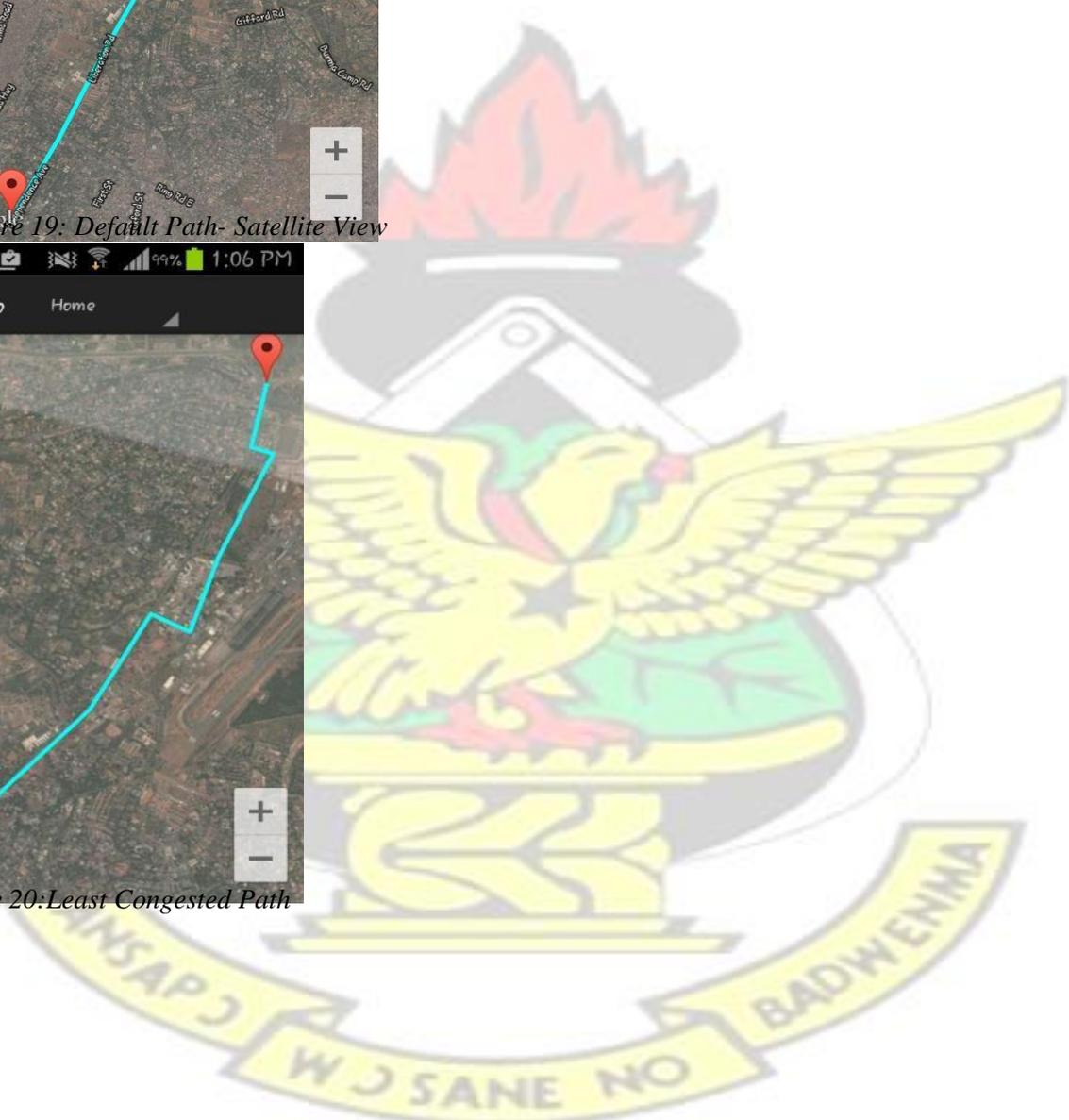


Figure 20: Least Congested Path

UNUST



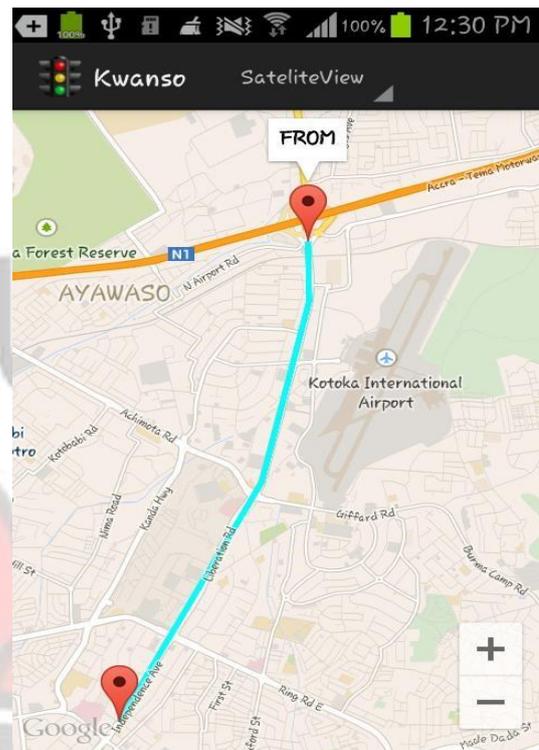
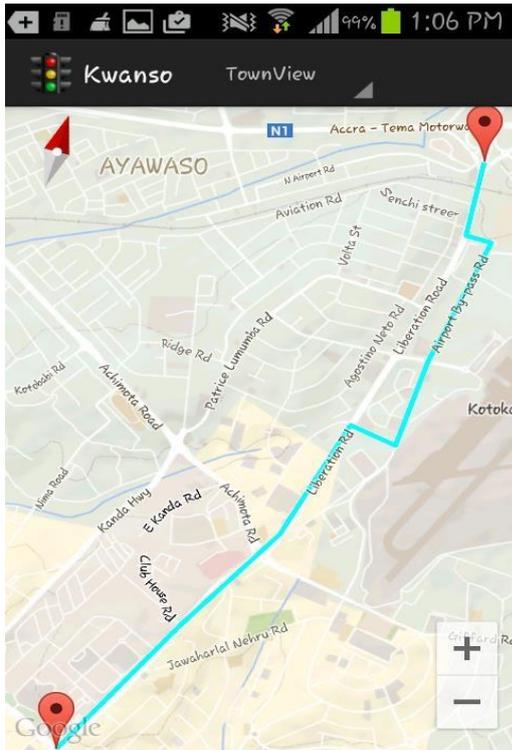


Figure 20: Least Congested Path

Town View

Town View

Figure 19: Default Path -

## CHAPTER 5

# CONCLUSION AND RECOMMENDATIONS

### 5.1. INTRODUCTION

Performance of vehicular networks almost globally has experienced almost constant deterioration as a result of the exponential growth in the number of vehicles. This has led to massive traffic congestion that plaques our major cities. Traffic congestion on a road segment occurs when the number of vehicles per unit distance of the road segment exceeds the routing capacity of that road. In extreme situations, the road usage increases beyond a point where the volume of traffic on a particular road segment demands for space greater than the available road capacity.

Meanwhile transfer of data on data networks has attained a state of better traffic management, better transfer protocols (e.g. Link State Routing, Distance vector Routing, Shortest Path First, etc.), proper control algorithms (TCP/IP, UDP), optimized routing and better traffic decongestion strategies relative to our road networks. This has caused the world to see an exponential growth in patronage of the use of data networks mostly the internet over the past decade. Data networks have, however, not been able to take over completely the relevance of vehicular networks as they are unable to perform the vehicular network's core mandates of transporting people and goods in time and space.

This thesis work has proposed a strategy to address the problem of decongesting vehicular traffic on road networks using transport telematics to compute the instantaneous least cost path with regards to congestion state and travel time for departure-destination nodes (junctions) of a journey.

The proposed strategy identified the Dijkstra's shortest path first algorithm as suitable for adoption and reengineering to device a fair vehicular routing mechanism in order to manage congestion on road networks.

The adopted algorithm has been re-engineered to use an estimated travel time as the only routing metric. Time is computed based on occupancy-speed relationship and speed/distance/travel-time dependencies that called for the adjustment of instantaneous occupancy for error. Instantaneous occupancy data is acquired from a sensor network superimposed on the target road network. Adjusting the instantaneous occupancy has been effected by estimating the error based on the classical PID controller model.

Based on the re-engineered of Dijkstra's shortest path first algorithm, a method of congestionaware routing of vehicular traffic has been formulated. The method assumes the existence of sensor network that feeds road occupancy data into a dynamic database. From the data the time metric is computed for each road segment.

The re-engineered algorithm has been analyzed to a time complexity of  $n^2 + m$  with  $n$  representing the total number of nodes and  $m$  representing the total number of edges. The method has been implemented as a sever-assisted mobile application and demonstrated. Also the method has been evaluated against a similar research work reported in literature. The proposed method proves to be easier to use by virtue of its server-assisted nature. The mobile application makes use of processed data that is meticulously adjusted for reliability through a non-mobile sensor network. Coverage of the network can be made as wide as possible and constant.

Overall, it can be stated that the objectives of the thesis work have been achieved.

## **5.2. RECOMMENDATIONS AND FUTURE WORK**

In the future I envision to analyze other data network algorithms that could be reengineered to solve the same problem at a better efficiency and probably less complexity. I intend to prototype and compare the performance of multiple reengineered algorithms and select the best for our final implementation. I can say that not only data network algorithms can be reengineered for use in vehicular transportation systems but also certain protocols used to control access to routes and flow rate on data networks. As stated earlier, this work is an opening into a broad domain with numerous possibilities and our hope is to go as deep as possible and to work assiduously in this novel area of study.

As part of future work, our solution will begin to explore less expensive methods that could be used to gather traffic data and also research more other data network algorithms and protocols that can be adopted for use in routing cars on road networks.

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