AN AGENT-BASED FRAMEWORK FOR INFRASTRUCTURE MAINTENANCE DECISION MAKING

by

Jephunneh Bonsafo-Bawuah

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THE PURDUE UNIVERSITY GRADUATE SCHOOL
STATEMENT OF COMMITTEE APPROVAL

Dr. Wubeshet Woldemariam, Chair
Department of Mechanical and Civil Engineering

Dr. Niranjan H. Desai
Department of Mechanical and Civil Engineering

Dr. Xiuling Wang
Department of Mechanical and Civil Engineering

Approved by:
Dr. Chenn Q. Zhou

This thesis is dedicated to my parents Mr. and Mrs. Bawuah Bonsafo and my siblings

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ABSTRACT

A transportation system plays a significant role in the economic development of a region by facilitating the movement of goods and services. No matter how well the infrastructure is designed or constructed, it is beneficial to know maintenance needs in the life cycle of the infrastructure so that the service life of the pavement is prolonged by minimizing its life-cycle cost requirements. The pavement life-cycle performance helps maintenance investment decision-makers to efficiently utilize the available infrastructure funds. This research focuses on developing a framework for identifying a more effective and efficient way of decision making on the management and maintenance of infrastructure. The developed framework uses an agent-based modeling approach to capture the interaction that exists between different components of the transportation system and their characteristics such as traffic volume and pavement condition, user cost, agency cost, etc. The developed agent-based is useful to investigate the effects of time-varying vehicular density on pavement deterioration and the road users' driving behavior. The developed framework was demonstrated as a two-lane highway as a case study. Using the developed agent-based simulation framework, it was possible to identify when the road infrastructure maintenance should be done to increase the desired PCR value. Also, it was possible to show a decrease in PCR can affect the cost of road users. The framework can track the time to determine when maintenance should be done based on the PCR values that determine whether the pavement is in good, moderate, or bad condition. Regardless of the degree of road users' patience to stay in their travel lanes (patience), the vehicle distribution on the road is balanced in the long run because road users tend to change their travel lanes to minimize their overall travel times. When the patient level is low, road users tend to change lanes more, causing a high number of vehicles on the left lane as it is considered the lane changing lane in two-lane highways. It was also observed that as the patience of the road users increases, the number of vehicles that use the right lane is almost the same as the number of vehicles that use the left lane.

1. INTRODUCTION

1.1 Background and Problem Statement

Management of civil infrastructure is a very essential part of economic prosperity also, the safety of users and non-users. No matter how well the infrastructure is designed or constructed it is important to know and understand that at some point in the life cycle of the infrastructure it will need maintenance due to deterioration over time. Even though there has been an investment and increase in the adoption of new technologies on the effective ways of decision making in infrastructure management.

Numerous researches have been conducted into infrastructure management and the effects of poor infrastructure management decisions. Studies in infrastructure management over the years have attempted to answer questions about:

- Traffic management and travel demand.
- The simulation of the shortest path in a traffic network to disperse traffic faster.
- Road network development effects.
- The distribution of people boarding and alighting from a train.
- The choices of a route for trips.
- The effects of transportation infrastructure on walking.
- The impacts on the attack on critical infrastructures.
- The decision on investing in a walk-bicycle infrastructure.
- Asset management.

A simulation is used in this research to represent traffic flow and rate of pavement deterioration because capturing how traffic and environmental factors affect pavement deterioration and predicting traffic volume is complex. This simulation is going to provide insight into maintenance decisions and in turn, reduce user cost. This simulation is going to help prevent more money spent on reconstruction when maintaining the infrastructure at the right time can avoid it.

The different parameters involved are complex to understand by just observing or doing surveys a simulation helps in better understanding what is happening. Their relationship with each other can be understood better with a simulation that shows how they interact and the effect they have on each other. The increase in vehicle volume increases the rate at which pavement deteriorates and in turn, increases the user cost of road users. The increase in user cost and pavement condition increases the budget involved in restoring the pavement roughness to a good level. Considering past researches done, authors built a framework that identifies the relationships between the parameters involved and ways the improvement of infrastructure management can be done. Since over the years no additional research has been done in creating a simulation that illustrates the relationships between the agents and their interactions with each other, this research is improving on Bernhardt et al. (2008) framework developed to improve infrastructure management by developing a simulation that can help transportation policymakers in decision making. Findings from this simulation serve as input for infrastructure to be precise pavement condition effects to help create a close representation of the real-life situation.

1.2 Research Motivation

The main purpose of this research is to find a more effective and efficient way of decision making on the management of infrastructure. Over the years although there has been a significant increase in the investment of different technologies in infrastructure management systems, studies continue to show that the poor conditions of civil infrastructure in the United States are still the same.

Assuming there is a road network, several factors affect the quality of the road pavement. The capacity and volume of vehicles that use the road, environmental factors affect the pavement, the safety of road users is of concern if the pavement serviceability is poor, among others. Maintaining civil infrastructures is difficult and the present situation has been worsened by the fact that maintenance was neglected for many years or postponed in favor of new construction. These changes in road pavement characteristics, in turn, affects the automobiles and even the users.

Poor management of civil infrastructure with an emphasis on road pavements lead to bad roads. For road users when roads are bad it leads to increase in delays because one has to take their time to commute on the road thereby reducing speed to the barest minimum to avoid any incidence, congestion occurs because road users have to travel at a speed lesser than the average speed they usually use, there is an increase in user-cost due to increase in maintenance and repair of vehicles, travel time and rapid vehicle deterioration. Also, some users may change their travel destinations in other to avoid the bad routes and that can lead to, for example, change in their preferred grocery shop to a new one, change gas stations, etc. Others may also decide to cancel trips or switch their regular modes of travel.

From the previous paragraphs, it can be inferred that a change in the road pavement characteristic due to poor management can lead to a myriad of behavioral changes in road users which this research intends to reduce if not avoid.

Past studies that have been done have generally focused on developing the framework and different possible solutions to effectively maintain and manage road pavement but none of them have developed and simulated a model to that effect.

This research presents agent-based modeling concepts based on frameworks that have been developed by different researchers to help policymakers improve infrastructure decision making on management and maintenance. A relationship between the users, policymakers, and the infrastructure itself will be established. Also, the link between pavement condition, user cost, and budget allocation will be established.

1.3 Thesis Organization

The thesis is divided into six chapters. The first chapter introduces the subject matter. Chapter two presents a literature review on agent-based modeling in transportation and infrastructure system engineering. Chapter three describes the research study area. Chapters four present the research methodology on developing the agent-based model for traffic simulation. In Chapter five, the research findings are presented and discussed. Finally, in Chapter six, summary and conclusions based on the research findings are presented.

2. LITERATURE REVIEW

2.1 Introduction

In this chapter, we discuss how past literature apply agent-based modeling primarily on the areas of transportation and infrastructure system engineering. The various assumptions used by different authors to generate the model. Also, the steps involved in forming the model that is, the agents, their relationship, and their environment. We will also look at the literature on various ways agent-based models have been applied in helping in decision making, problem-solving and answering questions on how things work, explain observed patterns, and predicting the behavior of a system due to change.

2.2 Agent-Based Modeling

Numerous agent-based modeling and simulation tool has been developed and used over the years each with a special reason for its existence. Each procedure denotes a specific programming sentence structure and semantics for the agents and has a varying based concerning the consensus, convenience, modifiability, versatility, and execution.

Osman (2012) explained that agents are the main component of agent-based modeling and they interact within their environment that is simulated to produce an action through processing data, and it is governed by a set of behaviors. Also, he explained that attributes define the characteristics of the environment and some of the attributes are static and others change with time for example type of user and user satisfaction respectively.

Over the years, many kinds of research involving agent-based modeling have focused on using agent-based modeling to make decisions concerning infrastructure management.

Zechman (2011) used agent-based modeling to simulate an event of contamination of water in a distribution system. The author simulated the interactions between the consumers, utility managers, and the water distribution system. The consumer in the water distribution and the utility operator is considered the agent and each consumer has specific behaviors. A contaminant is introduced, and each consumer's action is different when they receive the news.

2.3 Application of Agent-Based Modeling in Transportation and Infrastructure System Engineering

Bernhardt et al. (2008) established how to use agent-based modeling to manage and maintain infrastructure assets effectively and efficiently. The author used three sets of experiments to understand how to decide on which infrastructure should be maintained and at what point. The author concludes that the longer an infrastructure is not maintained, that is when you will see the significant increase in user cost and degrade conditions of the infrastructure. Also, the author concluded that the use of agent-based modeling considers long term impacts of decision making of which other models do not do hence, using agent-based models is efficient.

Osman (2012) used a generic agent-based model called the ontology model for infrastructure asset management. The author considered assets, users, operators, and politicians as the agents of the simulation, and their level of service, income, conditions, budget, risk, use affects each other. The simulation considered water, sewer, and road infrastructure asset from projects in Canada and Egypt. The users consume service provided by an asset for example by driving on a roadway, by consuming water in their homes, the users report when they have a problem with the services provided to either the operators or the politician and the operators will solve the problem by repair, rehabilitation or replacement. The politicians on the other hand allocate funds, various activities, policies, levels of service target for the intervention of the operators.

Namoun et al. (2013) also worked on reducing the emission of carbon-dioxide and offering a flexible intermodal commuting solution through a multi-agent system, real-time traffic information, and traffic forecasts. The parts were concocted relying upon the progression of data to and from the suburbanites and from and to the urban vehicle place information sources. The suburbanites present an excursion demand using a cell phone alongside its inclinations in the method of transport, time of travel to the multi-agent framework. The model assists clients with finding suitable courses for their movement demands by thinking about the cost of travel. The model finds the shortest route to destination considering cost and travel time to reduce the amount of carbon dioxide that is released into the atmosphere.

Huynh et al. (2014) use an agent-based model to simulate road traffic and transport demand of southeast Sydney, Australia. The author simulates dynamic interacts between population growth, transportation, and traffic demand and mobility. The model consists of six components and goes through a series of questions that help in decision making. The author reasoned that the agent-based model can catch the dynamic of the populace concerning movement and transport and its capacity to reenact dynamic connections between land use, transport request, and populace development which different models can't catch.

Coxon et al. (2015) also used an agent-based model to test the efficacy of platform and train passenger boarding, alighting, and dispersal. The high patronage to suburban railways is causing a delay, crowding, reduction in accessibility, and passenger comfort. The author used a model called Unity to design a 3D content that has a built-in pathfinder which permits the creator to characterize which territory of the scene that is walkable to maintain a strategic distance from travelers from strolling through dividers and solid objects. The pathfinder helps operators in seat finding. The agent enters the train carriage and searches for a free seat settling on the one nearest. As the agent walks towards the seat and constantly checks whether it is free. As the agent gets close enough to sit and the seat is still free the agent sits. Once the agent is seated the simulation is considered complete but if the seat is taken by another agent, they would have to look for another empty seat closed by and if there is none then the agent will find a standing position. The author concluded that the simulation improved the boarding and alighting time but when all the seats are taken, and the excess capacity begins to build and cluster around the doors, a delay occurs due to the fact the passengers need to alight and significant numbers need to board.

Auld et al. (2016) used POLARIS to simulate an environment focusing on travel demand and traffic management. The author considered person agents, activity planning agents as the main agents that will interact with each other in the simulation. The author also considered sub-agents including perception agent, planner agents, routing agents to help in the decisions made by the person agents for activity generation, planning, scheduling, and traveling.

The impact of road network development was simulated by Milevich et al. (2016). The authors modeled the road network did a population synthesis, compared system behavior using current and improved road networks, and did a sustainability analysis of the system. The authors considered how traffic will flow after the semifinals match of the FIFA World Cup in Russia. The simulation was done for the people departing from the stadium to their various destinations using MATSim. The simulation was done for two cases where one a bridge was introduced to connect Tusistskaya street and the other the bridge was omitted. From the simulation when the bridge was added a significant decrease in congestion was observed.

Lemoine et al. (2016) examined the effects of transport infrastructure on walking. The author used a hypothetical city based on Bogota, Columbia, and its bus rapid transit (BRT), TransMilenio (TM). The agents were the adults' population in the city and each agent was allocated a home, a workplace, and a car. The neighborhood to which an agent was assigned determines the socioeconomic status of the agent. The mode of transport was determined by considering the cost and time needed to reach a destination. Two scenarios were taken into consideration to understand the influence of bus and TM on walking for transportation. The first one was varying the BRT lanes from 0 to 10 and decreasing bus lanes from 33 to 23. Secondly, randomly distributing bus and BRT stations at differing densities. The author concluded that the minutes for walking increased due to the distance to BRT stations and the availability of other modes of transport.

Lu et al. (2018) used an agent-based model to devise ways to reduce traffic congestion and pollution due to the increase in population growth by stimulating the use of bike-sharing services (bike infrastructure extensions and bike-sharing incentives) in Taipei city. Passengers and modes of transport were the agents used in the simulation. The simulation used the attributes of passenger agents that is, their income level, travel time, origin and destination, and the variable of model agents that is travel speed, travel cost, bus stops, and others. The simulation also took into consideration the six modes of transport. The author concluded that the use of bikes and walking reduces the number of gases released into the atmosphere, also the percentage of death reduced due to the increase in physical activity and the model dynamically display how the mode choices by the agents change under the influence of varied transport policy strategies.

In 2018, Xiong et al. (2018) designed a model for travel behavior and transportation network dynamics. The model was used to predict the changes in travel behavioral adjustments and dynamics in traffic conditions in the future. The author used SILK-AgBM a travel behavioral model and DTAlite a traffic simulation tool to develop the application ready model. The model considers the mode choice, departure time, and route choice and it also accommodated real-time decision making on the part of travelers in response to network conditions. The model was tested in a study area in White Flint region in Montgomery County, Maryland. The model performs a day to day output which records all the agents' travel information, including their path sequence, departure times. The author concluded that the model was able to focus on modeling the actual traveler behavior as compared to other models that emphasize how the traveler should behave.

Research by Aziz et al. (2018) on using a high-resolution agent-based model to support the walk-bicycle infrastructure investment decision assumed that agents sharing the same work location and or home location can impact the mode choice of another operator. Additionally, the degree of impact relies upon the number of agents that decide to impact different agents and the likely benefits of picking the transportation modes. Also, the agents' mode choice decision is influenced by their built environment and their socio-demographic attributes (age, income).

Zhuge & Shao (2018) built up an agent-based transport facility model for finding both charging stations and other electrical vehicles (EV) related framework. The author utilized two modules; initialization modules and simulation modules. The previous instates the base-year situation by creating a manufactured populace and offices and the last reproduce how the land use-transport framework develops. The author utilizes a connection-based facility model and a node-based facility model. The offices without node-based facilities compute the potential demand dependent on the MATsim-EV reenactment and if the potential demand surpasses the predefined edge, at that point the particular number of facilities will be included. The author reasoned that the EV drivers will charge their vehicles in parking areas given that charging posts are accessible. drivers would like to charge at home, and they may not want to charge outside if their charge state is high.

Karaaslan et al. (2018) used agent-based modeling to stimulate and the environment with electrical vehicles, internal combustion vehicles and pedestrian to check which vehicle type pose as a threat to pedestrian safety when on the road. Using the anylogic model the author simulated an environment using Orlando, FL as a case study. Ambient sound and illumination levels were varied in the simulation also, the sight distance and detection distance of vehicles and pedestrians respectively were taken into consideration. The near-crash experience was considered as crashes as opposed to real life and from the simulation, electric vehicles have a higher pedestrian safety risk than the internal combustion vehicles under ambient sound levels while for ambient illumination both electric vehicles and internal combustion vehicles have high near-crashes.

In considering the effects of travel demands and travel patterns, Saadi et al. (2018) used the case of Liege, Belgium where there is a lot of river floods that affect commuting. The author extracted the network into MATSim and with ArcGIS, the road segment at risk with the use of flood maps is identified. The simulated environment is varied by the levels of service by the critical lanes by 10%, 25%, 50%, 75%, and 100% and estimating their deviations from the standard scenario in terms of travel time and traffic patterns. From the results as the level of service reduced the travel times increased. Also, the traffic flow was uniformly distributed across the network, and roads that had important traffic volumes activities were decreased whiles roads with low traffic volumes were increased.

Melnikov et al. (2016) developed a large-scale agent-based traffic simulation system for Amsterdam urban area, the author used MAT-sim, python, and ALBATROS agent-based travel demand model to simulate a model with the road users as the agents. The activities of the agents for the whole day are collected. The mode of travel, route choice, destination, departure time of agents is re-planned by the model to produce a better score. The author generates road network model for Amsterdam urban area road network extended by the major roads of the Netherlands, travel demand models to depict realistic traffic flow of private vehicles in Amsterdam during normal working days, population synthesis model to show the distribution of vehicles, agent activity model and inflow and outflow models for vehicles going outside the simulation border and coming into the simulation area.

Zhu & Levinson (2018) also used agent-based models for the exchange of information among travelers by following the cognitive map theory to help travelers in route choice. The authors used the Chicago sketch network also referred to the Sioux falls network as their case study. An agent-based route choice (ARC) model was developed to track the choices of travelers in a road network over a period and the individual choices were map into a macroscopic flow pattern. The author introduced three interactive agents: travelers, nodes, and links. Each agent follows a set of rules and attributes. The travelers are characterized by their willingness to pay at a toll, the value of their time, and the ability to get information. The decision-makers (travelers) share information to centroids and intern the information is shared with frequent visitors. The links represent the roads in real life, and they are labeled with the origin and destination, capacity, travel time, free flow, and toll rate. The nodes are the intersections or points where two or more links (roads) join. The model (ARC) simulates individual route choices, each node keeps information of the shortest possible path from an origin node to itself. From the numerical experiment conducted on the Sioux Falls network, the survey data shows that the value of time is important to travelers.

A travel demand model was developed by Zhang & Levinson (2004) by the interaction of three agents in the system: node, arc, and traveler. Each traveler is supposed to find an activity and get to that activity taking into consideration the travel cost which must be the lowest. The travelers learn the cost of using a route when they search for a path to travel on. The arcs which are the roads in real life connect the supply node to the demand node. The traveler agents were limited in pursuing one activity which does not depict real-life situations because a traveler can have multiple destinations. From the simulation, the model was able to provide the shortest-path algorithm based on the distributed agent learning activities. The author applied the demand model to the Chicago sketch network and trip distribution from origins to a destination was done with trip length distribution reasonably close to the observed ones and traffic was assigned to shortest routes.

Zhang et al. (2008) built a more advanced demand model based on the one developed in Zhang & Levinson (2004) considering trip frequency, destination, and route choices by heterogeneous users to explore the welfare outcome of product differentiation on congested networks. The decision-makers can learn, interact with each other, have individual behavioral rules, and adjust their behaviors adaptively over time. The decision-makers (travelers), arcs, and nodes are the agents defined in this paper. The travelers are characterized by the value of time, travel budget, residential location, and perception threshold. The travelers have two goals: to make use of travel budget and to identify the route to a chosen destination with the lowest generalized cost. The nodes presented in the model speaks to a vertex of the physical system where streets are associated, a centroid where occupants and movement openings are found, a spot where voyagers can trade data and work together. They store just the data of the briefest travel-time ways and least cost ways from each other node to itself. The circular segment speaks to a directional street fragment. Each bend is named with its starting point node, destination node, limit, free-flow travel time, cost rate, and possession status. A blended possession organize is created by including an equal private expressway to each of the untolled seventy-six open streets in Sioux-Falls network. Two levels of product differentiation are introduced: path differentiation and space differentiation. The outcomes show that value rivalry is a more critical source of item separation than the limited rivalry. At the point when costs are high, clients with a high estimation of time (high pay) can pay much when contrasted with clients with a low estimation of time (low pay). Much of the time, clients with a low estimation of time benefit less when contrasted with clients with a high estimation of time who consistently benefits from item separation. The author presumed that it is essential to gather information on genuine client circulation as far as the estimation of time for government assistance examination of private and open expressways.

Tolone et al. (2004) used software agents in GIS to model simulation for critical infrastructures, with emphasis on the analysis of the result of cross-infrastructure dependencies. The software agents can be divided according to their degree of autonomy (their ability to sense and act upon their environment without intervention). The autonomous an agent is, the less need for intervention. The agent's intelligence is measured by their ability to interact with other agents. The author simulated an eight-city block area with two critical infrastructure that is, electric power and gas distribution. The simulation was a predictive simulation (i.e. "what-if") analysis. A feature of interest (power distribution) is disabled in a part of the system, the agent community identifies the change in infrastructure and reasons and identifies downstream of the system might be affected by the change that has occurred in the system and a request is sent to the GIS network analysis support to analyze the downstream impacts. The impacts are accepted a rendered taking into consideration what the outage has also impacted in terms of gas distribution to an electric-powered pump in the community. Again, a request is sent to the GIS network analysis support to analyze the downstream impacts. The author explains that as one infrastructure is disabled at a point it affects other infrastructure which is depending on it thus, disabling a small segment of electric power infrastructure has led to a bigger segment without gas.

In investigating how to reduce traffic delay and probably eliminate collisions at intersections Zou & Levinson (2003) developed a distributed multi-agent system to provide microscopic adaptive control. Intelligent agents introduced in-vehicle software will control vehicles and help with route choices. The intelligent agents are integrated with mobile Ad-hoc networks (MANETs) to provide a communication link between agents: network agents, intersection agents, and vehicle agents. The vehicles' intelligent agents control the speed of the vehicles using techniques like adaptive cruise control, it also knows the destination of the vehicles. The intelligent agents in the vehicles communicate with other vehicles about their position, speed, etc. This communication helps determine which vehicle passes the intersection conflict point first hence, prevent collisions at the intersection. The author compares infrastructure-based and vehicle-based scheme to choose the scheme which is more efficient and effective. The author concluded that even though the delay may increase the amount of stop-and-go will be reduced to reduce the use of gasoline and safety is increased.

Waraich & Axhausen (2012) implemented a parking model in a traffic simulation to know how it reacts to space differences in parking demand and supply capturing elements like capacity and pricing. The agents settle on choices on the decision of parking spot from a given arrangement of spaces situated close to their destination. The author thought about four sorts of parking, public parking which is available to all, private parking which is allocated to explicit activities and structures, reserve parking which is saved for select agents, for example, Handicapped individuals and favored parking which is saved for vehicles with specific qualities, for example, electric vehicles needing an electrical plug. The choice of parking is influenced by the distance to destination, cost of parking, etc. The author assumed that agents had an idea about parking situations at their destinations and so the parking decision didn't consider agents making parking decisions while traveling on a link in traffic simulation. MATSim was used for the simulation and the results show that agents used short routes to reach their destination and the volumes of traffic changed as the day went to an end because some agent changes their mode of transport.

An attacker-defender game multi-agent-based model was simulated using ABM-EPANET and a threat ensemble vulnerability assessment and sensor placement optimization tool (TEVA-SPOT) by Monroe et al. (2018). This paper seeks to illustrate an attacker contaminating a system node with high assault utility and a gathering of protectors tries to limit the public health impact from intentional assault. An attacker agent representing a terrorist causing the chemical attack is introduced and a defender agent representing a person with decision making power, like utility manager set strategies to eliminate the attack and to prevent consumer agents representing the people the water is being distributed to for consumption from further consuming the contaminated water by introducing police and security agents at nodes (points of water consumptions). The defender gents consider the critical nodes first. A threat ensemble vulnerability assessment and sensor placement optimization tool (TEVA-SPOT) is used to identify critical nodes to prioritize in the attack. The author concluded that increasing the security equipment will reduce exposures, but attackers may look for other alternative nodes in areas of low police traffic also, the increase in police officers at critical nodes can results in an increase in attackers but at lower exposures.

Bernhardt & McNeil (2004) used complex systems theory for decision-making related to transportation infrastructure systems. Under various scenarios, a simulated pavement network characterized by 1) many agents or decision-makers acting side by side with dispersed control, 2) the presence of many organizational levels, 3) agents having the ability to adapt depending on decisions made at other levels, 4) forecasting using internal models. A network-level pavement model was designed. A deterioration model based on pavement condition index between 100 and

0 was defined where PCI of 95 represents a pavement that has been newly rehabilitated and a PCI of 30 triggers rehabilitation. Three different scenarios were used: 1) reducing funding, 2) changing exogenous factors causing accelerated deterioration, 3) changing technology to provide better information. The author found out that reduced funding through deferral of rehabilitation etc. results in the overall condition and reduced agency cost but in term increase in user costs. Also, changing external factors rapidly increases deterioration rates, traffic increases from one segment to the other, there is a difference in initial construction quality, etc. The introduction of new technology provides more information to decision-makers on historical data, better and consistent condition assessment, etc. the authors concluded that complex system theory recognizes the environment for decision-making and involves various agents interacting and adapting to current situations.

Bernhardt (2004) described a proof-of-concept spreadsheet simulation of the pavement network. The simulation comprised of 1000 pavement segments over time. The traffic environment, design, deterioration rate, maintenance, and expected life was all assumed to be the same. The pavement segment was each assigned an initial pavement condition index (PCI) randomly between 20 and 95. At a PCI of 30 rehabilitation is triggered and the PCI of the segment is restored to 95. To better understand real-world behaviors, some of the assumptions of the base case were changed and from that the average conditions reduced. Even though the spreadsheet simulation produced the results that were expected it was understood that the spreadsheet was not designed for simulation because its time-consuming updating cells repeatedly. Therefore, a more appropriate modeling tool was researched and an agent-based framework considering agents, their attributes, and interactions with each other were being developed for the appropriate modeling tool.

Lucey et al. (2019) used pavement performance indicators to evaluate pavement rehabilitation treatments and maintenance methodologies. In this evaluation long term pavement, performance database was used in studying how traffic conditions and environmental conditions affect various pavement structures. The traffic data were provided as equivalent single axle load (ESAL), the roughness data as international roughness index (IRI), pavement inventory data as Age, and pavement layer structural properties as structural number (SN). Two Artificial neural networks were used alongside the McCulloch and Pitts model (MCP) to predict pavement performance indicators and the author concluded that comparing the predictions to the observed data from the LTPP database, the predictions were reasonable. A sensitive analysis that was done showed that the pavement age, traffic, and structural numbers are the most impacting parameters when predicting pavement roughness.

3. CASE STUDY

3.1 Introduction

To capture the real-life scenario a case study was chosen, and traffic volume studies was done on the road. The traffic volume study was done according to vehicle classification. These studies were conducted to capture the impacts each agent has on each other.

3.2 Traffic Volume Studies

Traffic volume studies were done on a stretch of road. Indianapolis Boulevard, the stretch between 45th street and Hart Road was chosen. This stretch was chosen because Indianapolis Blvd is one of the main streets and the stretch does not have any turns which will affect the traffic volume that enters the stretch.

The Indianapolis Boulevard runs through the city of Hammond and Highland, located in Northwest Indiana, was used as our case study. The city of Hammond is part of the Lake County and had a population of about 77,134 as of 2016. Figure 3.1 shows the Indianapolis boulevard stretch between the 45th street and Hart Road with the highlighted part showing the northbound of which the traffic studies were done.

Figure 3.1 Indianapolis Boulevard stretch between Hart Road and 45th Street

3.3 Simulation

An agent-based simulation was developed to help transportation decision-makers in making maintenance decisions. The agent-based simulation used traffic volume data from Indianapolis Boulevard stretch between 45^{th} street and Hart Road, as shown in Figure 3.1.

From the traffic count data collected, vehicle classification was done to find the equivalent single axle load (ESAL) of the vehicles that used the road. The ESAL was fixed into Equation 4.28 to find the pavement condition rating (PCR) as the age of pavement serviceability increases.

4. METHODOLOGY

4.1 Introduction

This chapter introduces Netlogo the agent-based software used to develop the simulation. Also, the components that come together to form the simulation were discussed in detail. The link between Pavement Condition Rating (PCR), user cost, Equivalent single axle load (ESAL) was established, and how each component affects each other.

4.2 Netlogo

In the year 1999 Uri Wilensky a computer science and complex systems professor at northwestern university developed an agent-based modeling software called Netlogo. His lab actively maintains and improves the software. Over the years many other agent-based models have been developed but Netlogo is easy to use because it has a lot of functions to make model development easy and you do not have to learn a full programming language to be able to use it.

Netlogo uses a programming language called Scala with some pats in Java. It enables emergent phenomena investigation. It comes with different models in its library in a variety of domains that can be modified by users to fit what they are working on.

4.3 Agents

An agent is an autonomous individual with specific properties, actions, and sometimes goals. The environment is the surface where the agents interact. There are four types of agents. Namely;

- Turtles
- Patches
- Links
- Observers.

The turtles are the mobile agents that move around the two-dimensional interface which is divided into a grid of patches. The turtles can represent any type of mobile agent. Every turtle has 13 attributes by default. They are; who, color, heading, xcor, ycor, shape, label, label-color, breed, hidden?, size, pen-size, pen-mode, and additional attributes can be defined. (http://www.cs.sjsu.edu/faculty/pearce/modules/lectures/nlogo/intro/turtles.htm)

The Patches are stationary agents that the turtles can move on. It is in the form of n x m square tiles in a rectangular space. They can represent anything for example mountains, shops, roads. Every patch has five default attributes. They are; pxcor, pycor, pcolor, plabel, plabel-color, and additional attributes that can be defined. (http://www.cs.sjsu.edu/faculty/pearce/modules/lectures/nlogo/intro/patches.htm)

The links are agents that connect two turtles (nodes). The links do not have a coordinate and the distance of a link cannot be measured. We have a directed link and an undirected link. The directed link can be modeled as a relationship between a parent and a child and an undirected link can be modeled as a relationship between spouses or siblings.

The observer exists outside the model. The observer is like the general overseer of the whole simulation. (Izquierdo, Izquierdo, & Sandholm, n.d.). It creates all the entities within the model, and it controls their simulation behavior.

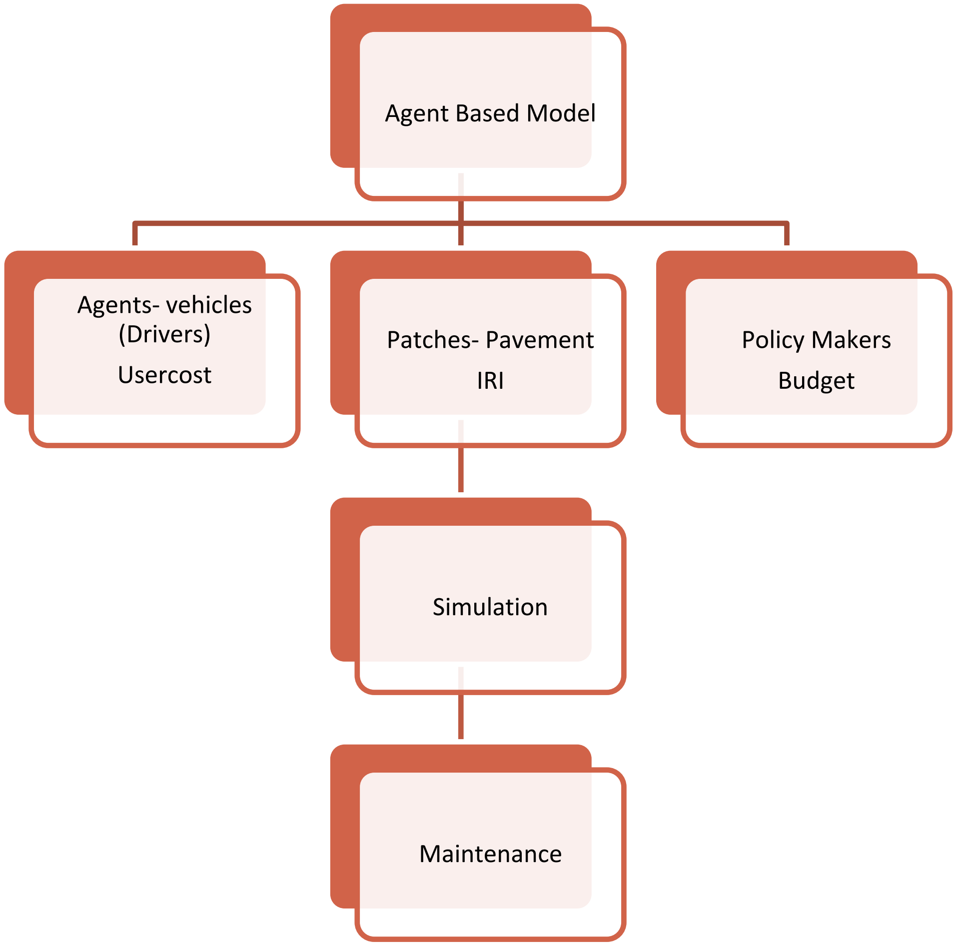


Figure 4.1 Agent-Based Model Process

4.4 Netlogo Simulation Methodology

Netlogo is a modeling environment for simulating natural and social phenomena. It's good for modeling complex systems developing over time. Netlogo uses agents that can be given individual instructions and they all operate independently and their micro and macro-level behavior and patterns that emerge for their interactions. Netlogo has tutorials and pre-written models in its model library that modelers can use by creating their own or develop on them.

The process of developing the simulation is shown in Figure 4.1, for the agent-based model to be developed, the automobile (agents), pavement (patches), and policymakers relate to form the simulation and the results of the simulation helps in maintenance decision making.

4.4.1 Agents and Their Attributes

Netlogo is fully programmable and the programming language is easy to use and understand. The model uses mobile agents that move over stationary agents.

For every simulation, there are agents used. In Netlogo there are default agents; turtles, patches, and links. But for simulation, the agents must represent something in your simulation. For the simulation, the agents that are being used are; automobile which represents the turtles, road pavement which represents the patches and policymakers which represents the observer. Each agent has its attributes and behavior.

4.4.1.1 Automobile

The automobile is the mobile agent in the simulation. They move around the environment and therefore on and across the patches (road). The attribute of the automobile is the cost involved in using the road that is user cost. The user cost is determined by considering the operation cost. Which is the cost of fueling the car, cost involves in maintaining and repairing the car, the cost of replacing tires, travel time. They also have certain variables like color and coordinates.

User cost is the cost incurred by the user of the transportation system. The cost of using the transportation system is widely affected by vehicle operation and travel time.

The vehicle operating cost is the cost that comes with the usage of the vehicle, the fixed cost, and variable cost. The fixed cost is not affected by the transportation system improvement, but the variable cost is affected. The variable cost is fuel use, tires, maintenance, repairs, and mileage.

Table 4.1 shows the unit vehicle operation cost in 2017 dollars which was converted from 2005 dollars using the consumer price index for the US labor statistics. The consumer price index of 2005 is 195.3 and 2017 is 240.007 (Bureau of Labor Statistics, 1982).

Table 4.1 Unit Vehicle Operation Cost

Unit Vehicle Operation Cost (2019 dollars)			
Vehicle Type	**Autos**	**Non-Heavy Trucks**	**Heavy Trucks**
Fuel and Oil	7.07	9.82	28.03
Tire (single)	0.65	2.48	4.85
Maintenance and Repair	4.58	5.67	14.52
Mileage-Dependent Depreciation	18.19	16.36	13.88
Total	30.50	34.33	61.27

Total Vehicle operation cost (VOC) = Unit VOC * Amount of Travel (VMT) (4.1)

Travel time is the time that elapses when one moves from an origin to a destination as shown in equation 4.2. We seek to reduce the time spent in moving from one place to another hence, transportation systems are enhanced to yield increased travel speed or decrease delays to reduce travel time. “Time is money”, they say but can it have a value? Due to the attributes of time, we can say that time cannot be bought or bartered so the term value of time means a time interval involved in the production of services or simply put the value of goods.

Travel time value = Vehicle hour traveled (VHT, hr) * Value of time ($/hr) (4.2)

Table 4.2 Value of Time to Vehicle Types

Vehicle Type	Value of time ($/hr)
Autos	$17.39
Non-Heavy Trucks	$26.74
Heavy Trucks	$31.12

From the information above and in Table 4.2 where the value of time can be picked from the user-cost can be calculated by the following;

User-cost = total vehicle operating cost (VOC, $) + travel time value ($) (4.3)

The increase in the user-cost is caused by road capacity and most importantly the condition of the pavement.

4.4.1.2 Road Pavement

The road pavement represents the patches in the simulation. They are the environment and thus the automobiles pass on them. The attribute of the pavement is the quality of the road pavement that is the serviceability index which is measured by the pavement condition rating (PCR).

The pavement condition rating (PCR) is one of the methods used for evaluating the condition of the pavement. The PCR is based on the pavement condition index (PCI) which is related to different factors; structural integrity, structural capacity, roughness, skid resistance, and rate of deterioration determined by measuring distress in pavement and by observation. (Headquarters, Department of The Army, Technical Manual Pavement Maintenance Management, 1982). The lower the PCR the rougher the road. Table 4.3 shows the PCI value as related to PCR.

Table 4.3 Pavement Condition Rating Relationship with Pavement Condition Index

Pavement Condition Rating (PCR)	Pavement Condition Index (PCI)
Excellent	100-86
Very good	85- 71
Good	70-56
Fair	55-41
Poor	40-26
Very Poor	25- 11
Failed	10-0

The PCI of the road affects the quality of a road as well as the user-cost and in turn, the budget allocated to maintaining and repair of the road. Therefore, as the PCI decreases so does the user-cost and budget.

4.4.1.3 Policy Makers

The policymakers are the agents that determine the resources available for pavement management. They rely on the information present by professional staff as well as users to inform their decisions. Their attribute is budget. The budget is the resource allocated for managing the pavement. The extent of damage to pavement and the type of maintenance to be done plays a key role in the resource that will be giving.

4.4.2 Building the Simulation

The first task is to create a world that will be the environment for the simulation's agents. It is done by using the graphical interface and by writing code. The modeling and simulation space can be edited from the model settings window. The topology, the origin of the x and y coordinates, and its dimensions are chosen in this window.

For a user to be able to execute any model procedure, a button must be activated within the interface. This button is the Setup button. The setup button is created by right-clicking a space on the interface a menu containing various elements will appear, then the user can select button. Another window will open with options for its configuration.

The commands text input field permits the user to describe the actions to be executed when the button is activated. The name of the button is what is written in the display name field and will use the text in the commands field by default if the display name field is empty. If there are any errors detected in the code assigned the button text will appear red.

The setup procedure is written in the code tab. When the procedure is defined, and the setup button is pressed, it begins the simulation by setting it back to its initial state due to the clear-all primitive: the values of all variables are set to default, all turtles are killed, and any output display is cleared.

Once the setup button has been created, a setup procedure must be written to be executed. The setup procedure sets the simulation back to its initial state due to the clear-all primitive. The variables are all set to their defaults, all turtles are reset, and all outputs are cleared. It resets the tick counter.

Another button that must be activated within the interface is the Go button. The Go button is created to activate the behavior of the patches and the agents. The Go procedure ends with the tick command, which ends the current tick, and incrementally increases the tick counter. There is a checkbox that says forever. When it is checked the go procedure will keep executing when the go button is pressed and will only stop when the button is pressed again.

Every code entered must begin with "To" and end with "end" or else the code will not be valid.

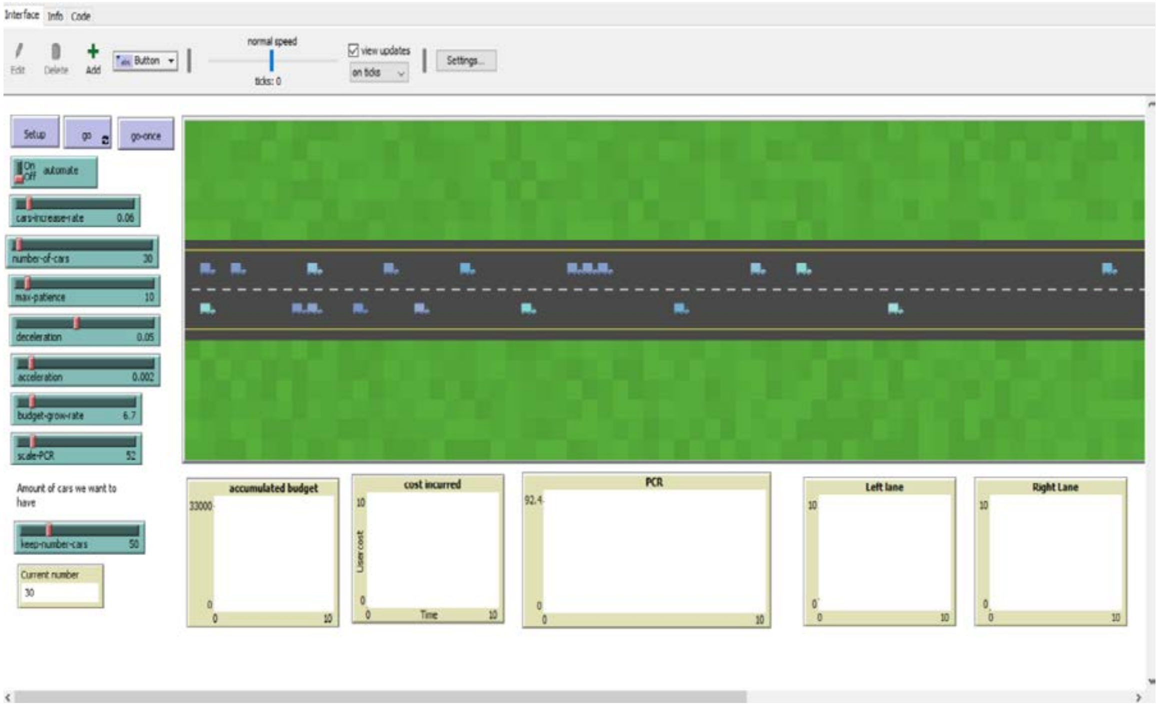


Figure 4.2 Pavement setup for the Netlogo simulation

4.4.2.1 Creating the Agents

For this simulation, the patches are the road. The mobile agents which are the vehicles will move on the road. The designing of the road involved the number of lanes, the road markings, and the color. A temporary turtle was created to draw the road lines then died off after completing its task. The road was given a color as well as the surrounding grass.

The road has an attribute which is pavement condition rating (PCR). The PCR of the road is determined by an equation fixed in the simulation relating the PCR to the age of pavement, equivalent single axle load (ESAL), and modified structural number (SNC) as shown in Equation 4.19. The PCR decreases to the age of pavement serviceability and increases when maintenance or reconstruction is done hence, the introduction of money (budget). The budget has a great effect on the type and amount of time maintenance can be done, but in this simulation, it is assumed that there’s no limit on the budget. In the simulation, a tick represents a vehicle movement. Every tick represents a day in the simulation.

In the designing of the turtles which is represented by automobiles in this simulation, the number of vehicles on the road is set to a specific number and it increases and decreases randomly because the number of vehicles on a road differs at every given time also, the number of vehicles was set in a way that they will not be more than the number of patches in the simulation. The color of the vehicles was set to different shades of blue so they could be distinguished. The direction of the vehicles was set, and the vehicles were restricted to stay in the patches containing the road network only.

The vehicles have properties like patience, speed, rate of acceleration, and deceleration. The Patience of a car is set to max patience at the beginning of the simulation and the patience reduces a little anytime the car brakes are used. A car can choose a new lane closest to the lane they are currently on when their patience runs to zero and the patience is reset to the maximum.

The vehicles are set to match the speed of the car in front of them then drive a bit slower than that car to avoid collision also, there is a set speed limit. The speed limit of the vehicles is set to 35MPH (0.35) to mimic the real-life conditions on roads. The code is seen below.

The vehicles are set to decelerate and accelerate at a certain speed which is regulated with a slider in the interface tab. The speed of the car is set to the deceleration speed when the speed of the car is less than zero and the speed of the car is set to top speed which is the speed limit when the speed of the car is greater than the top speed.

4.4.3 Calculating the User Cost of Vehicles

From table 1, Unit Vehicle Operating Cost (VOC) for trucks is \$57.51 and the amount of travel (VMT) is 0.35 miles which were calculated by measuring the stretch of the road.

$$Total\ Vehicle\ Operating\ Cost = Unit\ VOC\ \times Amount\ of\ Travel \tag{4.4}$$

$$= \$61.27\ \times 0.35\ miles \tag{4.5}$$

$$= \$21.44\ miles \tag{4.6}$$

$$Travel\ time\ value\ = Vehicle\ hour\ travelled\ (VHT)\ \times Value\ of\ Time\ \left(\frac{\$}{hr}\right) \tag{4.7}$$

It takes 2 minutes to drive 1 mile at a speed of 30 miles per hour (mph); to drive 0.35 miles it takes 0.7 minutes which is 0.012 hours. From Table 4.2 value of time (\$/hour) for heavy trucks is \$31.12/ hour.

$$Travel\ time\ value = 0.012\ hrs\ \times \$31.12\ per\ hour\ = \$0.373 \tag{4.8}$$

$$User\ cost\ = \$21.44\ miles + \$0.373 \tag{4.9}$$

$$= \$21.813\ miles \tag{4.10}$$

For each tick which represents a vehicle movement in the simulation, the user cost is calculated as;

$$Total\,Vehicle\,Operating\,Cost = Unit\,VOC\ \times Amount\,of\,Travel \tag{4.11}$$

$$= \$61.27\ \times 0.00022\,miles \tag{4.12}$$

$$= \$0.013\,miles \tag{4.13}$$

$$Travel\ time\ value\ = Vehicle\ hour\ travelled\ (VHT)\ \times Value\ of\ Time\ \left(\frac{\$}{hr}\right) \tag{4.14}$$

$$Travel\ time\ value = 7.33\ \times 10^{-6}\ hrs\ \times \$31.12\ per\ hour \tag{4.15}$$

$$= \$0.228 \tag{4.16}$$

$$User\ cost\ = \$0.013\,miles + \$0.228 \tag{4.17}$$

$$= \$0.241\,miles \tag{4.18}$$

4.4.4 Data Collection for Simulating Vehicular Volume

For the simulation to represent a real-life situation the vehicular volume used for the simulation should represent what happens in real life. Data about the road network in the case study area had to be collected. Turning movements at intersections were collected to be able to represent the reality on the roads in the simulation.

Data on vehicles turning onto the northbound of the 45th and Indianapolis Blvd. road was taken. To have a representation of a realistic traffic stream in the simulation, a camera was mounted at the intersection to capture vehicles entering the intersection. All vehicles were counted and not divided into turning movements. At every continuous fifteen minutes, data were recorded for two consecutive days. The vehicular volume for the two days and the average vehicular volume table can be found in Appendix B.

The peak hour volume was calculated by adding the volumes of the four 15 minutes intervals consecutively and the highest volume's corresponding four 15 minutes is considered the peak hour. From the data collected, 7:15 am – 8:15 am is the peak hour, and the peak hour volume is 1591 vehicles, also the peak 15 minutes in the hour is 430 vehicles. The simulation considers the trucks because the equivalent single axle load (ESAL) of trucks affect the road more than passenger vehicles. For the simulation, the percentage of trucks for peak hour volume was used.

From dividing the volume of vehicles into their axle type, the percentage of trucks was calculated. The percentage was about 6% which amounts to thirty (30) vehicles.

4.4.5 Finding Pavement Condition Rating (PCR)

For the simulation to provide the information needed, there should be a link between how long the pavement has been in service and PCR. This relationship helps the simulation determine the rate at which the PCR is affected by how long the pavement has been in service in the simulation. Figure 4.3 shows the relation between the age of pavement and PCR.

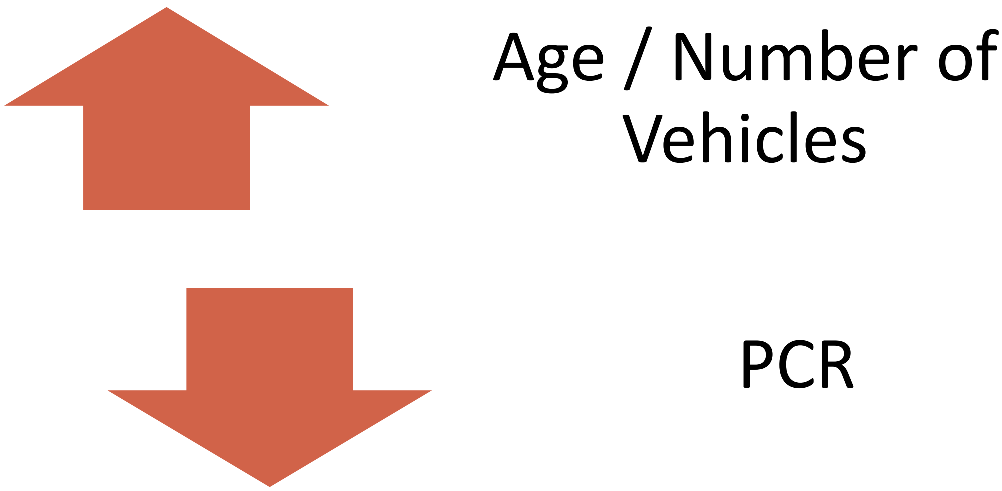


Figure 4.3 Relationship Between Pavement Age or Number of Vehicles and PCR

(George, Rajagopal, & Lim, 1989) developed an equation (Equation 4.19 through 4.20) to predict pavement deterioration. The equation was developed for the flexible pavement with overlay. The equation takes into consideration the ESAL, Age of pavement, and the modified structural number.

$$PCR(t) = 90 - a\,[\exp(age^{b}) - 1]\log[\frac{ESAL}{SNC^{c} * T}] \qquad (4.19)$$

Where

SNC = Modified structural number. (The American Association of State Highway Officials (AASHO) structural number, modified to account for subgrade support, is designated as modified structural number) (Equation 4.20)

T = Thickness of the last overlay, in inches

a = 0.8122

b = 0.3390

c = 0.8082

All other symbols are explained above.

$$SNC = \sum a_i h_i + SN_g \tag{4.20}$$

Where

a_i = material layer coefficients,

h_i = layer thickness (in.),

SN_g = subgrade contribution, and

$$= 3.51 \log CBR - 0.85\ ((\log CBR)^2 - 1.43 \tag{4.21}$$

In which CBR = in situ california bearing ratio of subgrade (percent).

The California bearing ratio (CBR) test is a penetration test used to determine the strength of the subgrade of pavements and roads. The result from the test is used along with curves to determine the different layer thickness of a road or pavement. The information on the value of CBR and the different layer thickness for my study area was gotten from the city engineer since finding the CBR and layer thickness were not part of my research.

The material layer coefficients, on the other hand, was referred from (Mannering, F., Kilareski, W., & Washburn, S., 2007) as shown in table 4.4.

Table 4.4 Material Layer Coefficients

Pavement Component	Coefficient
Wearing surface	
Sand-mix asphaltic concrete	0.35
Hot-mix asphaltic (HMA) concrete	0.44
Base	
Crushed stone	0.14
Dense-graded crushed stone	0.18
Soil cement	0.20
Emulsion/ aggregate- bituminous	0.30
Portland cement/ aggregate	0.40
Lime-pozzolan/ aggregate	0.40
Hot-mix asphaltic (HMA) concrete	0.40
Subbase	
Crushed stone	0.11

The CBR value is 3% hence,

$$SN_g = 3.51 \log CBR - 0.85 \left(\log CBR\right)^2 - 1.43 \tag{4.22}$$

$$= 3.51 \log 3 - 0.85 \left(\log 3\right)^2 - 1.43 \tag{4.23}$$

$$= 0.051198 \tag{4.24}$$

The layer thicknesses are; 3 inches for wearing surface, 6 inches for base and 10 inches for subbase.

$$SNC = \sum a_i h_i + SN_g \tag{4.25}$$

$$= [(0.44 * 3) + (0.14 * 6) + (0.11 * 10)] + \ 0.051198 \tag{4.26}$$

$$= 3.311198 \tag{4.27}$$

4.4.6 Finding the Equivalent Single Axle Load (ESAL)

Traffic count was done on the road and the vehicles were classified by their axle type. The equivalent single axle loads (ESALs) per vehicle was multiplied by the number of vehicles for the different axle types to get the total ESAL as shown in Tables 4.5 and 4.6.

Table 4.5 ESAL Calculation for Right Lane (From FHWA, 2001)

Axle type	ESALs per Vehicle	Right Lane	Total ESAL
Class 2 or 3	Negligible	577	
Class 6	0.42	16	6.72
Class 8	0.30	7	2.1
Class 9	1.20	33	39.6
Class 10	0.93	3	2.79
			51.21

Table 4.6 ESAL Calculation for Left Lane (From FHWA, 2001)

Axle type	ESALs per Vehicle	Left Lane	Total ESAL
Class 2 or 3	Negligible	522	
Class 6	0.42	1	0.42
Class 8	0.30	4	1.2
Class 9	1.20	10	12
Class 10	0.93	0	0
			13.62

The total ESAL is 64.83 and for the year it will be 19449.

$$PCR(t) = 90 - a\,[\exp(age^{b}) - 1]\log[\frac{ESAL}{SNC^{c} * T}] \tag{4.28}$$

$$PCR(t) = 90 - 0.8122\,[\exp(age^{0.3390}) - 1]\log[\frac{19449}{3.311198^{0.8082} * 3}] \tag{4.29}$$

The age in the equation changes as time goes on. It starts from one when the pavement is in service.

5. RESULTS AND DISCUSSIONS

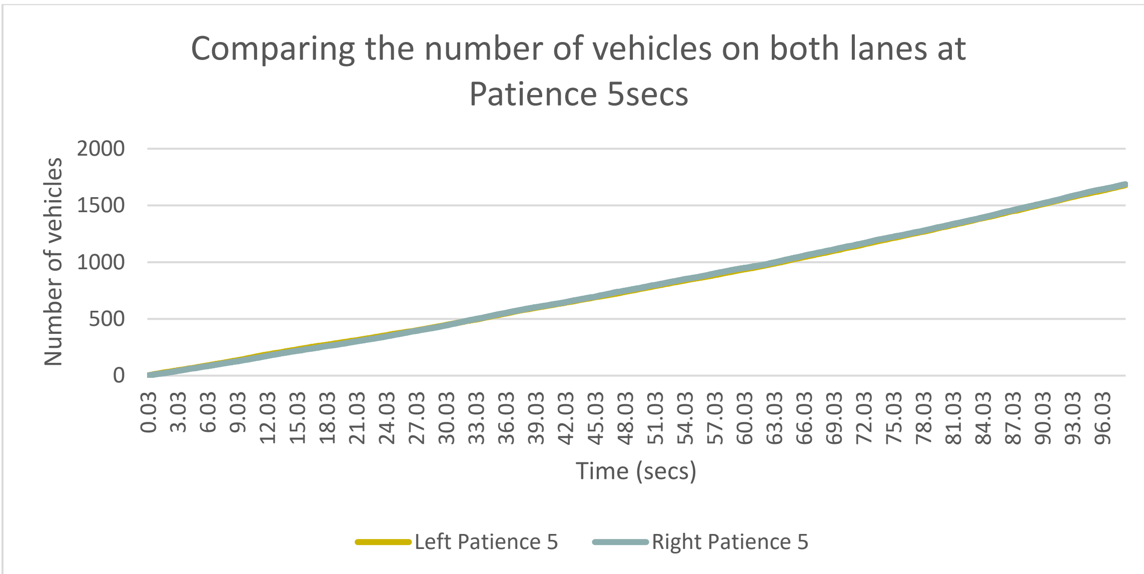
5.1 Introduction

The traffic simulation in Netlogo was conducted by running the simulation a couple of times to take the average. The simulation was conducted by gradually increasing and decreasing the number of vehicles on the road to mimic real-life traffic. The number of vehicles on each lane was counted whiles the patience level of drivers was varied to show how drivers behave when driving. The traffic flow was simulated to show the changes in PCR as maintenance is done, as the years go by and how it affects the cost of users.

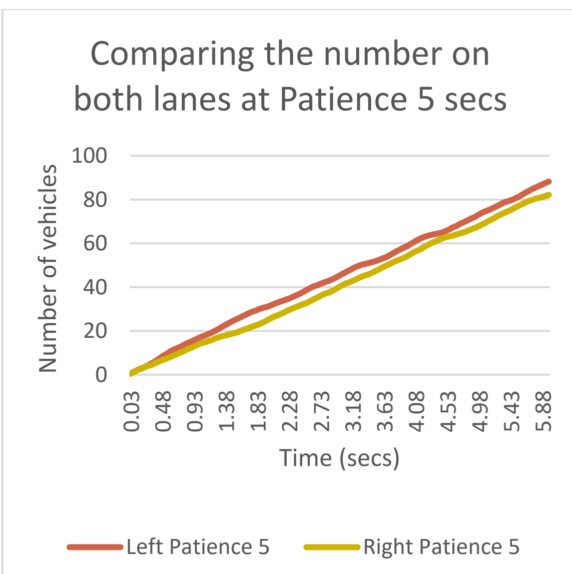
5.2 Comparative Analysis of Vehicles against Different Patience Levels

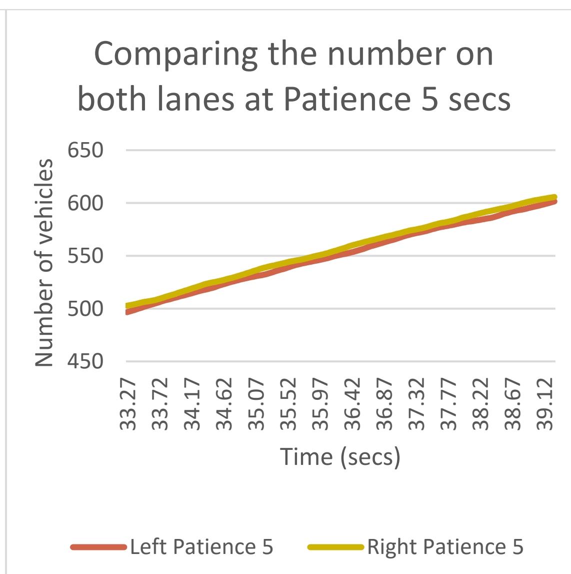
The patience of the users of the roads was varied that is 5, 10, 15, and 20 seconds and the simulation was run several times to collect the volume of vehicles on each lane as it crosses the end of the road by plotting it in a graph in Netlogo. After the plot was extracted and Excel was used to calculate the cumulative volume of the vehicles as time passed for each simulation and the average was taken for each patient level. This was done so the pavement deterioration of each lane could be calculated also to identify the lane which was used most when the patience was varied.

The average cumulative volume of vehicles for each lane according to the four (4) patience variations of the users was plotted to compare each variation according to the two lanes as shown in Figure 5.1 – Figure 5.4.



(a)



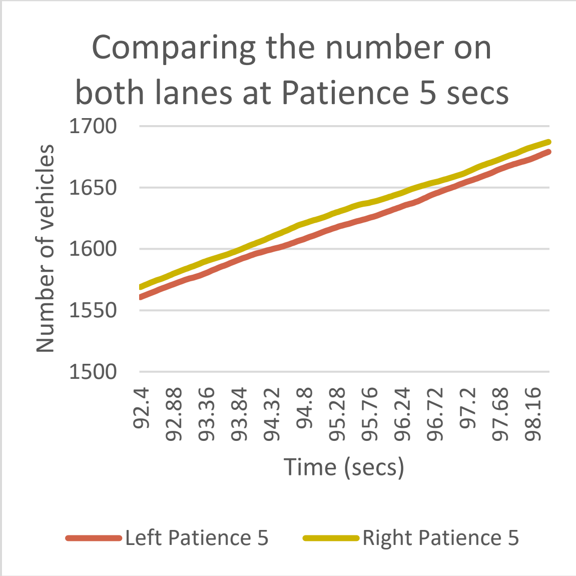


(b)

(c)

Figure 5.1 Comparing the Number of Vehicles on Both Lanes at Patience 5 Secs (a) showing the full simulation length, (b) - (e) showing the simulation in four sections

Figure 5.1 Continued



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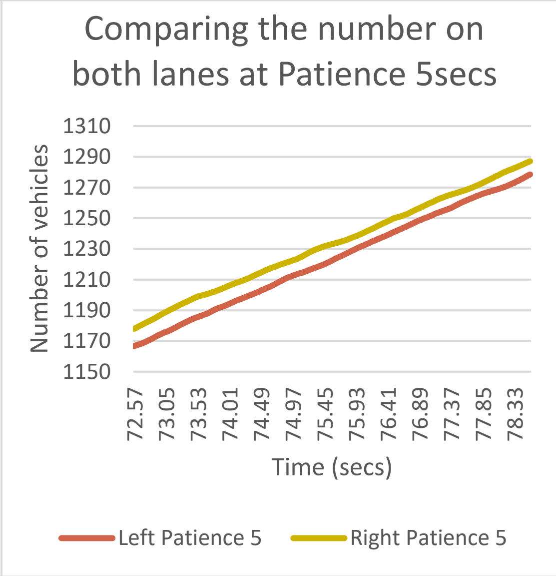

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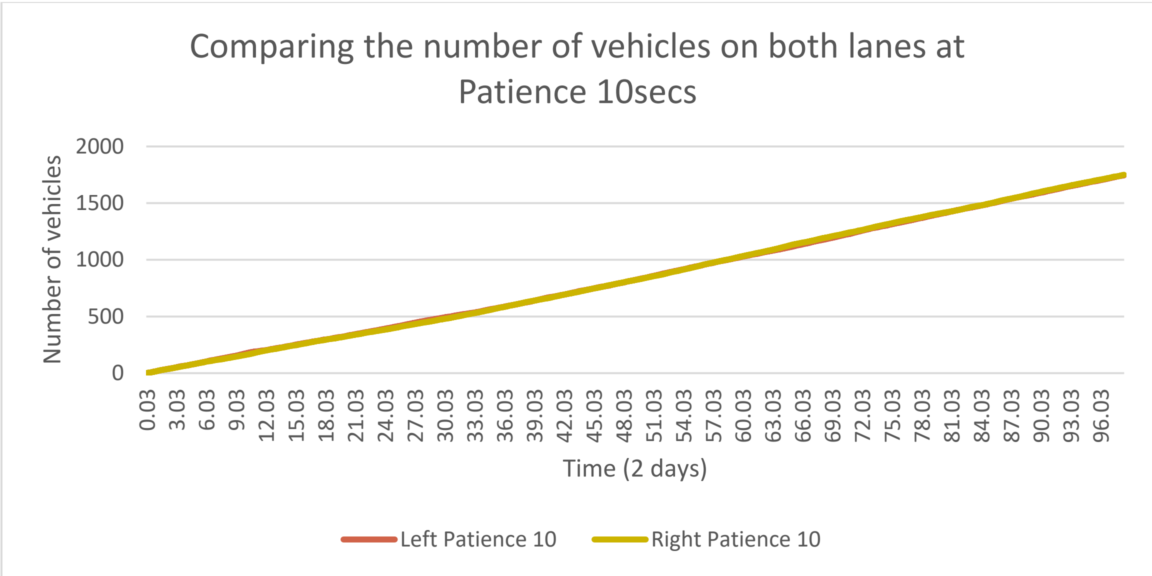
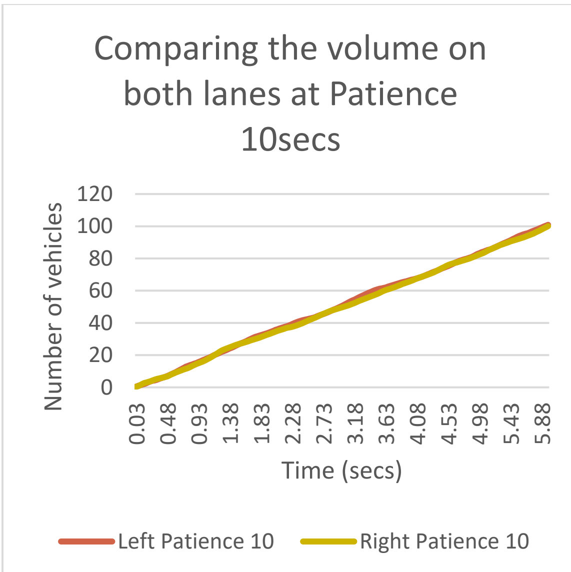


(a)

Figure 5.2 Comparing the Number of Vehicles on Both Lanes at Patience 10 Secs with (a) showing the full simulation length and (b) - (e) showing the simulation in four sections

Figure 5.2 Continued



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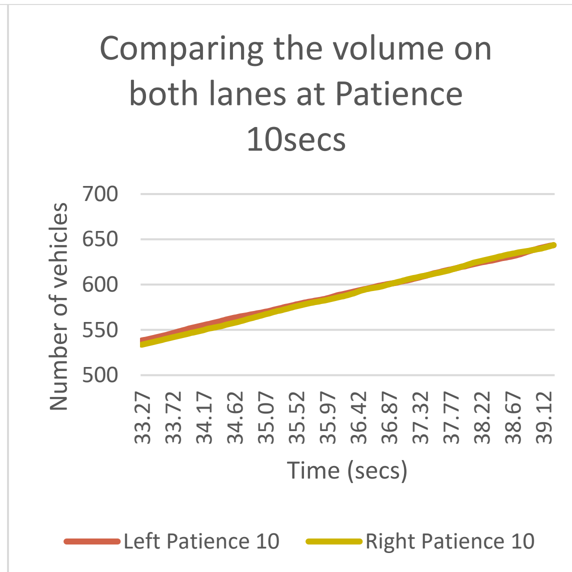

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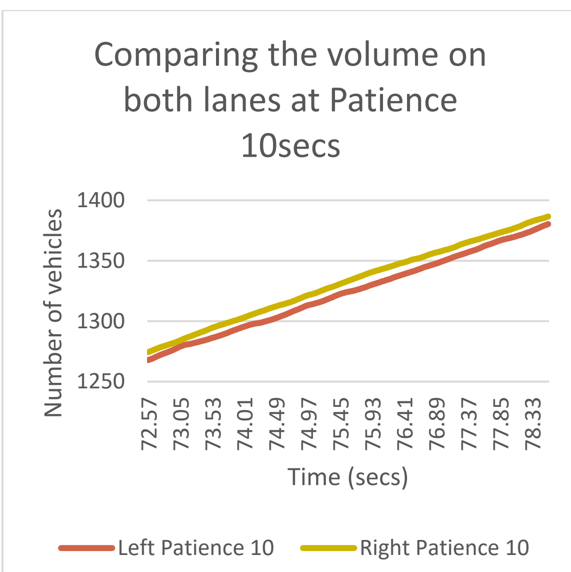

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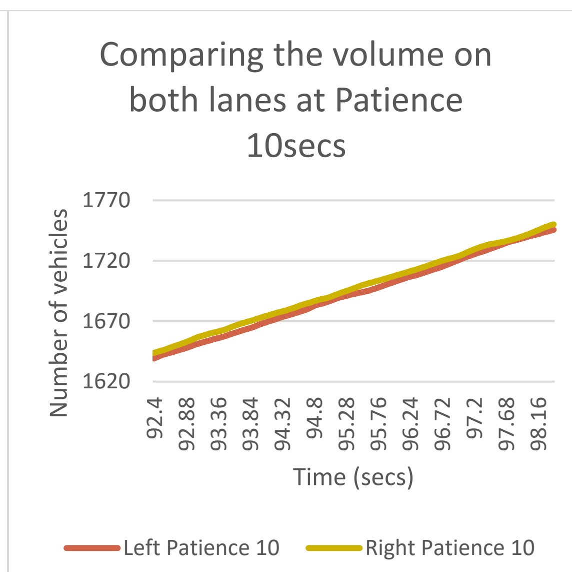

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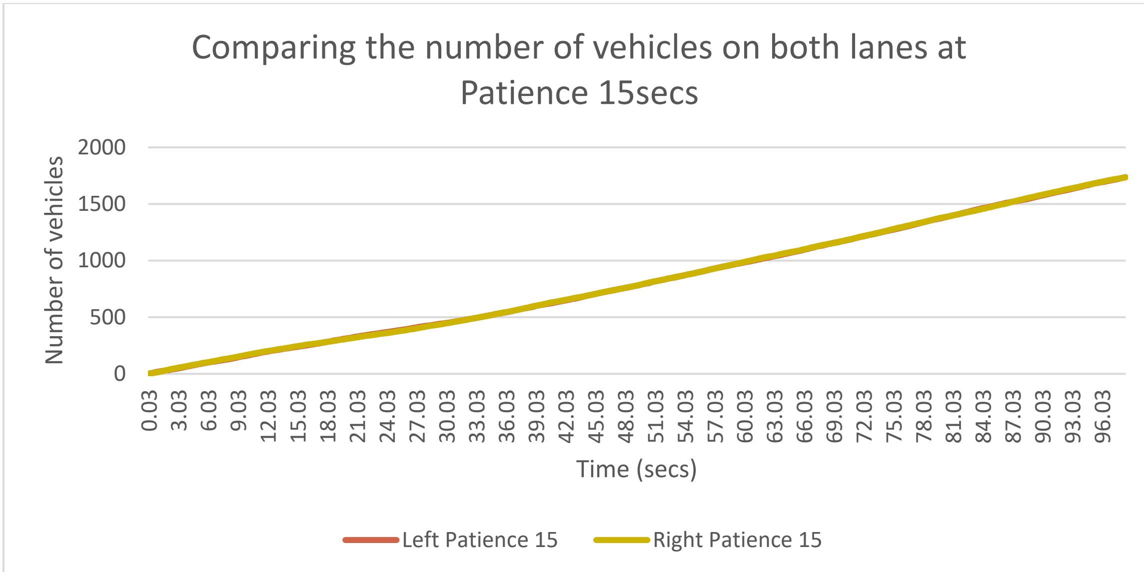

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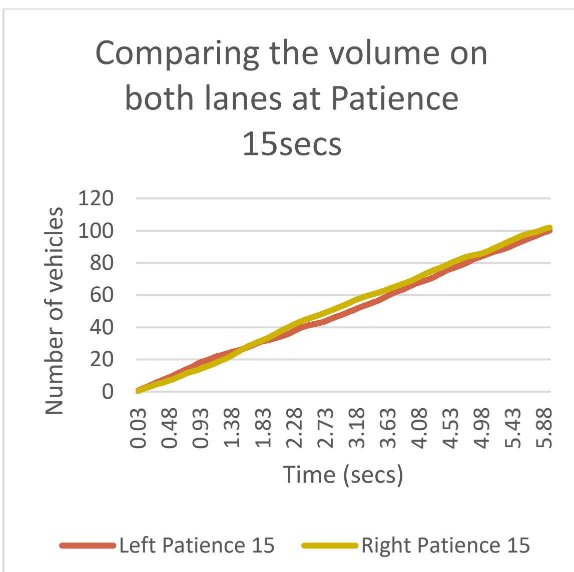

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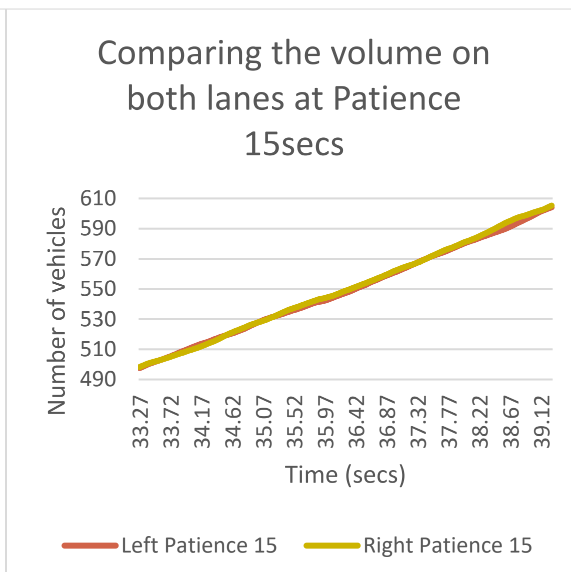
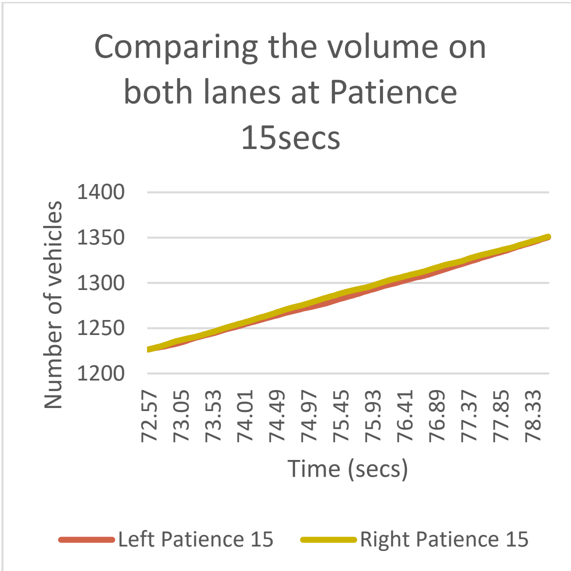


(c)

Figure 5.3 Comparing the Number of Vehicles on Both Lanes at Patience 15 Secs (a) showing the full simulation length, (b) - (e) showing the simulation in four sections

Figure 5.3 Continued



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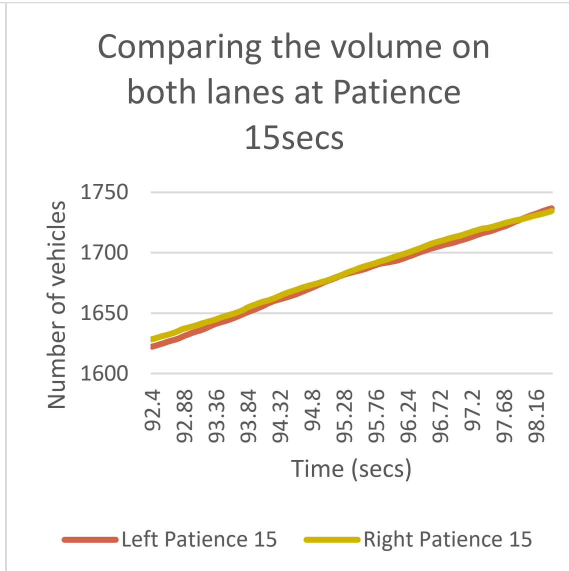

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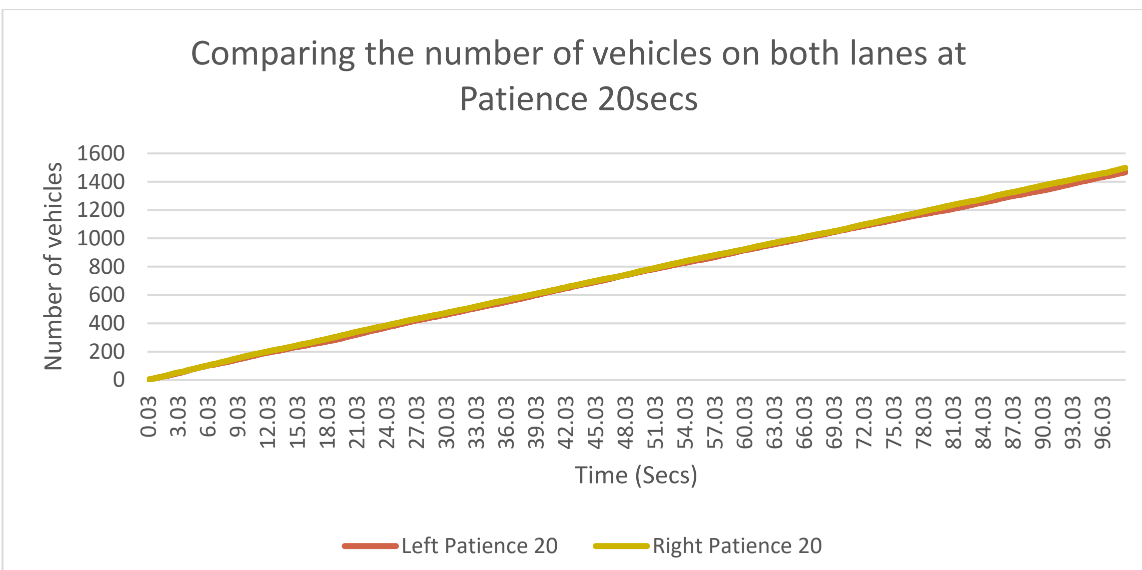
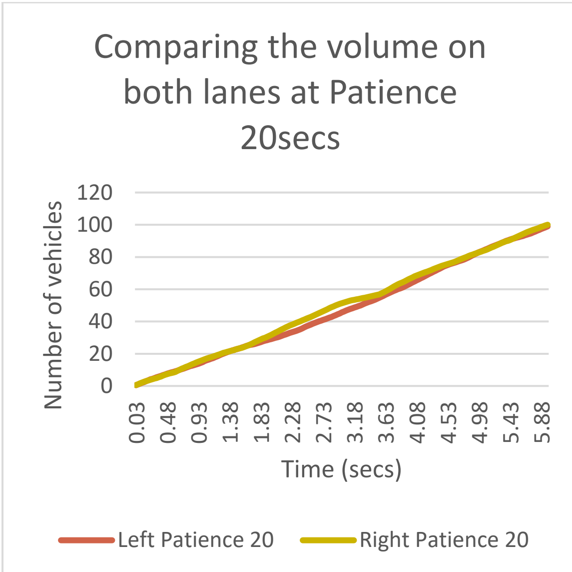


(a)

Figure 5.4 Comparing the Number of Vehicles on Both Lanes at Patience 20 Secs (a) showing the full simulation length, (b) - (e) showing the simulation in four sections

Figure 5.4 Continued



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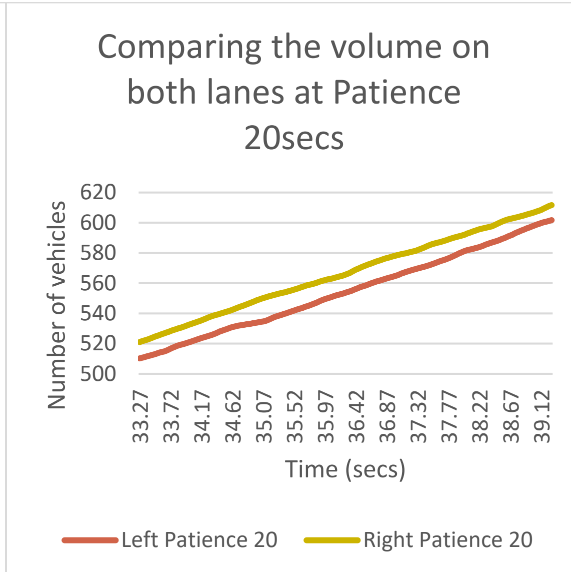

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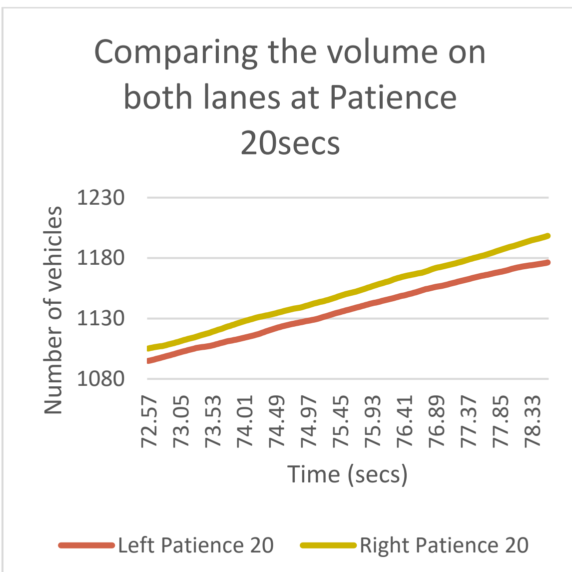

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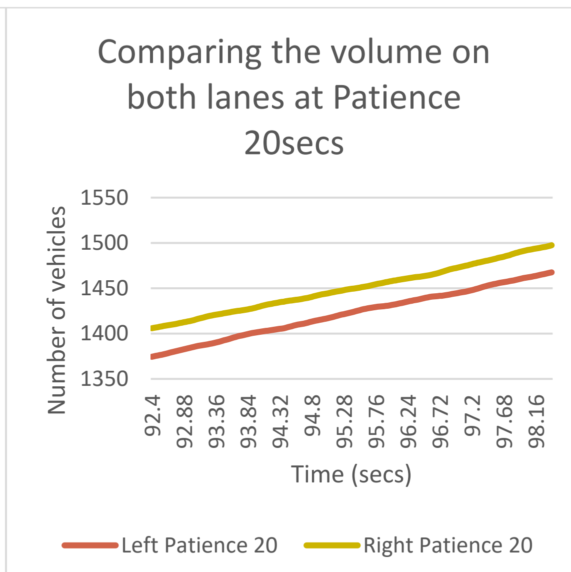

(e)

Looking at Figures 5.1 through Figures 5.4, comparing the volume of vehicles on both lanes to the four different patience levels, we can see that the volume of vehicles is approximately the same on both lanes. In real life, drivers tend to join the lane with the lowest number of vehicles, and with that, the number of vehicles on the lanes tends to balance out. The difference can be understood better by looking at Figures 5.5 through Figures 5.8.

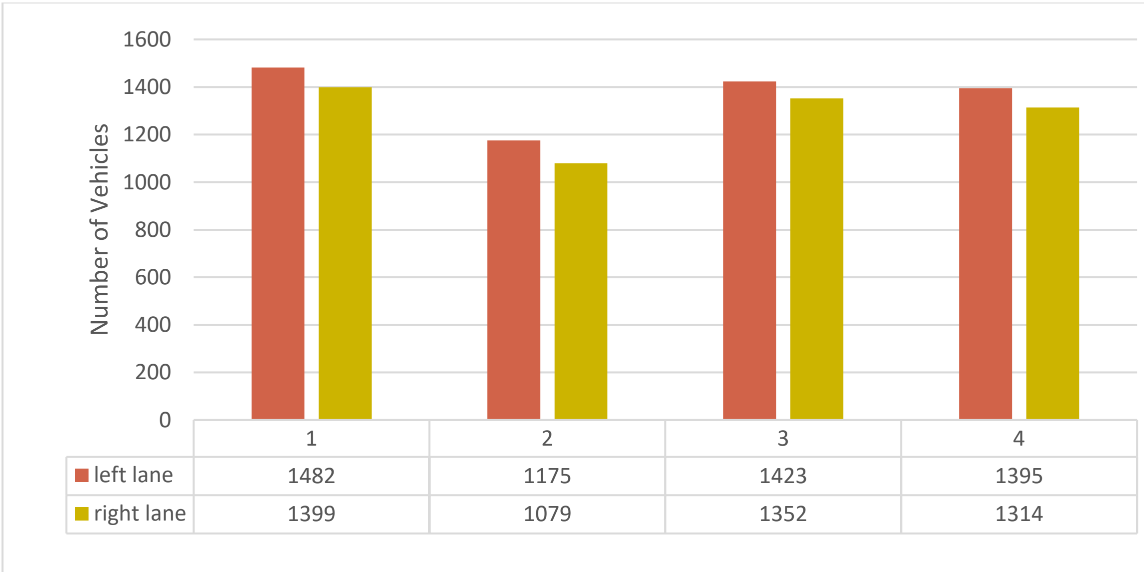

Figure 5.5 Comparing the number of vehicles on each lane at four different sections of the road at Patience 5 Seconds

In all sections, the left lane has more vehicles and the number of vehicles on both lanes are almost the same.

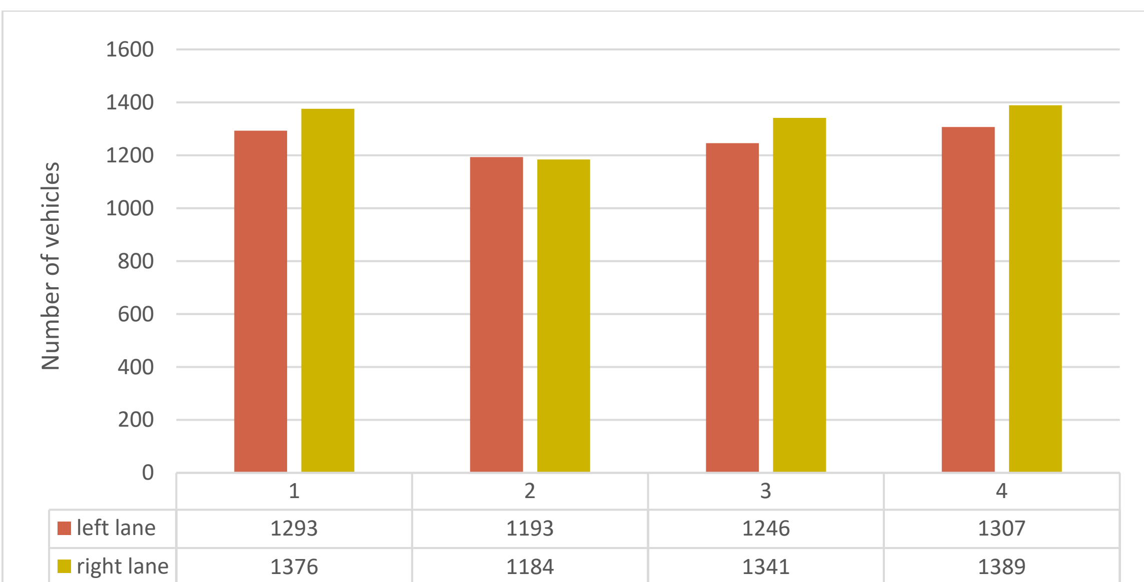

Figure 5.6 Comparing the number of vehicles on each lane at four different sections of the road at Patience 10 Seconds

In most of the sections the right lane has more vehicles and the number of vehicles on both lanes is almost the same.

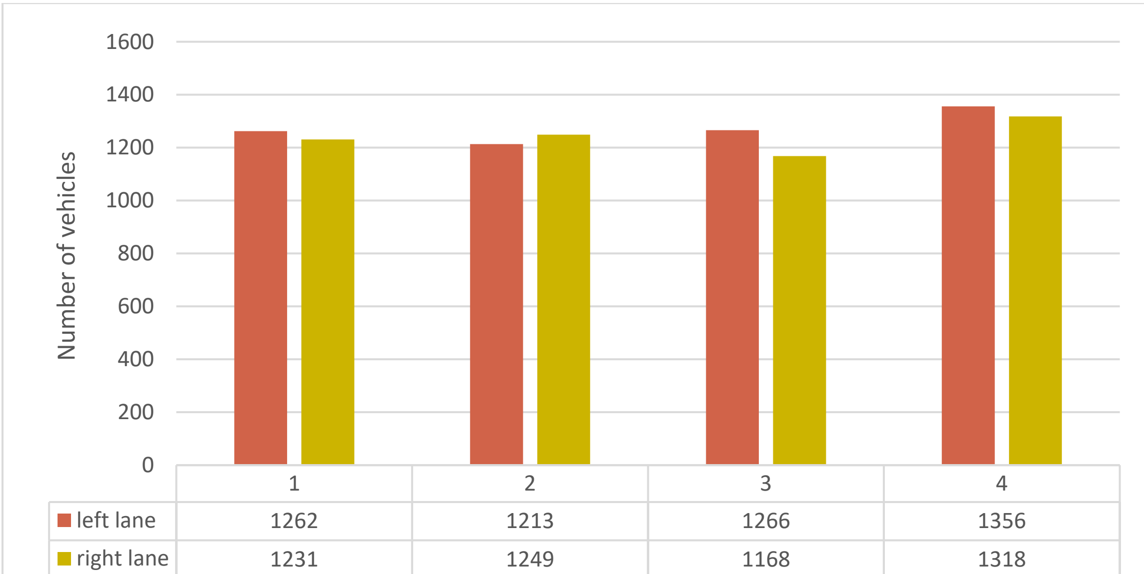

Figure 5.7 Comparing the number of vehicles on each lane at four different sections of the road at Patience 15 Seconds

The number of vehicles on both lanes is close as compared to patience level 10 and 5 seconds and the number of vehicles on both lanes is almost the same.

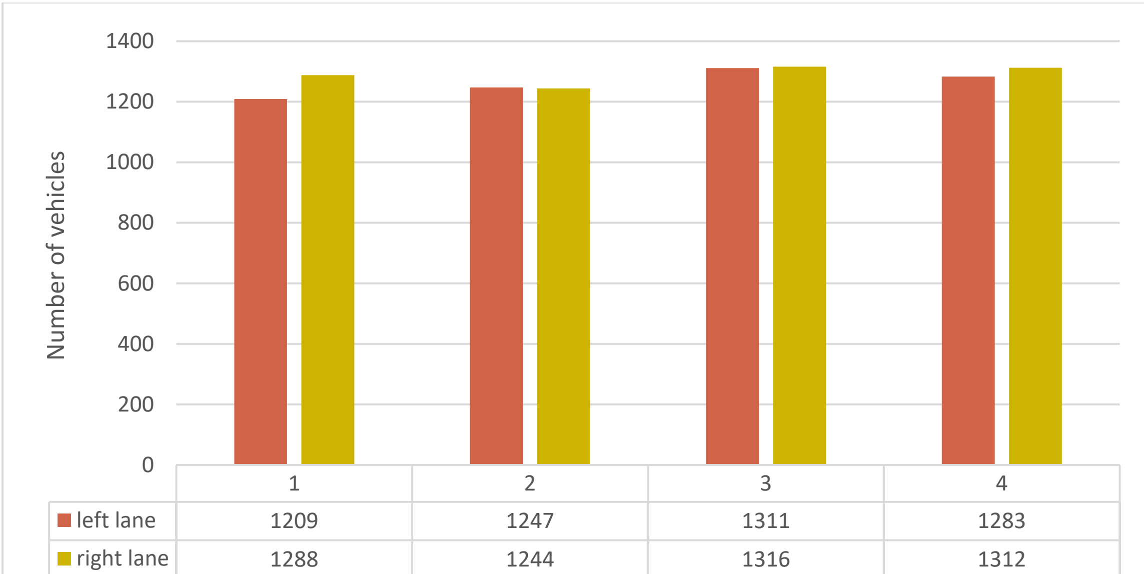

Figure 5.8 Comparing the number of vehicles on each lane at four different sections of the road at Patience 20 Seconds

The number of vehicles on both lanes is close as compared to patience levels 15,10 and 5 seconds and the number of vehicles on both lanes are almost the same

5.3 Impact of Pavement Maintenance and Age on Pavement Condition Rating

Figure 5.9 shows the changes in PCR of the pavement as the years go by, in real life we understand that different factors come together to affect the rate at which pavement deteriorates. The simulation considered the age of pavement and the number of vehicles that use the road. From Figure 5.9 we see that as the days go by, the PCR of the pavement decreases and when maintenance is triggered the PCR increases and the PCR starts to decrease again until another maintenance is triggered. The PCR increases to the highest point when relayering of the surface layer is done and the cycle continues. The age of the pavement is in an increment of two days for every unit in the simulation. Looking at the PCR values to the age of pavement will help policymakers in planning for pavement management decisions per the resources available.

At year 9 of the pavement being in service, the PCR is 58 which falls between the Good range referring from Table 4.3 and in real-life situations there will be cracks and some potholes in the road hence, general maintenance can be scheduled to be done to improve the road surface condition which will, in turn, increase the PCR value to a more acceptable value. The PCR continues to decrease and another general maintenance is suggested to be done around year 19 which is providing a PCR value of 44 (fair on the PCR range table) and a resurfacing is suggested at the next drop which is providing a PCR value of 27 (poor on the PCR range table).

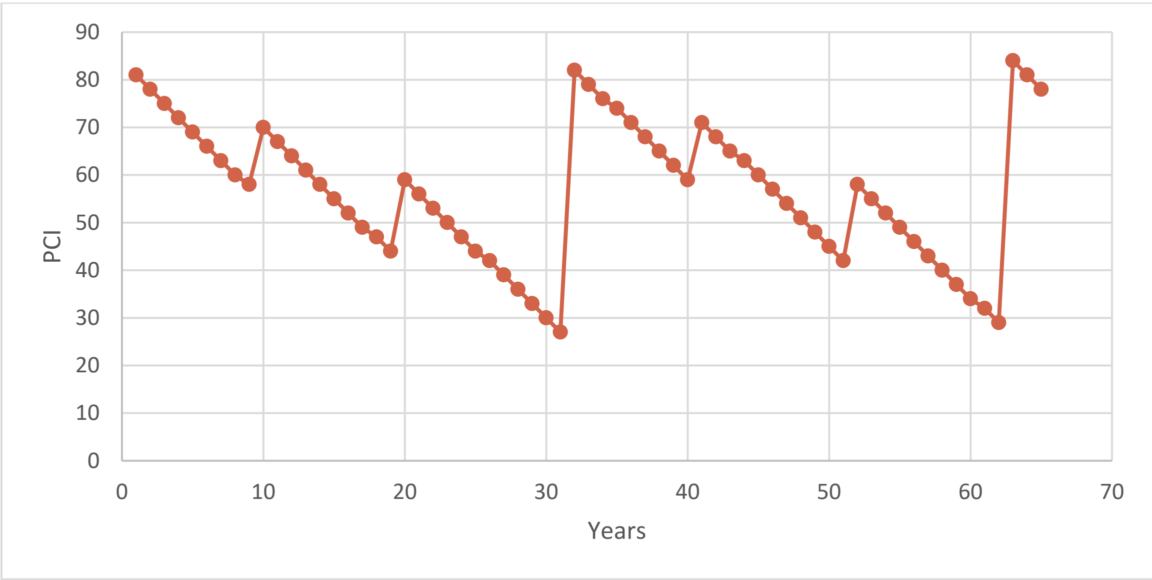

Figure 5.9 Changes in PCR with Pavement Age Increase

5.4 Effects of Pavement Ages and Maintenance on User Cost

The user cost of each movement is shown in Equation 4.18. From Figure 5.10 the user cost increases with an increase in the age of the pavement and there are reductions at some points. The reductions and increases can be related to maintenance triggered by the decrease in PCR in the simulation. In Figure 5.11 the user cost and PCR are put on the same graph and it can be identified that the points where the user cost reduces are the exact say points where the PCR increase and those are the times where maintenance is done on the road pavement.

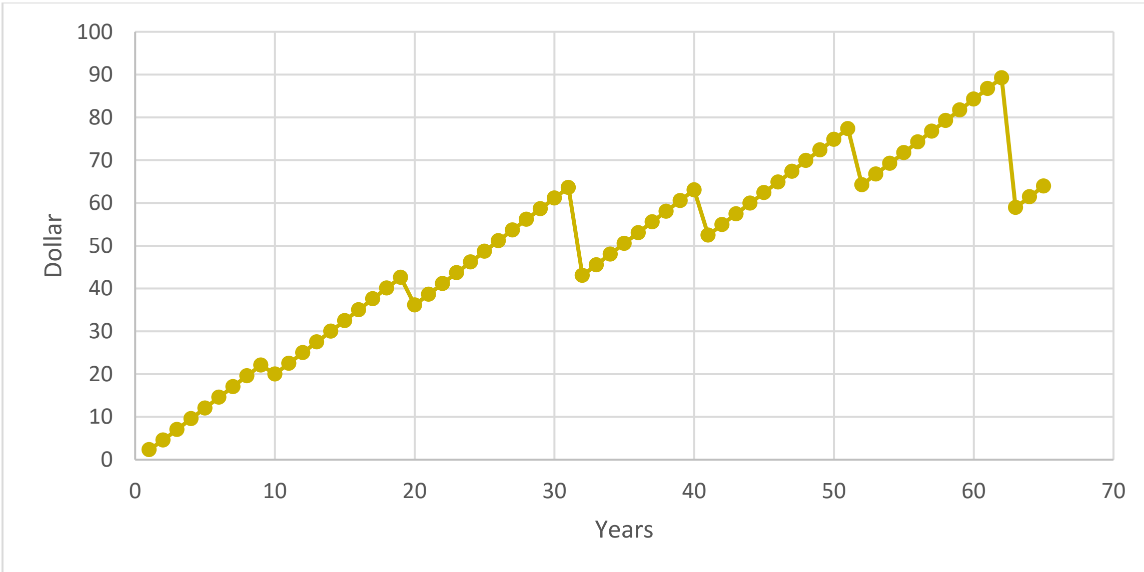

Figure 5.20 Changes in User Cost with Pavement Age Increase

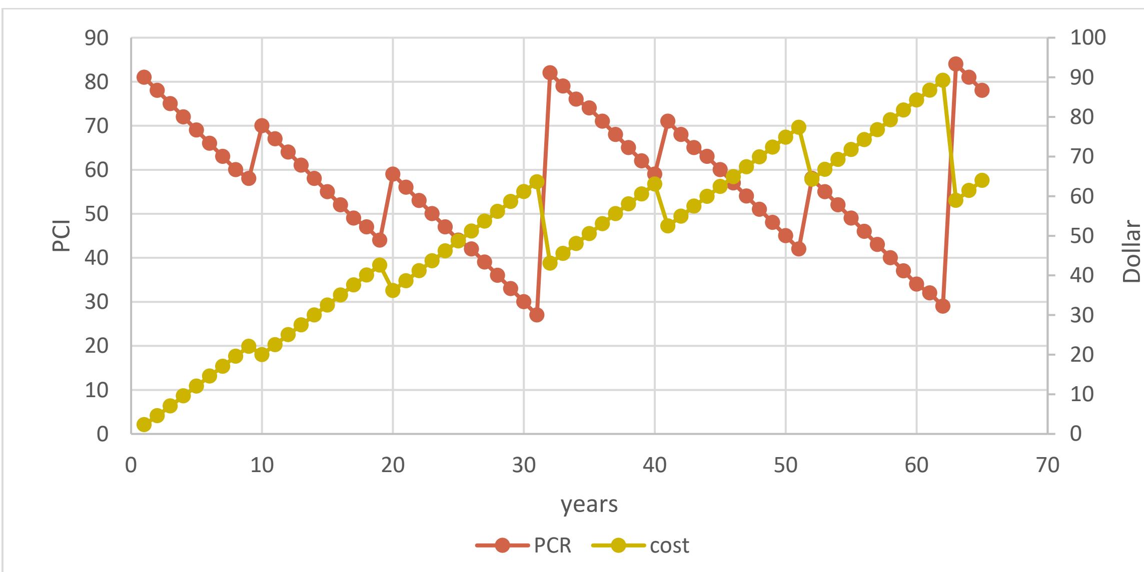

Figure 5.11 Changes in PCR and User Cost with Pavement Age Increase

6. SUMMARY AND CONCLUSION

6.1 Summary

As days go by and vehicles pass on road pavements, the pavement surface goes through wear from friction caused by vehicle tires. These wears caused by pavement aging, weather conditions and movement on the surface affect the pavement surface deterioration. This research sought to assist in pavement management decision making. Determining times maintenance should be done on the pavement, effects it has on the cost incurred by users, and budget availability. The final aspect of this research gives policymakers an idea when maintenances should be done and the pavement condition rating at that time to plan accordingly with the budget available for transportation works.

The traffic data collected on the Indianapolis Blvd road showed an average passage of class 6 and upwards axle types on the road hence, the ESAL which was calculated as 19449 annually was not that large which indicates that the rate of deterioration will be low as the years go by. The user cost of the vehicles that traverse the road was calculated as approximately $22 from Equation 4.10 and the initial pavement condition rating at year one of the pavement surface was 84 from Equation 4.29 which falls between the very good criteria on Table 4.3. With all the information provide the simulation was run and the various attributes of the agents interacted with each other and graphs were plotted which showed how the individual components affect each other.

The results from the plots will assist the policymakers when budgeting for transportation projects and help in deciding when maintenance works can be performed on various road networks.

6.2 Conclusions

From the research conducted for this thesis the following conclusions can be drawn:

- The larger the value of ESAL the higher the rate at which the pavement surface will deteriorate.
- The aging of the pavement has a significant impact on the rate of the deterioration of the pavement surface.

- The user cost is highly affected by the aging of the pavement surface even if the pavement is maintained from time to time.
- The PCR is largely affected by the aging of pavement and the number of vehicles that use the road.
- The PCR increases when maintenance is triggered which in turn reduces the cost incurred by the road users.
- The PCR values at specific times help in making pavement management decisions.
- It does not matter the kind of patience a road user has, the vehicle distribution on the road is almost balanced most of the time.
- When the Patience is low road users tend to change lanes more hence the high number of vehicles on the left lane since in road design it’s the changing lane.
- As the Patience of the road users increases the number of vehicles that use the right lane is almost the same as the number of vehicles that use the left lane.

6.3 Challenges and Future Scopes

The major challenge experienced in this simulation development was the software used. It did not allow for the equations to be embedded in the code for automatic generation of answers but rather the answers had to be coded allowing more manual work. Acquiring data from experts prove more difficult because they were less forthcoming with the information or had no records of the information.

In the future, a more flexible and automated software can be employed to make the simulation easier to work with and give clearer predictions. Also, with experts more forthcoming with information and keeping records on the information about pavement layers will help to develop the simulations faster and more simulations can be done on different pavements.

Also, in the future other entities that affect pavement deterioration and management for example weather, etc. and a budget limitation can be introduced to make the simulation more realistic.

APPENDIX A. CODE

```
globals [ lanes
  selected-car
  current-budget
  PCR
  PCR-period
]

turtles-own [
  speed
  top-speed
  target-lane
  patience
  user-cost
  budget


]

patches-own [

  age
  period
]

to setup
  clear-all; clears the interface
  draw-road; draws the road
  set-default-shape turtles "truck"; the turtle agents are cars
  create-cars
```

```
  set PCR 84
  set PCR-period 1
  ask patches with [ abs pycor <= number-of-lanes ] [
    set age 1

  ]
  ask turtles [set budget 1000]
  set keep-number-cars 50
  set current-budget 1
  reset-ticks; every time you click setup the ticks start all over
  reset-timer
end



to draw-road
  ask patches [
    ; the road is surrounded by green grass of varying shades
    set pcolor green - random-float 0.5
  ]; the random float 0.5 varies the green shades
  set lanes n-values number-of-lanes [ n -> number-of-lanes - (n * 2) - 1 ]
  ask patches with [ abs pycor <= number-of-lanes ] [
    ; the road itself is a shade of grey
    set pcolor grey - 2.5
  ]
  draw-road-lines
end



to draw-road-lines
  let y (last lanes) - 1 ; start below the "lowest" lane. The white dashes do not appear below
the lane
```

```
    while [ y <= first lanes + 1 ] [
      if not member? y lanes [
        ; draw lines on road patches that are not part of a lane. The white dashes do not appear
above the lane.
        ifelse abs y = number-of-lanes
          [ draw-line y yellow 0 ]  ; yellow for the sides of the road
          [ draw-line y white 0.5 ] ; dashed white between lanes
      ]
      set y y + 1 ; move up one patch
    ]
  end


  to draw-line [ y line-color gap ]
    ; We use a temporary turtle to draw the line:
    ; - with a gap of zero, we get a continuous line;
    ; - with a gap greater than zero, we get a dashed line.
    create-turtles 1 [
      setxy (min-pxcor - 0.5) y
      hide-turtle
      set color line-color
      set heading 90 ; turtle move east
      repeat world-width [
        pen-up; do not draw
        forward gap
        pen-down; draw line
        forward (1 - gap)
      ]
      die; turtle dies after the procedure
    ]
  end
```

```
to-report number-of-lanes
  report 2; set the number of road lanes
end



to go
  increase-number-cars
  create-or-remove-cars

  ask turtles [ move-forward ]; the comand makes the turtles move
  ask turtles with [ patience <= 0 ] [ choose-new-lane ]; the car changes lane when its patience is less than or equal to zero
  ask turtles with [ ycor != target-lane ] [ move-to-target-lane ]; turtles not within the target lane should move to the target lane

  ; when car ride through bad road it will spend more money

  ask turtles [
    set user-cost (user-cost + random-float 1)
    ]



  ask turtles [ set budget (budget + budget-grow-rate)]

  ; PCR update
  if  ticks mod scale-PCR = 0 [
    if (PCR > 56) and (PCR-period = 1) [
      set PCR PCR - 1]

    if (PCR = 56) and (PCR-period  = 1) [
      set PCR-period 2
```

```
  set PCR 72
  ask turtles [
    set budget (budget - 50000 / count turtles)
    set user-cost user-cost * 0.8
  ]

]

if (PCR > 41) and (PCR-period  = 2) [
  set PCR PCR - 1]

if (PCR <= 41) and (PCR-period = 2)  [
  set PCR-period 3
  set PCR 60
  ask turtles [
    set budget (budget - 50000 / count turtles)
    set user-cost user-cost * 0.8
  ]

]

if (PCR > 26) and (PCR-period  = 3) [
  set PCR PCR - 1]

if (PCR <= 26) and (PCR-period = 3)  [
  set PCR-period 1
  set PCR 84
  ask turtles [
    set budget (budget - 100000 / count turtles)
    set user-cost user-cost * 0.64
  ]
```

```
    ]

  ]

  tick
  show timer

end



; this is for setup

to create-cars

; make sure we don't have too many cars for the room we have on the road
  let road-patches patches with [ member? pycor lanes ]; send commands to patches that contain the lanes only
  if number-of-cars > count road-patches [
    set number-of-cars random count road-patches
  ]; prevents the number of cars from being more than the road patches.

    create-turtles (number-of-cars - count turtles) [
    set color car-color
    move-to one-of free road-patches
    set target-lane pycor
    set heading 90; it indicates the direction of the turtles movement which is 90 degree from the true north
    set top-speed 0.35
    set speed 0.30 + random-float 0.1; it indicates the speed of the cars 35MPH (0.35) and varies by 5MPH (0.05)
    set patience random max-patience
```

```
    set user-cost user-cost + 0
  ]
end

; this is for go
to create-or-remove-cars
 ; make sure we don't have too many cars for the room we have on the road
  let road-patches patches with [ member? pycor lanes ]; send commands to patches that contain the lanes only
  if keep-number-cars > count road-patches [
    set keep-number-cars random count road-patches
  ]; prevents the number of cars from being more than the road patches.

  if count turtles < keep-number-cars [
    let n count patches with [ member? pycor lanes and
       pxcor = -50 and
      not any? turtles-here
    ]
    if n <= keep-number-cars - count turtles [
    create-turtles n [
    set color car-color
    move-to one-of free road-patches with [pxcor = -50]
    set target-lane pycor
```

```
    set heading 90; it indicates the direction of the turtles movement which is 90 degree from the true north
    set top-speed 0.35
    set speed 0.30 + random-float 0.1; it indicates the speed of the cars 35MPH (0.35) and varies by 5MPH (0.05)
    set patience random max-patience
    set user-cost user-cost + 0
  ]
  ]
  ]

  if count turtles >= keep-number-cars [
    let m count turtles - keep-number-cars
    if any? turtles with [xcor > 50][
      ifelse m >= count turtles with [xcor > 50] [
        ask turtles with [xcor > 50] [die]
      ][
        ask n-of m turtles with [xcor > 50] [die]
      ]
  ]
  ]
end


; increase the number of cars if automate is on

to increase-number-cars
  if automate [
  if random-float 1 < cars-increase-rate [
  set keep-number-cars keep-number-cars + 1
    ]
```

```
  ]
end


to move-forward ; turtle procedure
  set heading 90
    speed-up-car ; we tentatively speed up but might have to slow down
  let blocking-cars other turtles in-cone (1 + speed) 180 with [ y-distance <= 1 ]
  let blocking-car min-one-of blocking-cars [ distance myself ]
  if blocking-car != nobody [
    ; match the speed of the car ahead of you and then slow
    ; down so you are driving a bit slower than that car.
    set speed [ speed ] of blocking-car
    slow-down-car
  ]
  forward speed
end


to slow-down-car ; turtle procedure
  set speed (speed - deceleration)
  if speed < 0 [ set speed deceleration ]
  ; every time you hit the brakes, you lose a little patience
  set patience patience - 1
end


to speed-up-car ; turtle procedure
  set speed (speed + acceleration)
  if speed > top-speed [ set speed top-speed ]; the speed of the cars will not go over the speed limit
```

```
end


to choose-new-lane ; turtle procedure
  ; Choose a new lane among those with the minimum
  ; distance to your current lane (i.e., your ycor).
  let other-lanes remove ycor lanes
  if not empty? other-lanes [
    let min-dist min map [ y -> abs (y - ycor) ] other-lanes
    let closest-lanes filter [ y -> abs (y - ycor) = min-dist ] other-lanes
    set target-lane one-of closest-lanes
    set patience max-patience
  ]
end


to move-to-target-lane ; turtle procedure
  set heading ifelse-value (target-lane < ycor) [ 180 ] [ 0 ]
  let blocking-cars other turtles in-cone (1 + abs (ycor - target-lane)) 180 with [ x-distance
<= 1 and  x-distance > 0 ]
  let blocking-car min-one-of blocking-cars [ distance myself ]
  ifelse blocking-car = nobody [
    forward 0.2
    set ycor precision ycor 1 ; to avoid floating point errors
  ] [
    ; slow down if the car blocking us is in front, otherwise speed up
    ifelse towards blocking-car <= 180 [ slow-down-car ] [ speed-up-car ]
  ]
end
```

```
to reset
  ask turtles with [ budget > 50000 and budget < 70000 ] [set budget 1000]
  ask turtles with [user-cost >= 50] [set user-cost 0]
end


to-report car-color
  ; give all cars a blueish color, but still make them distinguishable
  report one-of [ blue cyan sky ] + 1.5 + random-float 1.0
end


to-report x-distance
  report distancexy [ xcor ] of myself ycor
end


to-report y-distance
  report distancexy xcor [ ycor ] of myself
end


to-report free [ road-patches ] ; turtle procedure
  let this-car self
  report road-patches with [
    not any? turtles-here with [ self != this-car ]
  ]
end
```

APPENDIX B. TRAFFIC DATA

Day 1 data	Indianapolis Blvd (US 41) Northbound			
Time	No. of Vehicles		Time	No. of Vehicles
6:00am- 6:15am	274		2:15pm- 2:30pm	350
6:15am- 6:30am	367		2:30pm-2:45pm	377
6:30am-6:45am	390		2:45pm-3:00pm	333
6:45am-7:00am	354		3:00pm- 3:15pm	394
7:00am- 7:15am	324		3:15pm- 3:30pm	397
7:15am- 7:30am	424		3:30pm-3:45pm	386
7:30am-7:45am	414		3:45pm-4:00pm	401
7:45am-8:00am	414		4:00pm- 4:15pm	364
8:00am- 8:15am	348		4:15pm- 4:30pm	435
8:15am- 8:30am	289		4:30pm-4:45pm	334
8:30am-8:45am	311		4:45pm-5:00pm	400
8:45am-9:00am	340		5:00pm- 5:15pm	390
9:00am- 9:15am	419		5:15pm- 5:30pm	386
9:15am- 9:30am	362		5:30pm-5:45pm	401
9:30am-9:45am	359		5:45pm-6:00pm	325
9:45am-10:00am	274		6:00pm- 6:15pm	363
10:00am- 10:15am	250		6:15pm- 6:30pm	349
10:15am- 10:30am	278		6:30pm-6:45pm	365
10:30am-10:45am	313		6:45pm-7:00pm	319
10:45am-11:00am	321			
11:00am- 11:15am	298			
11:15am- 11:30am	346			
11:30am-11:45am	327			
11:45am-12:00pm	350			
12:00pm- 12:15pm	390			
12:15pm- 12:30pm	344			
12:30pm-12:45pm	317			
12:45pm-1:00pm	424			
1:00pm- 1:15pm	388			
1:15pm- 1:30pm	414			
1:30pm-1:45pm	332			
1:45pm-2:00pm	370			

Day 2 data	Indianapolis Blvd (US 41) Northbound			
Time	No. of Vehicles		Time	No. of Vehicles
6:00am- 6:15am	247		3:45pm-4:00pm	320
6:15am- 6:30am	329		4:00pm- 4:15pm	350
6:30am-6:45am	388		4:15pm- 4:30pm	389
6:45am-7:00am	323		4:30pm-4:45pm	342
7:00am- 7:15am	363		4:45pm-5:00pm	418
7:15am- 7:30am	436		5:00pm- 5:15pm	349
7:30am-7:45am	400		5:15pm- 5:30pm	416
7:45am-8:00am	378		5:30pm-5:45pm	359
8:00am- 8:15am	367		5:45pm-6:00pm	388
8:15am- 8:30am	316		6:00pm- 6:15pm	368
8:30am-8:45am	301		6:15pm- 6:30pm	331
8:45am-9:00am	336		6:30pm-6:45pm	361
9:00am- 9:15am	288		6:45pm-7:00pm	315
9:15am- 9:30am	307			
9:30am-9:45am	256			
9:45am-10:00am	238			
10:00am- 10:15am	249			
10:15am- 10:30am	280			
10:30am-10:45am	275			
10:45am-11:00am	338			
11:00am- 11:15am	298			
11:15am- 11:30am	350			
11:30am-11:45am	301			
11:45am-12:00pm	359			
12:00pm- 12:15pm	347			
12:15pm- 12:30pm	330			
12:30pm-12:45pm	334			
12:45pm-1:00pm	374			
1:00pm- 1:15pm	347			
1:15pm- 1:30pm	441			
1:30pm-1:45pm	328			
1:45pm-2:00pm	383			
2:00pm- 2:15pm	348			
2:15pm- 2:30pm	363			
2:30pm-2:45pm	381			
2:45pm-3:00pm	326			
3:00pm- 3:15pm	401			
3:15pm- 3:30pm	314			
3:30pm-3:45pm	368			

Average data	Indianapolis Blvd (US 41) Northbound			
Time	No. of Vehicles		Time	No. of Vehicles
6:00am- 6:15am	261		3:45pm-4:00pm	361
6:15am- 6:30am	348		4:00pm- 4:15pm	357
6:30am-6:45am	389		4:15pm- 4:30pm	412
6:45am-7:00am	339		4:30pm-4:45pm	338
7:00am- 7:15am	344		4:45pm-5:00pm	409
7:15am- 7:30am	430		5:00pm- 5:15pm	370
7:30am-7:45am	407		5:15pm- 5:30pm	401
7:45am-8:00am	396		5:30pm-5:45pm	380
8:00am- 8:15am	358		5:45pm-6:00pm	357
8:15am- 8:30am	303		6:00pm- 6:15pm	366
8:30am-8:45am	306		6:15pm- 6:30pm	340
8:45am-9:00am	338		6:30pm-6:45pm	363
9:00am- 9:15am	354		6:45pm-7:00pm	317
9:15am- 9:30am	335			
9:30am-9:45am	308			
9:45am-10:00am	256			
10:00am- 10:15am	250			
10:15am- 10:30am	279			
10:30am-10:45am	294			
10:45am-11:00am	330			
11:00am- 11:15am	298			
11:15am- 11:30am	348			
11:30am-11:45am	314			
11:45am-12:00pm	355			
12:00pm- 12:15pm	369			
12:15pm- 12:30pm	337			
12:30pm-12:45pm	326			
12:45pm-1:00pm	399			
1:00pm- 1:15pm	368			
1:15pm- 1:30pm	428			
1:30pm-1:45pm	330			
1:45pm-2:00pm	377			
2:00pm- 2:15pm	362			
2:15pm- 2:30pm	357			
2:30pm-2:45pm	379			
2:45pm-3:00pm	330			
3:00pm- 3:15pm	398			
3:15pm- 3:30pm	356			
3:30pm-3:45pm	377			

APPENDIX C. SIMULATION DATA

Years	PCR	Cost		Years	PCR	Cost
1	81	2.335416		39	62	60.54581
2	78	4.558722		40	59	63.04677
3	75	7.051202		41	71	52.46153
4	72	9.565142		42	68	54.94425
5	69	12.05775		43	65	57.45405
6	66	14.56908		44	63	59.93499
7	63	17.0537		45	60	62.41179
8	60	19.58746		46	57	64.89114
9	58	22.10022		47	54	67.39114
10	70	19.99314		48	51	69.90309
11	67	22.50609		49	48	72.37384
12	64	25.01598		50	45	74.84183
13	61	27.50351		51	42	77.36562
14	58	30.00063		52	58	64.23744
15	55	32.49868		53	55	66.72784
16	52	35.03409		54	52	69.25122
17	49	37.58586		55	49	71.74174
18	47	40.09278		56	46	74.25569
19	44	42.59017		57	43	76.75766
20	59	36.15227		58	40	79.24804
21	56	38.64631		59	37	81.72021
22	53	41.15294		60	34	84.25778
23	50	43.68277		61	32	86.73581
24	47	46.17834		62	29	89.22886
25	44	48.68342		63	84	58.92955
26	42	51.17082		64	81	61.43244
27	39	53.67275		65	78	63.94488
28	36	56.15301				
29	33	58.6224				
30	30	61.12897				
31	27	63.61774				
32	82	43.05203				
33	79	45.53448				
34	76	48.031				
35	74	50.5399				
36	71	53.0362				
37	68	55.57801				
38	65	58.04711				

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