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**Evaluating the Effectiveness of a Traffic Signal Control Agent Using Reinforcement Machine Learning**

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1. Abstract

Contents

[1 Introduction 4](#_Toc512308016)

[2 Motivation 6](#_Toc512308017)

[3 Related Work 7](#_Toc512308018)

[4 Description 8](#_Toc512308019)

[5 Methodology 9](#_Toc512308020)

[5.1 Overview 9](#_Toc512308021)

[5.2 Simulation 9](#_Toc512308022)

[5.3 Algorithm Development 10](#_Toc512308023)

[5.4 Algorithm Application 10](#_Toc512308024)

[6 Design 11](#_Toc512308025)

[6.1 Simulation 11](#_Toc512308026)

[6.1.1 Block Objects 12](#_Toc512308027)

[6.1.2 Traffic Light Objects 12](#_Toc512308028)

[6.1.3 Vehicle Objects 13](#_Toc512308029)

[6.1.4 Wait Times 14](#_Toc512308030)

[6.2 Algorithm 14](#_Toc512308031)

[6.2.1 Proportion Variable 14](#_Toc512308032)

[6.2.2 Red Counting 14](#_Toc512308033)

[6.2.3 Machine Learning Algorithm 15](#_Toc512308034)

[7 Implementation 16](#_Toc512308035)

[7.1 Simulation 16](#_Toc512308036)

[7.1.1 Object Generation 16](#_Toc512308037)

[7.1.2 Draw Times 16](#_Toc512308038)

[7.2 Algorithm 17](#_Toc512308039)

[7.2.1 Proportion Variable 17](#_Toc512308040)

[7.2.2 Red Counting 18](#_Toc512308041)

[7.2.3 Machine Learning Algorithm 18](#_Toc512308042)

[8 Evaluation 19](#_Toc512308043)

[8.1 Testing 19](#_Toc512308044)

[8.1.1 Without Algorithm 19](#_Toc512308045)

[8.1.2 With Algorithm 19](#_Toc512308046)

[8.2 Performance Evaluation 21](#_Toc512308047)

[8.3 Expert Evaluation 22](#_Toc512308048)

[9 Acknowledgements 23](#_Toc512308049)

[10 Bibliography 24](#_Toc512308050)

# 1 Introduction

This project is an experiment into the application of a reinforcement machine learning algorithm on a custom-made simulator. It utilises a C++ framework provided by Jason Atkin of the University of Nottingham Computer Science department and relies on feedback of the proposed algorithm by Mike Hu of Nottingham City Council Traffic Signal Management.

The aim of this project is to develop a model of a set of traffic lights and evaluate how implementing an algorithm using deep reinforcement learning to alter the traffic signal control will affect the average length of journey time for vehicles travelling through the set crossroads.

The key objectives are:

1. To investigate traffic light sequences around the world that apply to junctions of different shapes and sizes.
2. To investigate the feasibility of utilising an already existing traffic simulator or whether it would be more appropriate to implement self-built simulator. If an existing simulator does not include the desired libraries or procedures then a self-built one might be necessary.
3. To construct a grid model representing an abstract pattern of roads and junctions. This model will depict variations of junctions and road types to present the effect a machine learning algorithm could have on the system as a whole. The model will include agents representing vehicles
4. To design an algorithm using reinforcement learning that will dynamically adjust to the conditions of traffic or the type of junction present. This algorithm will take the existing state of a single junction sequence and make increments to improve the wait times at that junction. It will accomplish this by continuingly using trial and error and measuring the results against the previous state. Learning from past experiences the algorithm will know not to try a certain path if that has been proven to be inappropriate. I expect that although the wait times will decrease at this location they could drastically increase elsewhere due to build up.
5. Apply the algorithm to every junction, making alterations based on junction type, and combine the results to try and obtain and overall better average wait time. The algorithm will require fine tuning to find it’s optimal result. As this system is being tested in an abstract simulator it is not expected to have to deal with lots of categorical data. However, it may be necessary to implement an already existing algorithm to handle any conversion type errors that occur. In this instance the Catboost algorithm by Yandex |1| could be appropriate as it automatically deals with category related problems thus permitting more focus on the actual fine tuning. A potential issue exists where the algorithm improves Junction A which directly deteriorates Junction B. Junction B then tries to improve itself yet regresses Junction A and so a mathematical tug-of-war occurs for optimisation. A possible fix would be to calculate the overall effectiveness of the two junctions at any one point and quantify this in a variable. This variable will be influenced by the priority of the junctions, e.g. one is on busier road, and a potential number of other factors which will contribute to the overall value. This means that although the improvement of Junction A deteriorates the quality of Junction B, Junction B won’t resist as the global efficiency has increased.
6. Evaluate the feasibility of the algorithm being applied to the real world by contacting Nottingham City Council – Highways and Energy Infrastructure |2|. The method of this would be to enquire if they are aware of any such system already in place and evaluate the potential of the new system. It is expected that they will provide feedback which can be actioned and developed upon.
7. If approval is met, then proceed with publishing findings and make note of the success of the algorithm. However if the feedback is negative then ensure that explanations are made to as to why. For example if the suggested fault was in the lack of consideration in the algorithm regarding weather or road works then comment about how a future project might utilise and benefit from such a feature.

# 2 Motivation

The average person in the UK spends up to 8 minutes a day stuck in traffic |3|. That’s 2 days in a year and 130 days in the mean life expectancy |4|. It may not sound insignificant but that’s over a third of a year doing nothing productive in your life. Traffic can be stressful especially when already in a tough working environment. It is therefore essential that this time is somehow cut down and the total time spent in traffic reduced.

## 2.1 Fixed Sequence

At crossroads in urban environments a fixed time light sequence is commonly implemented as it helps to ease congestion and distribute fair green light time to each avenue approaching the crossroads |5|. This can be a practical solution during rush hour but in times when the frequency of road traffic is heavily reduced this can be a burden upon drivers who are required to halt even though there is little traffic around. A significant positive of the current system is that it is predictable. A local citizen who is setting off on a journey would know that the time they’ll spend at a traffic light is going to be the same assuming similar traffic frequency. This comfort may need to be sacrificed to improve the wait efficiency for everyone at a crossroads.

## 2.2 Automated Sequences

In certain areas where traffic data is readily available to use there may be the installation of an automated traffic light sequence. The council interviewee gave a good insight into what kind of systems are used in this scenario.

“There are two major types of automated adaptive control for traffic signals that we use in the UK. One is called the SCOOT system and one is called MOVA. SCOOT is an acronym for Split Cycle Offset Optimisation Technique and it is based on a software algorithm. And it optimises certain aspects of traffic signal timings. The timings can be split down into certain aspects of it. If you look at the split like a pie: how much of the traffic gets this portion of the pie and how much traffic gets this much portion of the time and much gets a different portion. So if you have a four arm junction, this arm gets this much green in the cycle, the next arm will get this much green in the cycle, the next arm will get so much and so on. So that’s what we called the split. The cycle is what we call the cycle time. So that could be a bigger pie or a smaller pie. So it might take longer or shorter to get round to the same arm on the junction. The offset is a different junction down the road – how the changes to the current junction are offset to the next to make for a progression along a corridor. So for these kind of optimisation techniques you put detectors in the road which detect a congestion practice. It’s done through inductive loops in the road, basically a coil cable that goes into the road surface and it detects metal vehicles going over. So it builds up a picture of what the traffic condition is and it uses an algorithm to optimise these particular aspects of a region. So for example with the split there may a lot of northbound traffic so I’m going to give that more green time than the other arms of the junctions. Or it might be a busy period and a more efficient use for the time I’ve got I can increase the cycle time and make the proportions bigger so that’s a more efficient use of that time. Or you might say down the road there’s empty space and therefore I should optimise that offset and sort of say “This traffic that I’m letting through, when it gets to the next junction I should start letting traffic through there as well”. So it is an algorithm but it doesn’t learn, apart from the way the data is generated. The data is generated in real time because as traffic conditions are changing the data that is being collected is changing to suit that and then the algorithm will adjust itself based on the real time data.”

* Mike Hu, Nottingham City Council, Department of Traffic Signal Management

## 2.3 Machine Learning

Traffic light systems using machine learning have been suggested previously in various iterations and most of them try to develop an algorithm that optimises a single junction rather than a grid model |6|. They don’t consider the wider impact of altering the sequence at one junction, as this may have a knock-on effect that disrupts traffic at many other surrounding junctions and thus results in a more inefficient system overall. The program that is desired would be one that can operate in a wider-spanning model and determine the most optimal algorithm for that whole area.

If a system can be created which dynamically adjusts to the intensity of traffic, then perhaps a lot of issues regarding effectiveness can be eliminated. It may introduce fresh problems like individual wait time increasing however, as it may benefit others, there is good reason to believe it will be an overall improvement.

# 3 Related Work

There already exist projects and research in~~to~~ improving a traffic light system at a localised junction. An example would be a paper by W.Genders *et al |*6| that implements a deep reinforcement learning agent for traffic signal control. They accomplish this by providing the agent access to three states, current state, an action state and a reward state. The agent observes the current situation and variables then analyses the various paths that could be taken. Upon making a decision, the agent receives a reward which indicates the effectiveness of the decision made. With each iteration the agent will be pursuing a higher reward and so will be constantly trying to improve its efficiency. The best thing about this proposal is that it suggests a relatively simple method in making the agent more efficient. It is, however, somewhat localised and can’t be easily adapted to other classifications of junction nor does it consider the impact to its neighbours.

In another paper, titled Adaptive Traffic Signal Control: Deep Reinforcement Learning Algorithm with Experience Replay and Target Network, the objective is to develop a complex and comprehensive agent that optimises a much larger junction with more external input. Authored by J.Gao *et al |*7|, it proposes that a deep reinforcement learning algorithm can automatically extract all features useful for traffic signal controls and optimise the policy based on them. The most important thing about this project is in its complexity, where the solution is developed with a 4 lane crossroads taken into consideration. This makes the mathematics and the computing behind the agent a lot more complicated yet yields greater results when applied correctly. Similarly to the previous example though is the fact that this agent only attempts to improve the congestion at a single junction, there is no consideration of the wider impact such a policy might have.

The importance of my project is that it intends to look at a wider scope than most other traffic light agents. Where other projects are designed to improve the efficiency of traffic flow at one junction, my agent will optimise the traffic flow at all surrounding junctions as well. This means that one junction may suffer from worse traffic congestion if it results in the improvement of several others. The product of this agent could be a more realistic algorithm developed that could be applied universally and make tangible change to the efficiency of urban infrastructure.

# 4 Description

The desired outcome of my project is to deliver an agent based learning algorithm to an abstract simulation and see significant reduction in traffic congestion times. The premise is to apply the algorithm to a simulated junction and then implement it across a custom-built road grid. This will hopefully adapt to the simulated environment and improve itself until an optimised solution can be found across all junctions. It may be the case that some junctions have an increase in congestion times, but this can be acceptable if it results in the improvement of others.

## 4.1 Simulation

The simulation is intended to represent an abstract view of a set of junctions. Vehicles created within the system will maintain correct position and appropriate interaction with other objects in the system. Traffic light objects will commit to a continuous cycle that allocates a proportionate amount of green and red light time dependant on the weight of congestion.

# 5 Methodology

## 5.1 Overview

The process of development for this project is in a three-part schedule. The foundation of the project is the simulation of the traffic light sequence. This model will allow me to construct junctions and mobile vehicles that interact with the environment and obey a predefined law of traffic signals. The second sequence of this project will be the deep reinforcement learning algorithm that will initially be applied to a single junction. The third section of the project will be inclusive of adjustment and optimisation. This involves the implementation of the algorithm across multiple junctions and the subsequent fine tuning of the algorithm to create the best results in the model. This stage will also require external feedback to assess the feasibility of the proposed system and then to action that response. Instead of working on each section in parallel I have elected to implement them in sequence, this will allow me to concentrate on each section individually and prevent disruptions to the work of other tasks if one section goes awry or requires further adjustment.

## 5.2 Simulation

The key part of developing the model is to recognise that it is not the focus point of the project. The purpose of my project is not to build a functional traffic simulator but to develop an algorithm that can use input data to modify itself to improve the results of the system it acts upon. Therefore my priority when researching and analysing different techniques of building a traffic light simulation was in ease of use and effectiveness. My options when it came to building a model were to utilise an already existing simulation program or to construct my own from scratch. Although existing simulators would save me the effort of having to design my own program they are overcomplicated. A popular traffic simulation program, Sumo, provides a lot of the basic functions that are required for effectively creating my algorithm. However, the program is also accompanied by a lot of unnecessary additions, such as pedestrian and cyclist inclusion. These extensions would be useful if more emphasis was placed on the model yet as the model is acceptable and preferable when simple, I believe that choosing this existing program would be inefficient for building the necessary model. Thus I investigated the feasibility of creating my own program using a language of my choice. There will be multiple entities that interact with each other suggesting the use of an object oriented programming language. This language will also have to be adept at handling mathematical inputs and processes so will need to have good processing power. I viewed Python as a potential candidate for my program yet I found that its IDLE framework was clumsy to use and I was inexperienced in its use. Any time spent learning the mechanisms of Python and its coding conventions would have been time that could be used more productively elsewhere. Conclusively I decided that Python would be an unsuitable programming language. As an alternative I turned to C++. Although the programming required would be arguably more complex than what Python demanded, I was already familiar with the language, having utilised it as part of a second year project to design a game. In order to give myself and my peers a boost in this language, we were provided a framework by the module convenor, Jason Atkin, as well as imports of various useful libraries like SDL – a crucial C++ library for implementing graphics. Initially I endeavoured to implement the libraries myself and build my own framework. I quickly learned that this was a meticulous and long process and wasted many hours attempting what had already been done by my module convenor. Therefore I abandoned my efforts and sought a quicker route to acquiring a framework for my simulator via Jason. Permission was acquired for the use of his framework through a personal enquiry and email correspondence. As a result of this the programming language that I wished to use for the construction of my model had been appropriately selected and provided a platform from which to build a model suitable for my ambitions.

## 5.3 Algorithm Development

Due to the structure of my development cycle I have yet to begin comprehensive research of how I’m going to develop an algorithm. Despite this, I have taken note of the existing methods of algorithm production. The paper by W.Genders (Genders & Razavi, 2016) details their idea for including a state system within their algorithm that the agent can act upon. By introducing a reward to the agent depending on which direction was taken, the algorithm encourages the agent to constantly seek improvements and become more efficient. I am intent on implementing my own algorithm with inspiration from this process as it provides a solid foundation that can be easily adapted and built upon. In spite of this basic research there is much more that demands investigation, such as how the agent will choose a path without extensive trial and error, thus saving time and providing consistent efficiency. There will also need to be a study into how the algorithm determines the efficiency of all the incoming lanes collectively at the junction. It is not yet clear how the algorithm will decide if the small congestion reduction at two of the lanes is worth a larger increase in congestion of just one.

## 5.4 Algorithm Application

Similarly to the algorithm development, the algorithm application is yet to be analysed and meticulously planned. Once again this is due to the priority of the sections of the project. The first section, the construction of the model, is incomplete and until it becomes clear it makes planning the third section abstract conjecture and subject to much change. Outlining any design is made more difficult by the fact that I have located no existing examples of this stage being attempted before. Therefore the results of my plan become impossible to predict and prevent me from analysing alternative ideas.

# 6 Design

## 6.1 Simulation

When considering how the algorithm would be best applied to a set of traffic lights I concluded that a completely abstract model would be the most appropriate. This is due to the lack of unpredictable behaviour in an abstract scenario. There are no external factors like weather or roadworks to consider as the model is purely hypothetical. Whilst it won’t display the effectiveness of the algorithm in a real world setting, the model can demonstrate the knock-on effect that a revised traffic signal control mechanism might have on surrounding junctions and traffic. It also eliminates unique features in the roadway such as roundabouts and five or more lane junctions. Whilst these occur in the real world they would interfere with the development of the algorithm and increase the complexity of the model beyond feasibility. Therefore I designed a system that contained two four-arm crossroads with two perpendicular branch roads.

**NW**

**SW**

**S**

**SE**

**NE**

**N**

**NW**

**NS**

**NE**

**NN**

**SW**

**SS**

**SE**

**SN**

*Figure 6.1.A*

The primary advantage of the design proposed is in its simplicity. The roads that remain consistently at right angles to each provide a good foundation on which to build mathematical equations for the physics of any vehicles in motion. The duplicity of the two types of junction allows for repetition of coding thus streamlining the development of the model.



*Figure 6.1.B*

### 6.1.1 Block Objects

When designing this simulator I initially looked at how to create the background and infrastructure of the system. These provide constant templates and fixed locations for the adaptive objects to interact with.

At the most basic level the background its self is set to a shade of medium grey to reflect buildings or other such impassable terrain that may be found in real life. This is constant shade and will not be changed during run time.

At the next level is the creation of the roads. These will be comprised of black rectangles placed in the pattern shown in figure 6.1.A, with one road running vertically lengthways in the simulator to represent an arterial road. The other two roads will be set at equidistant locations, bisecting the arterial road and thus acting as branches onto the artery.

Through each of these road blocks is a thinner white block that represents the road markings one would find to distinguish the boundaries of each lane. The colour is set to white as this is the most commonly used line colour used from the standard road markings listed in The Highway Code |8|

### 6.1.2 Traffic Light Objects

An essential part of the simulator is the system of traffic lights. Each one is responsible for ensuring that traffic flow is regulated yet allowed to pass through without too much delay.

Similarly to the block objects, the traffic light objects are initialised as rectangles at the end of each lane. This means that when a vehicle reaches the end of its respective lane it must past through the traffic light object in order to progress. The colour of the light is initially set based on an internally attributed green variable which determines the whether the light is green or not. If this green variable is changed throughout the run time of the simulator then the colour of the traffic light will also change to reflect that.

In order to create a basic sequence for the traffic light within the simulator there is a simple algorithm constructed. Utilising a variable that increments with each time step, the algorithm acquires the modulus of this time variable by dividing by 400 and returning the remainder to a modulus variable. This results in the modulus variable constantly incrementing until 399 then resetting back to 0, thus creating a light cycle for each traffic light. The value of 400 was chosen because it is an easily manipulated number and will provide ease of use in implementation. In reality the number could be any sufficiently high yet this is the one I chose. Next in the sequence, in a conditional statement, the modulus variable is compared with a threshold value. If the modulus variable is less than this threshold value then the green variable will be allocated to be one of true or false, depending on the location of the traffic light object. If the modulus variable is greater than this threshold variable then the green variable is set to the opposite. Thus the altered green variable will determine the colour of the traffic light at each timestep.

### 6.1.3 Vehicle Objects

The vehicle objects are the catalyst that instigate change within the simulator. When they interact with surrounding objects they can demonstrate patterns that emerge ibn the system as well as show how changes to the traffic light sequence might impact the flow of traffic.

The vehicle object is designed to be easily identifiable and simple to track. Each one is set at a bright orange colour that stands out from the drab background and can’t get mixed up with the traffic light objects. Their size is slightly smaller than the width of a lane so that it is clear what section of the simulator they occupy. In addition, they are in a circular shape so as to reduce difficulties with identification when pressed together with other objects.

The idea for the vehicles is that they enter the simulator at different rates. So, in the example of the South vehicle object type, 30 vehicles may be spawned yet they will enter the simulator in a staggered pattern in an attempt to mimic reality. This staggering is also generated randomly to further emulate the potential randomness of normal life. Once in the simulator each object will be locked into a lane section – the parameters of which are determined manually. This means that if the top left x and y coordinates are within a lane area then they follow the movement rules for that area. So for example if the vehicle is in the South Left lane then they are instructed to change their coordinates at rate of 2 pixels per time step, thus creating a movement mechanic in the system. If the vehicle then migrates to a different lane area the instructions it receives may be different and thus the direction the vehicle moves in might change.

Upon entering a junction, the vehicle will shift into a void space where no lane area has control. In this void space the vehicle will randomly determine the direction it will take. Each time the vehicle reaches this position is generates a direction variable which is set to a random number between 1 and 100. Then, using conditional statements, the vehicle can determine a direction depending in what margin the direction variable lies. If the direction variable is less than 45 for example, then the South vehicle will shift its y position by -1. This will move it into the middle left lane as the shift has placed it within that lane area. Thus, new commands are issued to the vehicle and the movement cycle will commence again.

Upon making contact with a traffic light object the vehicle will assess what colour the light is set to be. If the traffic light colour is determined to be red, then the vehicle will enact the procedure required to halt its movement. Only once it detects the traffic light changing to green will it continue along its path.

### 6.1.4 Wait Times

To keep track of the changes made to the system and to act as a metric by which the effectiveness of the system is measured the average wait times of all vehicles will be recorded.

First of all, a universal variable will be added to each vehicle which increments with each time step. If the vehicle leaves the visible range of the simulator then this variable is reset to zero to reflect the vehicle having reached its destination. This variable is then extracted by the engine of the simulator and added to another variable that counts the total wait time of all vehicles of that specific vehicle type. This sum is then divided by the number of vehicles in the system of that type to produce an average waiting time which is then output in the display on the simulator screen. The output is done to provide a visual representation of the effects that the traffic light sequences might have on their respective vehicles. This process is repeated for every vehicle type.

Further to this, an average total wait for the entire system is generated using the same initial method yet getting the sum of the respective wait times for all vehicle types which is then divided by the total quantity of vehicles in the system. The value produced by this is then output into the simulator to be used as the metric of success of any sequence algorithms applied to the traffic lights. As the purpose of the project is to evaluate the potential improvement a reinforcement machine learning algorithm might have on the entire system, this output value is the most important of all.

Finally, to add a marker at which data can be consistently taken, a simple timer will be implemented that counts, in seconds, the time passed since the running of the simulator began.

## 6.2 Algorithm

Due to the impact that a machine learning algorithm would need to have on the system, I decided that it would be placed within the engine of the simulator. This is beneficial because it provides easier access to many of the fundamental and core members and methods that might be in the code. It is also the most efficient place for it to be written as it can directly impact all of the traffic light objects simultaneously.

### 6.2.1 Proportion Variable

As a preliminary to the algorithm the instructions that are given to the traffic light objects needed to be altered slightly. Instead of just setting a constant value that acts as a threshold for the modulus of the time, a dynamic variable needed to be implemented as this is the key to altering how the sequence of the light signals can change. Each traffic light objects extracts a proportion value from the engine depending at what junction they are located. This means that the proportion value can be altered and tinkered with from inside the engine and the changes made will pass on through automatically to the traffic light object.

### 6.2.2 Red Counting

The Red Counting function acts as an auxiliary part of the machine learning algorithm. This is a function that produces values required for the main algorithm to make suitable improvements.

It accomplishes this by first introducing red variables to every vehicle object for each potential traffic light they may encounter. Within the vehicle collision method these variables are set to be true respective to what traffic like they are stuck on red at. So if a South vehicle was waiting at the South South traffic light then the red variable for South South will be true. Once the light turns green and the vehicle is released the respective red variable is set to false.

Back in the Red Counting function within the simulator engine a red counter variable is initialised for each traffic light. The function then loops through every vehicle object in the system and at each one determines if it is in contact with the specified traffic light. For every one that is, the red counting variable for that traffic light is incremented by one so by the end of the loop the total number of vehicles stopped at the traffic light whilst it is on red is known.

### 6.2.3 Machine Learning Algorithm

The machine learning algorithm is applied to only one junction at a time and all changes made will only impact that specific junction. The result of this algorithm is hopefully a more optimised proportion value that can be provided to the traffic light objects at both this junction. This means that every time the machine learning algorithm runs it must return an integer proportion variable.

The premise of this algorithm is that a reward is provided to the algorithm if the results it produces move it in the direction of a more optimised solution. By comparing the total average wait time from the last timestep to the one produced most recently by the learning algorithm it is possible to detect whether there has been improvement, worsening or no change. If the total average wait time has been improved, then a reward is issued. The reward comes in the form of not changing the current proportion variable thus continually moving the ideal position of the modulus threshold in the same direction. The basic formula of the learning algorithm is to say that if the total average wait time is moving in the direction of a more optimised solution then continue with the same proportion value.

If a reward is not issued to the algorithm, then the algorithm is punished. It must attempt to generate a new proportion value until the average wait time begins to improve. It accomplishes this by using the variables for each traffic light produced by the red counting function. The red counting variables for both the traffic lights in the x axis are added together to produce a total weight pushing upon the lights in the x axis. The same is done with the traffic lights in the y axis. The total weights of the axes are compared with each other and the procedure following depends on the result.

If the combined weight on the y axis is greater than that on the x axis, then the difference between the two is calculated. A multiplier variable of 1 is then adjusted by subtracting the difference in weights multiplied by 0.01. The 0.01 value is decimal selected because it allows changes made to the proportion to be significant enough to be noticed but not too large that an optimal position may be overshot. The current proportion value is then multiplied by the multiplier variable thus creating a new proportion that will be slightly less than the one from the previous time step. Once passed to the traffic light objects this new proportion value will be used to then assign more green, light time to vehicles in the y plane and reduce the green light time to vehicles in the x plane.

If the combined weight on the x axis is greater than that on the y axis, then the difference between the two is calculated. A multiplier variable of 1 is then adjusted by adding the difference in weights multiplied by 0.01. The current proportion value is then multiplied by the multiplier variable thus creating a new proportion that will be slightly more than the one from the previous timestep. Once passed to the traffic light objects this new proportion value will be used to then assign more green light time to vehicles in the x plane and reduce the green light time to vehicles in the y plane.

# 7 Implementation

## 7.1 Simulation

The development process for the simulator followed the design ideas astutely. There were a few intended ideas that were not as practical as predicted and therefore were altered.

After careful analysis in the preliminary research stages it was decided that C++ would be the most suitable language. C++ is a compile language meaning that it must be compiled before run. This prompted me to investigate the potential of an IDE like Visual Studio: a platform which would be more than adequate for the task required. The code built upon the foundational framework provided by Jason Atkin and offered the necessary functions and classes that would allow the construction of the simulator.

### 7.1.1 Object Generation

The main engine, TrafficLightEngine, which was implemented in my program was responsible for the generation of all objects and simulator-wide algorithms applied to the system. Within the engine, the function Initialise Objects controlled the methods that allowed the objects in the code to be displayed and interactive. This function first added all of the stationary objects, the block objects and traffic light objects, to an object array that ensured that objects within would be created and visualised.

For the manoeuvrable objects the Initialise Objects function went through each type of vehicle object and added a specified quantity of them using a spawn function. Each vehicle type had a corresponding spawn function built within the engine that first randomised a variable to be that specific objects start position. The start position would then be passed to the vehicle object to be stored in the array. Off screen the vehicles would be placed and would each manoeuvre at the same speed towards their entry point in the simulator. This would create the effect of a staggered entrance for vehicle and, coupled with the randomised positioning, would make the entrance of the vehicles and the spacing between them feel far more natural. The randomised range of the start positions would change depending on what “time of day” it is – a variable that determines the intensity of traffic from certain directions.

#### 7.1.1.1 Problems Encountered

There were a few problems that I discovered upon implementing the simulator and they range in cause and effect. The first problem I encountered was more to do with my understanding of the framework. I had an issue where I was unable to reliably call variables between classes. This was a result of changes I made to the format of the code not being reciprocated within the framework. There was a significant time delay in development whilst I endeavoured to correct this issue and move forward. I was able to fix the problem with the assistance of Jason Atkin, the developer of the framework, who informed me of what I needed to do to in order to resolve the issue.

#### 7.1.1.2 Changes Made

As a result of the issues I faced with the passing of variables between classes, I changed my plan from trying to alter the framework of the system to instead changing my methodology. This involved the strict references each class must make toward the main engine class. The classes switched their inheritance from the BaseEngine class of the framework to instead inheriting from the subclass of BaseEngine – my main class, TrafficLightEngine. This allowed me to directly called variables from the TrafficLightEngine class itself, rather than taking a longer route through BaseEngine.

### 7.1.2 Draw Times

Before creating any string objects I had to import several public C++ libraries into the TrafficLightEngine class: sstream, string and time.h. These libraries gave me the methods that I would need to deal with string conversions and time counting. The commitment to the design described in the previous chapter was fulfilled for the most part. Each vehicle type average wait time values were obtained in the anticipated fashion. These were then printed out alongside an applicable statement to produce the average wait time of all vehicles from that type.

The total wait time average initially went as expected where the total value was simply the sum of all vehicle wait times divided by the quantity of vehicles in the system. An issue occurred though where the value printed on screen did not demonstrate the way that the total average wait time should change over large periods of time.

The printing of the time counter progressed smoothly and produced the desired outcome of a value that increments in seconds. This was then displayed in the simulator to be observed and noted when collecting data.

#### 7.1.2.1 Problems Encountered

Although relatively trivial, an issue I had with the average wait times for each vehicle type was that the final value produced could not be printed due to it being an integer variable.

The problem with the total average wait time was that it’s produced value was two large and erratic to accurately record data as well as it polarising results depending on the number of vehicles on screen at any time.

#### 7.1.2.2 Changes Made

The integer value produced by the average wait times for each vehicle type was converted into a string by utilising the string related libraries. This new string variable was subsequently passed into the output function and printed.

To improve the result of the total average wait time I placed every value I generated into an array of 10000 size. Any empty positions would be filled with the most recent value acquired. A sum of all values in the array would be created and then the average of that sum would be found. This would present a total average time value that increases or decreases at a slower rate as well as eliminating the erraticism of the output, thus allowing simpler analysis of the data produced and making it easier to identify trends of that output value. After this is done the array filled with total average wait times would be shifted so that the oldest entry is removed and space is made for fresh input.

## 7.2 Algorithm

For the development of the algorithm I had to make some changes to the way that it could be written as well as the features it might contain. As a key part of the development this stage took a large amount of time to write and demanded a lot of my attention.

### 7.2.1 Proportion Variable

Like described in the design section the proportion variable was implemented with ease into the traffic light objects. They adapted fine to being passed a variable rather than a set constant.

#### 7.2.1.1 Problems Encountered

A bizarre issue encountered with the proportion variable was the production of a flicker from the traffic lights when the change colour. This typically occurs when a new green or red cycle commences and is sometimes followed by a rapid change back to the previous colour then back to the new colour. I discovered that the reason for this is when the proportion variable is increased or decreased and the modulus counter is already close to the current threshold. The proportion value would ‘leap’ above and below the modulus counter as new proportion values are generated. This results in the conditional threshold for red/green light shifting erratically. As a result so do does the colour of the traffic light as it is being given orders to change colour every few time steps. Fortunately this effect does not last for too long as the modulus variable out paces the rate of change of the proportion value.

### 7.2.2 Red Counting

Fortunately I found zero issues with the creation of the Red Counting function as the code that operates within it is quite simple to produce.

### 7.2.3 Machine Learning Algorithm

#### 7.2.3.1 Problems Encountered

Despite being a key tenant of machine learning I found that neural networks were too cumbersome to be implemented into the learning algorithm. They involved too many parameters and were overly complicated for the objective that the algorithm needed to achieve.

#### 7.2.3.2 Changes Made

To maximise the efficiency that the algorithm had on the system I removed the prospect of including a neural network within the procedure. The algorithm would instead rely on conditionals and a rewards system that encourages the algorithm to generate a proportion variable that keeps it moving in the right direction towards to an optimal solution.

# 8 Evaluation

## 8.1 Testing

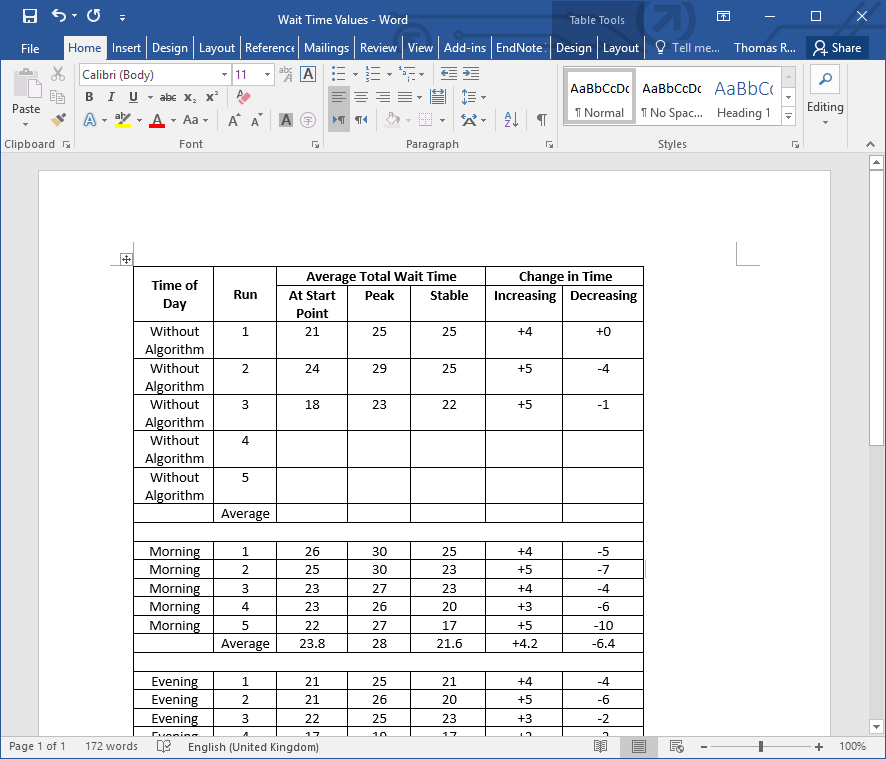
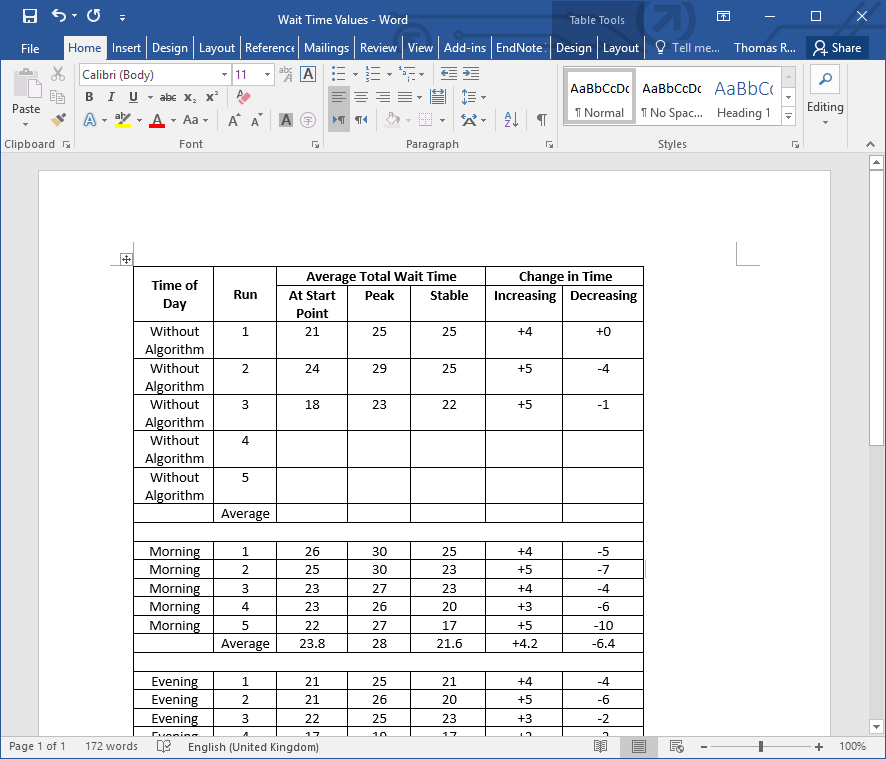
Testing the efficiency of my algorithm involved making runs in different environments hard coded into the program. In the constructor of the TrafficLightEngine class I set a time of day variable which dictates the intensity of traffic in specific areas. If the time of day is morning then the variable is set to be 1. If the time of day is evening then the variable is set to be 2. If the time of day is midday then the variable is set to be 3. Each of these settings indicate how traffic would behave typically in such environment. The variable is used by the spawn vehicle function to generate a certain spawn location for each vehicle. If the variable is 1, for morning, then the randomisation range for the spawn is set at a mere 3000 pixels. This means that although there are an equal number of South and North vehicles generated in their locations, the rate at which the South vehicles enter the simulator will be much greater. The spacing between the vehicles will be largely reduced in comparison and the time for a vehicle, after leaving the screen, to return to the simulator will also be much lower.

### 8.1.1 Without Algorithm

### 8.1.2 With Algorithm

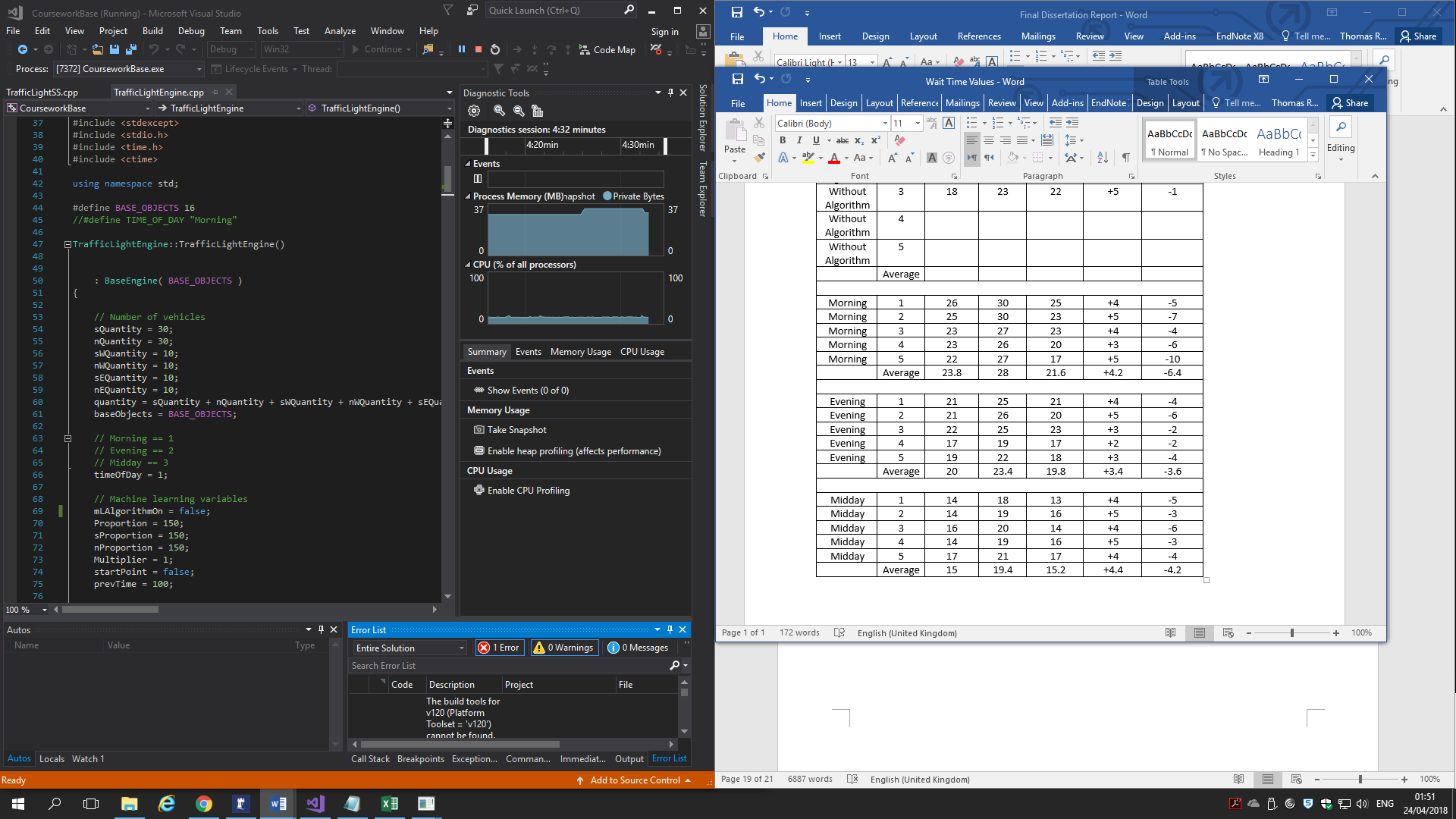
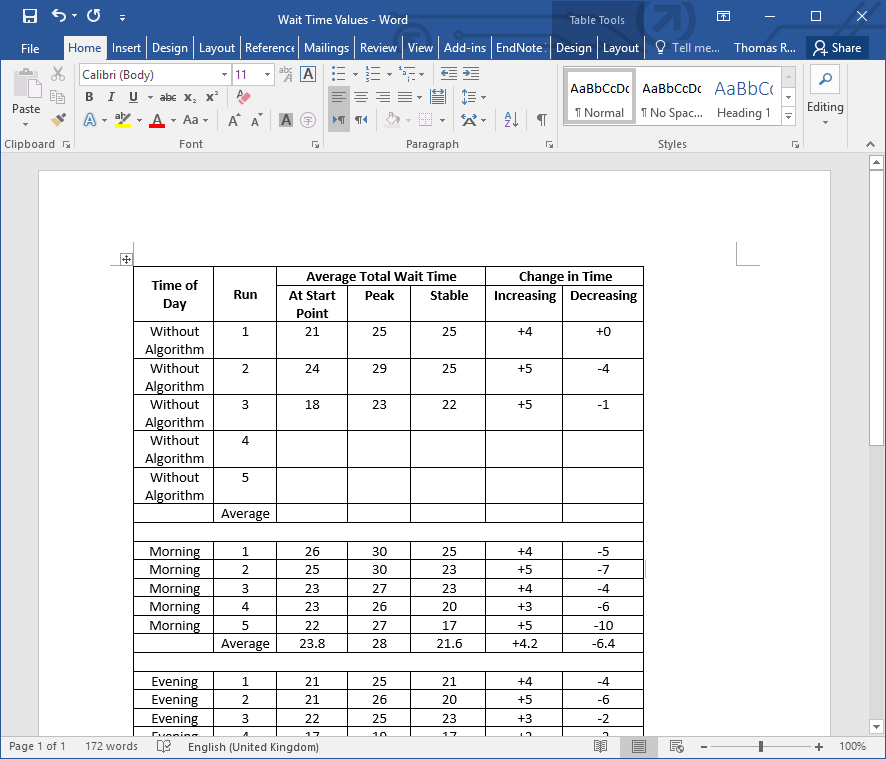
In order to view the algorithm’s effectiveness I need to have the system run for a certain amount of time. This ensures that a sufficient number of vehicles have been around the simulator so that the total average wait time is representative of the system without the algorithm. This is accomplished by measuring the time that has elapsed so far in the simulator. If 150 seconds have passed then the algorithm is activated and begins to take effect on the system.

#### 8.1.2.1 Morning



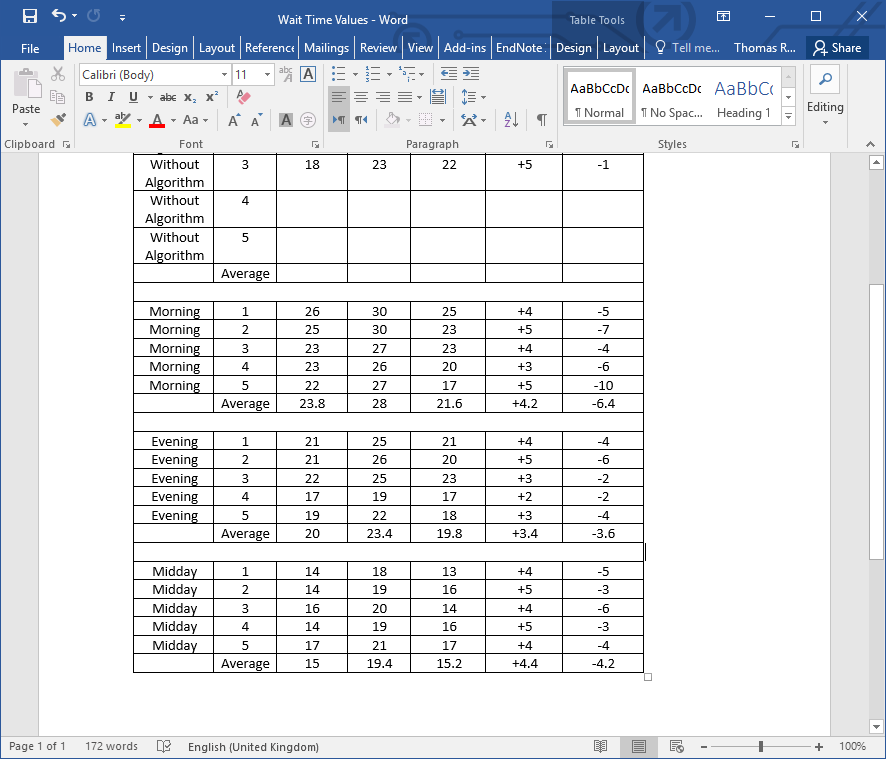
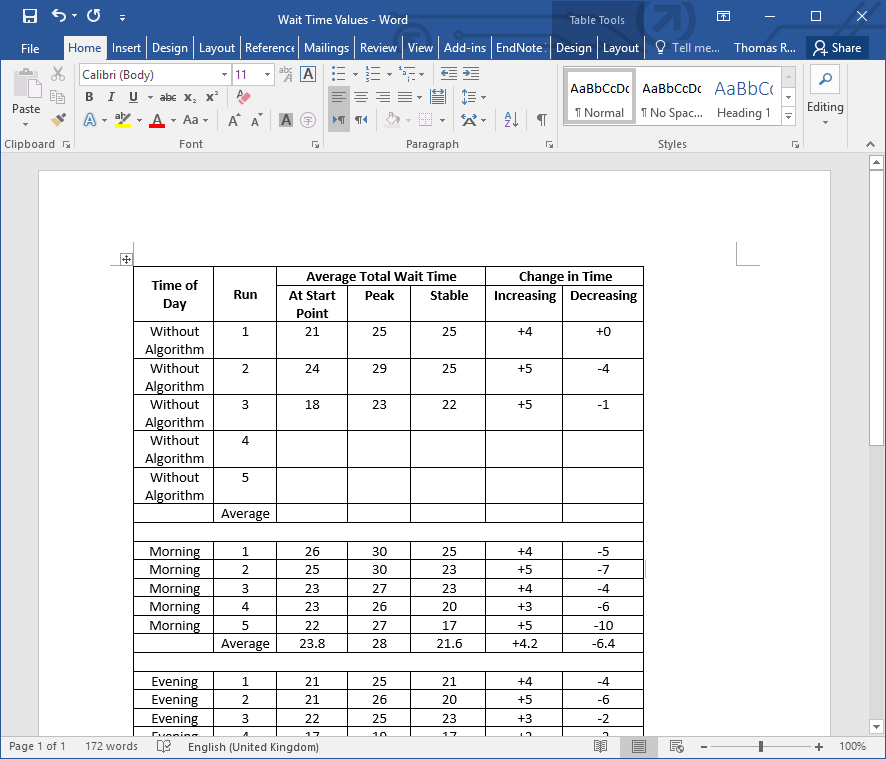
As the results show, once the algorithm has been activated the total average wait time still continues to increase. However it isn’t long before a peak average wait time is summited and then the value begins to decrease. As it shows this will continue until the total average wait time oscillates between a couple of lower values – the result of the optimisation of the proportion variable.

#### 8.1.2.2 Evening



Similar to the morning runs, once the algorithm has been activated, the total average wait time still continues to increase. Again however, it isn’t long before a peak average wait time is summited and then the value begins to decrease. As it shows this will continue until the total average wait time oscillates between a couple of lower values – the result of the optimisation of the proportion variable.

#### 8.1.2.3 Midday



Whilst the midday runs follow the same pattern as the morning and evening ones in that they ascend to a peak before reducing to a lower stable value, the actual values received from the system are significantly lower. The obvious reason for this is that the randomisation for the spawning of most vehicles is larger than in the morning and evening spawns. This would results in vehicles being more spread out in almost every direction so the weight and incremented time spent at each traffic light is reduced.

## 8.2 Performance Evaluation

To understand the effect of the algorithm one must understand fully the function of the proportionate variable. When the simulator is initially run the proportionate value is set at 150. This means that until the machine learning algorithm is activated the traffic lights at a junction will have a consistent cycle of green and red time. As this value is not optimised it generates inefficiency and thus the total average wait time will steadily climb at a consistent rate.

When the algorithm is activated suddenly the proportionate is dynamically able to change depending on the input provided to it by the learning algorithm. If the weight put upon the traffic lights in the y axis is greater than the weight put upon the traffic lights in the x axis the algorithm will create a multiplier that is 1-(0.01\*difference in weight between the axes). The difference in weight between the axes can be compared to a percent value that the proportion variable will be shifted by. Thus the new proportion will be slightly different to the previous one. This results in the change in proportion over time being gradual rather than large jumps around the point optimisation, meaning that the proportion is much more likely to get closer to the optimal value as it is incrementing or decrementing in smaller steps.

Once the new proportion has determined the threshold for the modulus variable in each traffic light object the engine is iterated through again. A fresh total average wait time is created and compared to the one previously recorded. If the new total average wait time is reduced from the previous then that’s a step in the right direction for the proportional variable. In this scenario we provide a reward for the algorithm. However, because the current proportion value is trending in the right direction, we leave it alone and allow it to remain constant until the total average wait time ceases to decrease.

Contrary to the reward the algorithm invokes a punishment if the proportion variable produces a poor result. If the new total average wait time is the same or higher compared to the last result then the algorithm will judge this as stagnation or degradation and will punish the proportion variable. This punishment entails forcing the proportion variable to search for a new value that could potentially be an improvement. So to observe this process at higher level the proportion variable goes through a system of trial and error until a value can be found that improve the total average wait time.

## 8.3 Expert Evaluation

A crucial part of my evaluation was to get the opinion of an expert on the feasibility and potential a reinforcement machine learning algorithm might have in the real world. Two meetings were set up with Mike HU, of Nottingham City Council Traffic Signal Management department, over the course of the research and evaluation stages of the project. The first meeting consisted of the discussion of the design of the model and how effective a machine learning algorithm could potentially be. The conclusion of this first interview established the ideal design for the simulation and also suggested what metrics were best for evaluating the effectiveness of new algorithms in the traffic signal system.

The more important of the meetings, the latter one, was conducted after the program had been completed and the simulator could produce consistent data. I began the meeting by explaining the final design choices I had made and how I had subsequently implemented them. This was followed by a description of the way the simulator works as well as the functions of the mechanics within it. Whilst this was not the focus of the meeting it was important that context and a basic understanding of the code was established. This meant that when discussing the benefits and ramifications of my proposed system Mike had the capacity to make educated suggestions that were specific to the simulator I had created. After bringing Mike up to speed on the workings of my simulator I proceeded to demonstrate the code in action. I presented captures of every type of run within the system and narrated the happenings within each video. I then displayed the tables filled with data relevant to each run so that he and I might reflect on them.

# 9 Project Management

## 9.1 Time Management

When looking back at the Ghant chart created far earlier in the project. It is easy to criticise the way that my time has been managed throughout development. There have been several instances where unanticipated events conspired to delay the progression of work yet insufficient recovery was made following these issues to make up for the time lost. Hence it is my belief that my time management has been poorly executed.

## 9.2 Resource Management

### 9.2.1 Source Code

Throughout eh duration of development on this project I have been updating a private Github repository that contained the code for the simulator, the machine learning algorithm and any important documents. The product of this investment was thatI did not have to worry about losing all my work in a system crash or accidental deletion. Returning the code and other documents to their original state was a simple method.

### 9.2.2 Materials

Attached to the source code and documents of this project are the auxiliary information sheets and recordings. There is an audible and written manuscript for both of the meetings with Mike Hu. In addition are the captures of the simulation running that demonstrate the effects the algorithm has on the system. All auxiliary files are backed up on the hard drive of my pc as well as being stored on an externals removable hard drive.

# 10 Reflections

## 10.1 Methodology

## 10.2 Design

## 10.3 Implementation

# 11 Acknowledgements

The primary acknowledgment that needs to be made in this report is to Dr Jason Atkin. My second year C++ module convenor permitted me to utilise his code framework to build upon and develop my model. Without this the programming task would have been significantly more difficult and would have wasted time that could have been used more productively in the important parts of the project.

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