Dissertation Type: research

DEPARTMENT OF COMPUTER SCIENCE

MARMOSET

Multi-Agent Route Management using Online Simulation for Efficient Transportation

Alexander Hill

A dissertation submitted to the University of Bristol in accordance with the requirements of the degree of Master of Engineering in the Faculty of Engineering.

Monday 2nd May, 2016

Declaration

This dissertation is submitted to the University of Bristol in accordance with the requirements of the degree of MEng in the Faculty of Engineering. It has not been submitted for any other degree or diploma of any examining body. Except where specifically acknowledged, it is all the work of the Author.

Alexander Hill, Monday 2nd May, 2016

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Executive Summary

A compulsory section, of at most 1 page

Supporting Technologies

This project has two parts - a back end engine written in Java, and a front end visualisation part running in the browser using JavaScript.

Back End

- OpenStreetMaps (OSM) [6] is used for the raw mapping data. Specific sections of the maps can be downloaded from Geofabrik.
- The Open Source routing engine GraphHopper [9] was used for performing basic routing requests and handling storage and processing of the OpenStreetMaps data.
- NanoHttpd [11] was used for a static file server to provide HTML, CSS and images to the front end.
- Java WebSocket [16] was used for communication between the front and back end.

Front End

- The map interface on the front end uses the JavaScript library Leaflet.js [2] for the map and marker APIs.
- Mapbox is used for the image tiles to display the underlying map.

Notation and Acronyms

OSM	:	OpenStreetMap
GraphHopper	:	Open Source Routing Engine, used for location to location routing requests
VANET	:	Vehicular-AdHoc NETwork
V2V	:	Vehicle to Vehicle
V2I	:	Vehicle to Infrastructure

Acknowledgements

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Chapter 1

Contextual Background

1.1 Routing in the 21st Century

When MapQuest first launched in 1996, most drivers found their way to new locations using physical paper maps as well as knowledge gained through experience. MapQuest was the first online service to change that - instead of figuring out a route yourself, you could enter your location and destination and have a route provided to you. Using these routes required printing out or writing down the instructions yourself, meaning changes to the driving environment (such as traffic or roadworks) could not be anticipated.

In 2005, the first online version of Google Maps was released. Unlike its predecessors, Google Maps used real-time traffic analysis to improve the routes it offered to its users. Initially, Google Maps lagged behind MapQuest, but with improvements to both their interface and their map and route quality they soon took the lead. However, for a time most routes were still printed - even vehicles with GPS navigation rarely used non-static mapping information.

It took the release of the iPhone in 2007 to take full advantage of the new information available - suddenly, people were able to plan routes and modify them whilst travelling, whilst Google could use this information to improve their data on congestion.

1.2 Self-Driving Vehicles

This technology has now been integrated into almost every modern vehicle available to purchase today. GPS based navigation, with traffic information and turn by turn routing instructions are standard features in many car models. Furthermore, we are seeing some further intelligence being added to cars, from two perspectives.

The first is modifying existing cars - adding features such as cruise control, automatic braking systems, reading of road signs, lane following on highways, and so on until eventually the car will need minimal or no human intervention. This approach is being taken by Tesla, who have released multiple software updates to their car software that enables further automation by the car itself. The second approach is from companies like Google, who have been building a self-driving vehicle 'from scratch', creating a vehicle that has no steering wheel and requires no human intervention to drive from one location to another.

1.3 Congestion

With the advent of Google Maps and the proliferation of mobile devices, many drivers are now provided with directions that can incorporate large amounts of additional information - including current traffic conditions and road closures. This is particularly important in cities, where the levels of congestion during 'rush hour' can have a drastic impact on travel time.

Looking forwards, we can see two trends that suggest that congestion will become more of an issue in future. Firstly, more and more people are living in cities - even with good public transportation, this will increase the number of vehicles on the road even if it lowers the proportion of households that own cars. Secondly, on-demand transport solutions (such as those provided by Uber) are leading to more vehicles on the road, especially at peak times. One of Uber's key insights is using market techniques to better match supply and demand than existing taxi and minicab services. If there is an increase in riders requesting vehicles in a certain area, Uber activates s̈urge pricing", increasing the cost of the ride by a fixed multiple - for example, 1.5x. This information is sent to their network of drivers, who will move to the location in search of higher paying riders. The net result of this is that high-demand in certain areas will create further congestion, even though on demand transportation is usually more efficient than personal car ownership.

At the same time, we are beginning to witness the rise of self-driving cars, capable of planning and executing routes themselves with no need for human intervention. This raises many questions about the role of personal transportation and the effect this will have on congestion. Will driving become as dated as horse-riding is today - or will people's enjoyment of it mean that there'll always be human driven vehicles on the road? More importantly, will self driving cars improve or harm congestion - and how will they decide what routes they should take?

Answers to these questions are important to many people, including individual drivers, companies owning large fleets of vehicles, and city planners. Although it is not possible to provide definitive answers, simulation provides a technique for evaluating how future transportation will look and the impact it may have.

1.4 Simulation

One way of finding answers to these questions is simulation - modelling and making assumptions about future behaviours and analysing the results. Vehicles simulation can be used in a number of ways:

- Simulating current vehicle behaviour and traffic conditions to identify improvements to the road network.
- Modifying the road and transport networks (e.g busses, taxis) in the simulation to identify the impact changes would have.
- Designing and running novel algorithms for simulating self-driving vehicles, modelling their behaviour in response to both human drivers and other self-driving vehicles.

1.4.1 Types of Simulation

V2V vs V2I etc

There are two main tools in use today for running vehicle simulations. The first is MATSim [1], and the second is SUMO [10].

1.4.2 MATSim

1.4.3 SUMO

Existing tools are cumbersome, slow, non-interactive and designed to be used for any type of multi-agent problem - from routing air traffic to planning for evacuation in crisis situations. This project aims to create a system designed exclusively for one goal - road based simulations for vehicles and traffic. By focusing on a specific use case, a tool can be easier to use, faster to setup and provide specialised functionalities for our use case.

Additionally, existing tools tend to focus on simulation then visualisation, without combining the two. Simultaneous simulation and visualisation allows a much tighter loop of testing and iterating on algorithm design and analysis.

The high-level objective of this project is to build an easier, faster way of simulating the behaviour of vehicles, primarily in cities. We will use this simulation engine to design and improve a potential algorithm for multi-vehicle routing. The concrete aims are:

1. Research existing algorithms and simulation tools to identify the strengths and weaknesses of current approaches.
2. Design a simulation architecture that allows for fast experimentation, easy integration with real world information and full implementation flexibility.
3. Build and optimise the simulation engine on top of existing open source tools.
4. Demonstrate the power and flexibility of the engine by experimentally creating a novel multi-vehicle routing algorithm.

Chapter 2

Technical Background

2.1 Algorithmic Background

2.1.1 Dijkstra's Algorithm

Dijkstra's Algorithm [5], originally designed in 1956, forms the foundation of most modern routing algorithms.

```
1  Function DIJKSTRA(G,s,d)
2      Q ← new Priority Queue
3      dist[s] ← 0
4      for vertex v ≠ s ∈ G do
5          dist[v] = ∞
6          prev[v] = undefined
7          Q.add(v, dist[v]) // Adds v to priority queue with weight dist[v]
8      end
9      while Q ≠ ∅ do
10         u ← Q.extract_min()
11         if u = d then
12             Return BuildPath(u)
13         end
14         for neighbour v of u do
15             d ← dist[u] + distance(u, v)
16             if d < dist[v] then
17                 dist[v] ← d
18                 prev[v] ← u
19                 Q.decrease_priority(v, d)
20             end
21         end
22     end
```

Algorithm 2.1: Dijkstra's Algorithm

The algorithm operates on a graph consisting of nodes connected to each other by edges. Each edge has a weight - this could be the length of the road in a real world map. Given two nodes S and D, the goal is to return a list of edges that represents the shortest path between the nodes.

At its core, the algorithm picks the edge with the next shortest distance from the source node and updates the distance value for that node. It repeats this process until it finds the source node connected to an edge, then works backwards to construct the shortest path between the two nodes.

Algorithm 2.1 shows how it works in pseudo-code. The implementation for the **BuildPath** function simply iterates through each nodes parent and adds it to the output list. We also define the **distance** function that simply returns the weight of the edge between vertices u and v.

Bidirectional Dijkstra's Algorithm

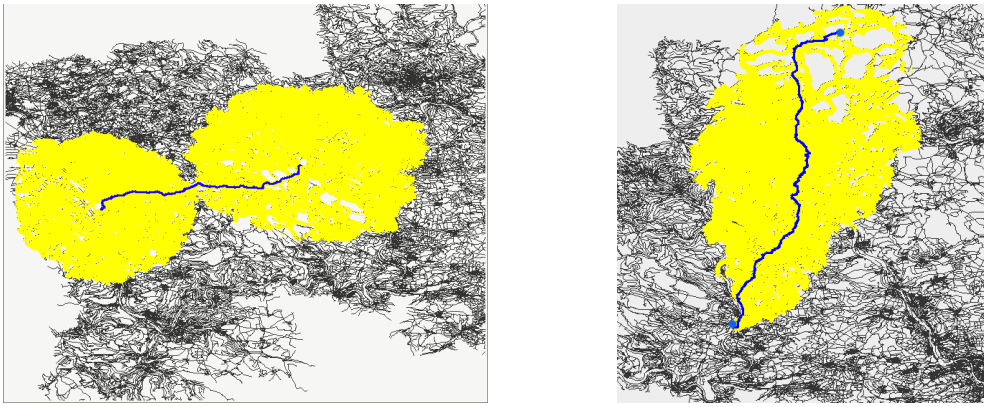
By default, the algorithm searches outwards from only the source. We can improve the performance of Dijkstra's algorithm by searching backwards from the destination and forward from the source simultaneously.

A* Algorithm

By itself, Dijkstra's algorithm will search all edges based on their cost from the start node. However, when routing on a real world map this leads to a lot of wasted work searching in the opposite direction from the destination.

In Dijkstra's algorithm, the distance from the source node is used as the key in the priority queue (line X). The A* algorithm [8] instead seeks to minimise the function $f(v) = dist[v] + h(v)$, where $h(v)$ is a heuristic that estimates the cost to destination.

A bidirectional version of the A* algorithm can also be used for further improvements to performance.



(a) Dijkstra's Algorithm (b) A* Algorithm

Figure 2.1: Paths searched by each algorithm

Contraction Hierarchies

If the weights on each edge are known in advance, we can process the graph to pre-compute the shortest path between key nodes and hence improve the performance of routing requests by orders of magnitude. Contraction Hierarchies [7] is one technique for graph preprocessing. It works by building shortcuts on top of each other in a hierarchy, and using a modified bidirectional Dijkstra's algorithm that only uses shortcuts higher than the current one to route between two points.

Although they double memory usage, in practice Contraction Hierarchies have a huge impact on query times. For routing from Moscow to Madrid, any Dijkstra based algorithm takes at least 10 seconds, compared to less than 0.05s for a processed graph. **Cite: https://graphhopper.com/public/slides/2014-locationtech.pdf**

2.1.2 Multi-Vehicle Routing Algorithms

Providing viable routes for a single vehicle is now essentially a solved problem, with various implementations used in many commercial products for both consumers and businesses. However, the problem of routing multiple vehicles simultaneously has many solutions [18, 14, 3, 19, 4, 13, 17], but no accepted 'best practice' technique.

Multi-Vehicle routing algorithms come in various forms, depending on the author's goals and expectations for future vehicle connectivity. Some algorithms are designed to have a large scale overview of where each vehicle is on the road, and will dispatch routing information to the vehicles centrally. On the other end, algorithms may assume no central information and instead rely upon vehicle to vehicle connections for passing information. Algorithms with a centralised component are referred to as **V2I**, standing for Vehicle to Infrastructure, whilst **V2V** refers to Vehicle to Vehicle algorithms. A simulation engine capable of implementing both V2V and V2I communication models is known as a V2X engine.

VANET

A VANET (Vehicular-AdHoc NETwork) is a high-level use of V2V communication. Although primarily theoretical at the moment, wireless networking protocols and algorithms have been designed to support the creation and use of a VANET. VANETs have a number of potential use cases - allowing vehicles to follow one another with no driver intervention, real-time calculation and distribution of traffic information and so on.

BeeJamA

The BeeJamA [18] algorithm is a V2I approach for multi-vehicle routing. It is based off an algorithm originally created for routing in packet switching networks that has been adapted for use on road networks. Its behaviour is inspired by the behaviour of bees, which are able to effectively search and scavenge for food in a large area surrounding their hive.

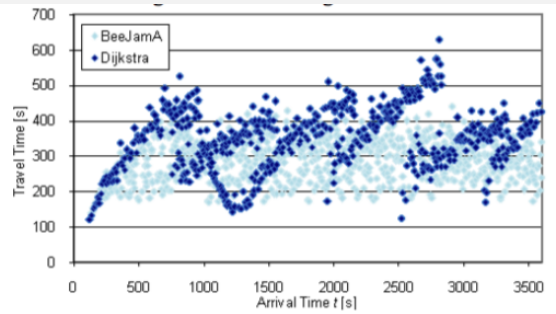


Figure 2.2: A comparison of BeeJamA to Dijkstra's Algorithm in terms of travel time.

The BeeJamA algorithm uses a quality rating function to determine a probability that a vehicle will be sent down a specific road. The map is split into regions called Foraging Regions. Each region stores two types of table - an Intra-Foraging Region routing table and an Inter-Foraging Region routing table. These store the cost from the quality rating function of using a particular route to reach the destination. The tables are kept up to date by sending virtual vehicles between regions, which record how long their journey took and inform the region they have entered.

Whilst routing, each vehicle consults the routing table and probablistically picks its next step. This is a key part of the algorithm that helps keep routes uncongested - if every vehicle took the optimal path, it would no longer be optimal as it would have high levels of congestion. Results from a custom-built simulation engine have shown that the algorithm can perform better than using Dijkstra's algorithm with delayed traffic information.

2.1.3 Nagel-Schreckenberg Model

The Nagel-Schreckenberg Model [12] is a cellular automaton model for the flow of traffic on roads.

The model splits roads into discrete cells, with each car taking up a single cell at a time. The vehicles then follow 4 rules, in parallel to simulate the flow of traffic. Each car has a fixed velocity v for that step, which represents the number of cells the vehicle will move forward in the final rule. The model does not allow for overtaking, and as a result exhibits realistic behaviour for traffic jams and flow.

1. **Acceleration** - if the vehicle is not at the max speed and there is enough space ahead, increase the velocity by 1.
2. **Slowing down** - if there is a vehicle nearer than the current velocity, reduce velocity to one cell less than the distance to the vehicle in front.
3. **Randomisation** - reduce the velocity by 1 with probability p.
4. **Car movement** - move each vehicle forward by its velocity v.

Each cell is meant to approximately represent the size of a single vehicle, whilst each step (running through all four rules) represents a discrete amount of time.

We'll now run through a brief example of the effects of each step. Our road will have 9 cells with two vehicles on them. Our max speed (v_{max}) will be 5. For this example, we will ignore the randomisation step.

	4				**0**			

We now perform the acceleration step for each vehicle. The second cell vehicle is currently at speed 4 - as the vehicle in front is only 3 cells away, it does not accelerate. The sixth cell vehicle increments its speed from 0 to 1.

During the slow step, the second cell vehicle must reduce its speed from 4 to 3 so it does not hit the sixth cell vehicle.

				3		**1**		

Finally, the vehicles move to their new destinations. This demonstration briefly shows the behaviour of two vehicles, but fails to demonstrate the creation and flow of traffic jams. In Figure 2.3, we can see how traffic jams form and move in the Nagel-Schreckenberg model. This graph shows what happens when there is a density of 0.1 cars per cell.

2.2 Implementation Background

2.2.1 OpenStreetMaps

In OpenStreetMaps, there are three main elements - nodes, ways, and relations. Each of these can have certain tags that describe the real-world object they represent. For example, a way could have tags describing it as a highway with 3 lanes, whilst a node could have tags identifying it as a park bench or phone booth.

A standalone node is usually a single entity with a latitude and longitude as well as an ID. By themselves, they can be used to represent small features such as traffic lights, lampposts, or pylons. However, a way is also defined by an ordered list of nodes.

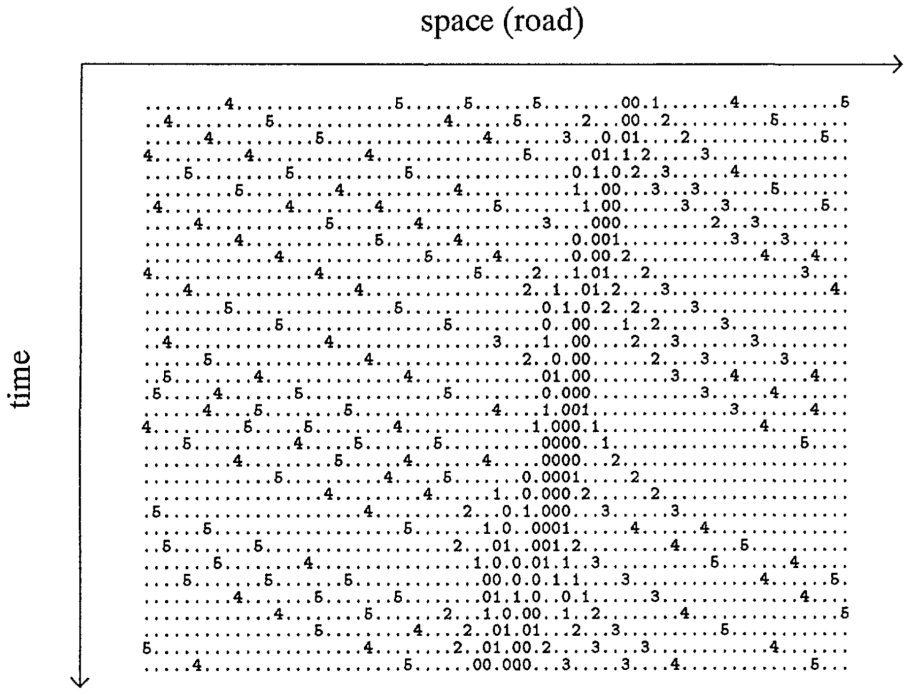


Figure 2.3: Formation of traffic jams in the Nagel-Schreckenberg Model

Ways are the most flexible element in OpenStreetMaps. If a way starts and ends at two different nodes, it is called an 'open' way. This is commonly used for sections of roads and paths. A way that starts and ends at the same node is called a 'closed' way. Often this is used to represent an area - such as a park or the shape of a building - but can also be used for roundabouts and circular barriers. There are tags for identifying if a closed way is an area or not (primarily the `area=yes` tag, but many things are defined as areas even without this tag).

Finally we have relations. These are the most complex type of element, holding an ordered list of ways, nodes and other relations and have tags for describing the relationship between them - for example, a bus route could be described as a list of ways and nodes. For the purposes of routing, it is only important to know that relations are used for turn restrictions - the rules that define which directions a vehicle may move from one road onto another. This is important for routing much more than mapping, as users would be frustrated to find that a route they had expected to travel on is illegal or unsafe in practice.

2.2.2 GraphHopper Routing Engine

GraphHopper has been built to be fast, flexible and powerful. It covers the full flow of creating a custom routing service - from parsing and importing OpenStreetMaps data, processing the network for performance improvements, routing using multiple Dijkstra and A* algorithms and running a web server for making requests. Additionally, it has built in support for car, bicycle, pedestrian and other types of travel as well as the ability to create custom vehicle types.

Figure 2.4 shows the salient parts of the architecture for this project. Note that we are not using the web or android modules, so no details regarding their functionality has been included. For the most part, the use of routing will be relatively high level - simply requesting a list of edges between two points. However, the underlying engine also has a number of features that make it easy to customise, which will be used for more complex situations.

It is important to note that the conversion from OSM data to GraphHopper data is done only once (as it is a time consuming process) and stores its results on disk.

OpenStreetMap Encoding

The first thing to understand is how GraphHopper converts the OpenStreetMap data into a graph that can be used for routing. For the purposes of routing, we are primarily concerned with ways that represent roads. However, a way does not represent the entirety of a given road - but is also not granular enough to allow routing. Figure 2.5 shows the difference between ways, roads and edges. We can see that the physical Holloway Road extends beyond the OSM way (red). However, if we used the way for routing we could not route from Hargrave Road to St John's Villas via Holloway Road. To perform routing, GraphHopper splits every way into an edge whenever there is a junction. GraphHopper's edges can be seen in orange. These can be used to perform the routing calculation mentioned above - there is now an edge along a subsection of Holloway Road that connects Hargrave Road to St John's Villas.

Flag Encoders

Internally, GraphHopper compresses the information about each edge into a single integer - so each edge takes up no more than 32 or 64 bits.

The `FlagEncoder` interface (and the `AbstractFlagEncoder` class) define what operations have to be done to convert a section of a way into an edge. Edges store a few key pieces of information - by default, GraphHopper stores the length, speed and ID of an edge, with additional information optionally stored by the flag encoder itself.

For example, the `CarFlagEncoder` uses the type of road to calculate the correct maximum speed of the vehicle and then sets the speed for the edge, using 5 bits. The `MotorcycleFlagEncoder` can do the same thing, but with different speed values for each type of road. The concept can be extended to storing even more information at each edge - for example, 3D graph data can be stored for bike and walking routes, whilst a FlagEncoder for trucks could store height, weight, width and length restrictions to ensure safe travel.

Weightings

Flag Encoders are used to define what information can be used whilst routing - but this data is fixed once the OSM file has been processed. A weighting defines how the data stored at the edges is used. For example, one can search for the shortest route, the fastest route, or a custom weighting that incorporates other information stored in the edge.

Routing Requests

As it is primarily designed to work with its web module, GraphHopper uses a request-response pattern for requesting and receiving routes.

```
GHRequest ghRequest = new GHRequest(startLat, startLon, endLat, endLon);
ghRequest.setWeighting("fastest");
ghRequest.setAlgorithm("dijkstrabi");
GHResponse ghResponse = graphHopper.route(ghRequest);
```

Listing 2.1: GraphHopper request and response

The `GHRequest` class stores all the information required to make a routing request, including the weighting and algorithm to use. An example of its use can be seen in Listing 2.1.

The response is returned in a `GHResponse` class, which holds information about the route in a number of different ways. The user is also responsible for checking the `hasErrors` method before requesting the route itself. Once this has been done, the route itself can be read.

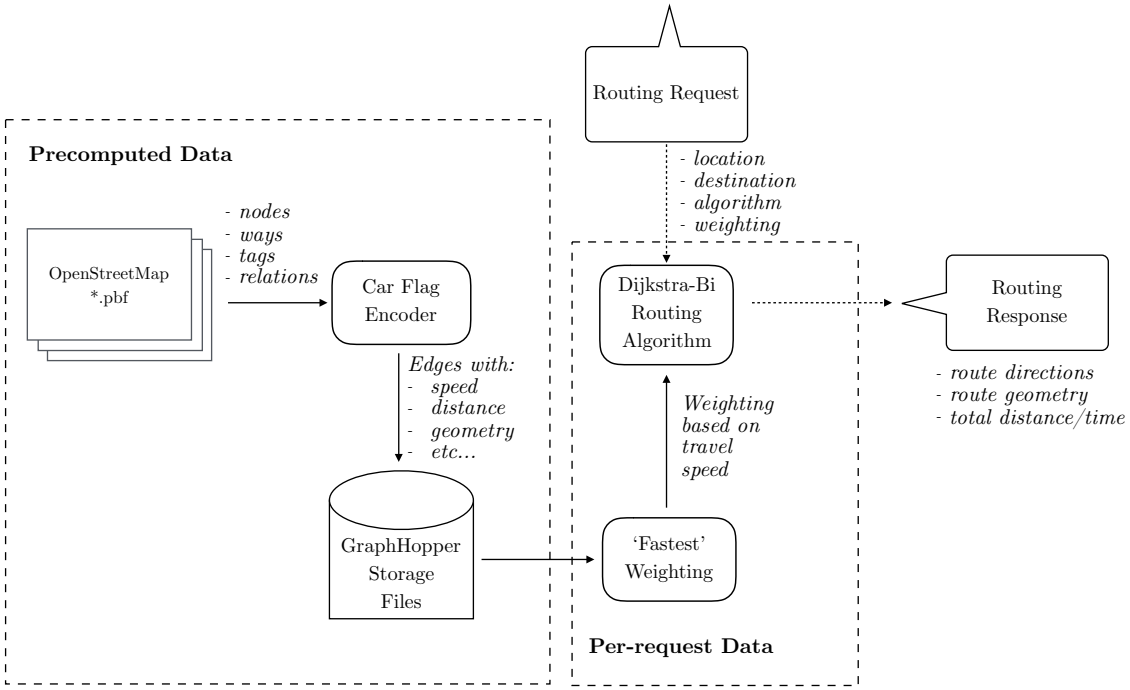


Figure 2.4: An overview of the GraphHopper Architecture

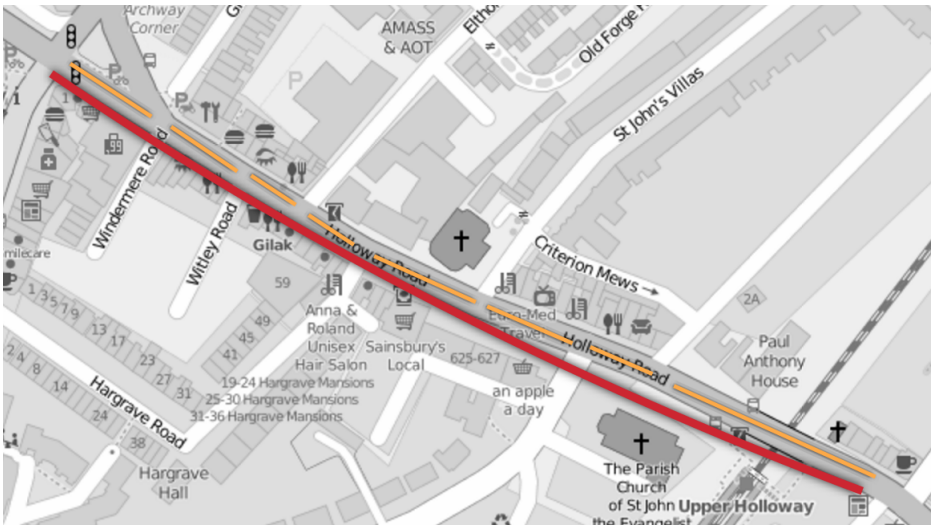


Figure 2.5: OpenStreetMap way representation compared to edges in GraphHopper

As GraphHopper supports the use of an alternative routes algorithm (meaning a single request can respond with more than one route), the GHResponse class has both a `getAll` and `getBest` method, which return a list of `PathWrapper`s and a single PathWrapper respectively. The PathWrapper holds the route itself as well as some metadata. The route can be accessed as a list of instructions or as the raw list of points for visual display. Additionally, the total distance and time of the route are recorded.

However, GraphHopper does not provide a list of edges or of OSM Ways that are included in the route. Internally, the list of edges is calculated with the `calcPaths` function, which returns a list of `EdgeIteratorState` objects. These objects are fundamental to the way the graph is stored an accessed in GraphHopper.

GraphHopper uses the flywheel pattern for efficient access to graph data. The EdgeIterator and EdgeIteratorState class are the primary way of interacting directly with the edge data. EdgeIteratorState is an interface containing getters and setters for the edge ID, its geometry, the flags stored by the FlagEncoder, and the name of the road the edge is a part of. It also allows access to the nodes at either end of this edge. The node at the start of the edge is called the Base Node, whilst the node at the end of the edge is the Adjacent Node.

Chapter 3

Project Execution

3.1 Overview

The execution of this project was split into 4 stages, each with its own goal.

1. **Initial Implementation** - create the initial client and server with vehicles moving on a map.
2. **Realistic Simulation** - implement the Nagel-Schreckenberg model to make the vehicle behaviour more realistic.
3. **Performance and Architecture Improvement** - make the simulation engine fast and flexible enough to deal with the challenges of algorithm design.
4. **Algorithm Design and Implementation** - creating and improving a novel approach to the multi-vehicle routing problem using the simulation engine.

3.2 Initial Implementation

The initial implementation had a few key goals, with the primary objective of having basic vehicles moving on a map. This stage was essentially a way of setting up the basic architecture of the project, without finalising the details of how routing algorithms would be implemented.

3.2.1 Architecture Design

Figure 3.1 shows a simple architecture diagram for the initial implementation of the engine. Once the client has made a request to the engine, it sets up and starts routing the vehicles. Each vehicle is responsible for storing and updating its own position on each timestep. This data is converted into a string and sent to the client, which then moves each vehicle on the map.

One of the goals of this project was to make it possible to visualise and simulate at the same time. This naturally lends itself to a client-server architecture, and with the rate of improvement of modern web browsers it seemed like a wise choice to use a browser for the visualisation component.

This also means that the server can be run remotely with no additional setup - more computationally expensive algorithms could be run on high-powered servers with the results still visible locally for the user.

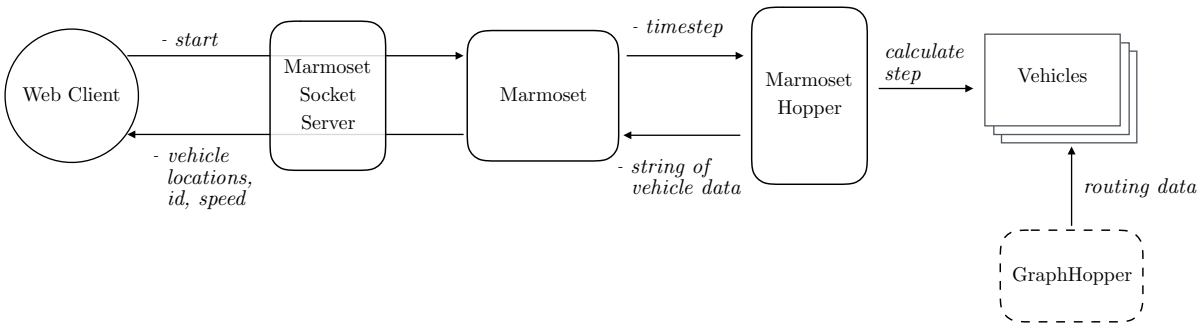


Figure 3.1: The initial architecture for the simulation engine

3.2.2 Project Setup and Modularisation

When setting up the project, it was important to be able to use and modify the underlying GraphHopper routing engine. The GraphHopper project is setup with four existing modules - core, tools, web and android. Although it would have been ideal to use GraphHopper as an external library, it was necessary to make minor internal changes to the main engine. As such, I created a GitHub fork of the project and added marmoset as a fifth module in the project.

GraphHopper uses the Maven dependency and build tool, with its own custom shell script for building, running and testing different versions of the engine. To keep Marmoset separated from the core project, I created my own shell script for building and running the marmoset engine. It supports four main actions - clean, build, rebuild and run. It also allows multiple commands to be run in succession for convenience.

Additionally, I wanted to create a modern codebase in spite of the core engine being written in Java. Although I briefly explored using Scala, much of my work would rely on extending and using the existing Java APIs in GraphHopper. Thankfully, Java 8 has introduced a number of key tools that allow functional-style code to be written. The code below shows the difference for performing a simple task - converting a list of objects into strings and joining them by commas.

```java
public String getVehicleData()
{
    StringBuilder sb = new StringBuilder();
    for (VehicleController v : vehicles)
    {
        sb.append(v.getVehicle().toString());
        sb.append(",");
    }
    // remove last comma
    sb.deleteCharAt(sb.length() - 1);
    return sb.toString();
}
```

Java 7 Implementation

```java
public String getVehicleString()
{
    return vehicles.stream()
        .map(Vehicle::toString)
        .collect(Collectors.joining(","));
}
```

Java 8 Implementation

Here we can see how six lines of code can be condensed into a single, more readable line using the Java 8 Stream API.

3.2.3 Server Implementation

For the raw file server, I used the NanoHttd [11] library, as it requires minimal setup and is easy to run on a separate thread. For the client-server communication, I initially used the NanoHttpd WebSocket implementation, but it did not appear to be fully functional. As such, I switched to using the Java-Websocket library [16], extending the WebSocketServer class to create the MarmosetSocketServer class.

In the architecture diagram (Figure 3.1), we see four main classes on the back-end.

The `MarmosetSocketServer` class handles the connection between server and client. It keeps track of each of the connected clients and offers a simple command to distribute vehicle position data to each of them.

The `Marmoset` class is a static class that is the main entry point for the program. It initialises the file server and WebSocket server, and creates a new thread for running the MarmosetHopper timesteps. It also handles passing data from MarmosetHopper to the socket server.

In most types of simulation, time must be split into discrete steps that represent a fixed time interval in the real world. Looking at Figure 3.1, we can see that it is the Marmoset class that triggers each timestep. At this stage of the project, I had not established how well the front or back end would perform. As a way of simplifying the data flow and processing, Marmoset simply waits one second between each call of the timestep function. As both front end and back end take significantly less time than a second to perform their tasks, this was an appropriate simplification for this stage of development.

The `MarmosetHopper` class holds the list of vehicles and and creates an instance of the GraphHopper routing engine. It initialises all the vehicles, instructs them to update on each timestep and gathers their position information together to be sent to the clients.

When initialising the vehicles, the starting location and destination are chosen as random latitude and longitude co-ordinates within London.

Finally, the `Vehicle` class represents a single physical vehicle on the map. Each vehicle holds its location and the route it plans to take. The routing information is obtained by requesting a route from GraphHopper. The route is returned in a number of ways, including as a list of points that can be used to draw the route. This does not include the speed of each road travelled, so cannot be used for realistic simulation. However, for this initial implementation the location is updated on each timestep by simply moving to the next point in the list. This is very innacurate, but it does allow us to verify the functionality of all parts of the system without touching the details of routing. The vehicles return their location as a string containing their id, latitude and longitude.

3.2.4 Client Implementation

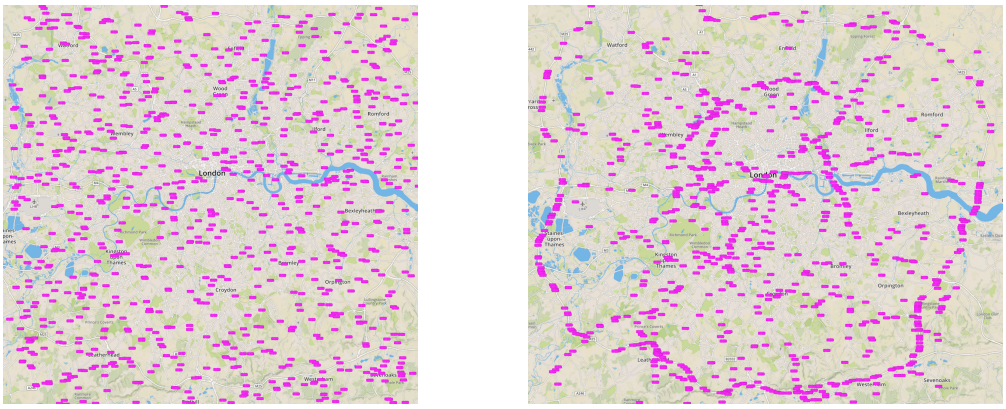
When loading the web page, a map is created and centred on the correct location. The client then connects to the WebSocket back end and listens for data. When it receives the vehicle data, it creates or updates the position of each vehicle marker.

The Leaflet.js [2] library is used for both map and marker creation. A simple `Car` class has been created to keep track of the location of each marker. It stores a reference to the Leaflet.js Marker object and provides a method to move the marker to a new location. The Leaflet.AnimatedMarker [15] library handles smoothly moving the points to their next location, making the cars look like they're driving around the map in real time.

Meanwhile, A single `CarSet` object connects to the WebSocket server and stores the Car objects. When data is received, it creates new Cars or updates the position of existing vehicles using their `moveTo` method.

3.2.5 Results and Improvements

At the end of this section of the project, the engine was capable of performing its core task of simulating and visualising vehicles. In spite of many of the simplifications in the system, it provides quite realistic results - 3.2b shows that even after a small number of iterations certain roads become more congested than others. This matches the reality of driving on London roads - the M25 and North Circular suffer frequent delays due to a high volume of vehicles driving on them.



(a) 10th Iteration (b) 200th Iteration

Figure 3.2: Vehicle positions at different iterations

However, there are many core features missing from the engine at this point.

- The engine simulates a fixed number of vehicles (1000) - no more can be added or removed.
- Vehicles do not move realistically. As they simply jump to the next point on their route, a curved path would take much longer to travel than a straight one.
- Vehicles are independent. Vehicles travel on their own with no sense of traffic or congestion.
- The timestep is fixed to one second, even though the actual processing takes substantially less time for both front and back end.
- Metrics are not tracked. Other than watching the simulation, there is no further understanding that can be gained from simulating.
- The simulation cannot be paused without terminating it and starting again.

For the next stage of development, I focused on improving the realism of the vehicle simulation.

3.3 Realistic Simulation

In section 2.1.3 we introduced the Nagel-Schreckenberg Model for traffic flow simulation. This section discusses the implementation of this model on top of the existing simulation engine described above.

The original model is designed for a single road, either in a loop or an extended straight stretch. Implementing this on a road network introduces some additional challenges, particularly when dealing with the integration with GraphHopper and OpenStreetMaps.

The two main concerns are how the cells should be stored and how the cells should be used in conjunction with the routes created by GraphHopper.

3.3.1 Cell Storage

A number of techniques for storing the cells were considered. Firstly, we must consider how we create edges. We have the option of using either GraphHopper edges - which are small, but do not have junctions - or OSM ways, which can be larger but would allow for more usable metrics and would make the system less dependent on GraphHopper.

Ultimately, I chose to use GraphHopper's edges as the base unit for cells. This is primarily due to the fact that GraphHopper does not have an internal mapping from its edges to OSM Ways, and does not return which Ways are used as part of a routing response. Additionally, GraphHopper provides an `AllEdgesIterator` that returns both the maximum edge ID as well as the data for every edge in the graph.

The next decision is how and where to store the cells. In the original paper, we saw that each vehicle was represented by its velocity stored as an integer in the cell array. As we are storing a much larger amount of information about each vehicle in the Vehicle class, this is not a viable option. If vehicles store their own velocity and keep track of the current edge and cell they are on, the cells only need to know if any vehicle is present in a cell. As such, each cell is simply a boolean value in an array. The cell is set to `true` if a vehicle is in the cell and `false` if the cell is empty.

In terms of physical storage, the are a number of options. At its core, we need a mapping from edge IDs to cell arrays. In Java, this would usually be represented as a Map of Lists (`Map<Integer, List<Boolean»`). However, the edge IDs in GraphHopper have been designed to be sequential starting from 0, with the highest ID accessible from the AllEdgesIterator. This means that we can instead use a list of lists (`List<List<Boolean»`). This has the advantage of allowing the lists to grow in size dynamically, but may have performance issues. In Java, Lists must store other Object types rather than primitive types. As objects in Java are all pointers, each Boolean will require a pointer to a separate memory location that holds the true or false values. This is likely to harm cache performance, something particularly important given the frequency that the cells will be accessed.

Instead, we can simply allocate a two-dimensional array of booleans for each edge as a raw array. This avoids the issues with pointers and is consistent with the way GraphHopper stores edges.

However, there is another challenge with regards to storing the data. When parsing the ways, GraphHopper identifies the direction of the edge - each edge can support moving either forward or reversed. When a route is provided by the routing engine, it is in the form of a list of EdgeIteratorStates. The EdgeIteratorState class has been designed to hide the 'true' direction of the edge, instead switching which node is the base node and which is the adjacent depending on the direction the vehicle is travelling in. The end result of this is that every edge appears to be a forward edge when received from the engine. For the cell model, we need to have two separate directions for the roads, or vehicles going in opposite directions will crash into each other and block the roads.

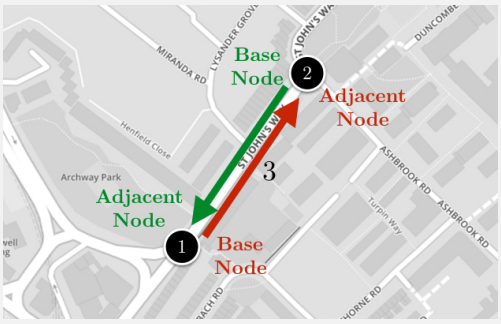


Figure 3.3: The problem with GraphHopper edges

In the diagram above, we see two nodes (with ID 1 and 2) joined by an edge (with ID 3). Imagine we've performed two routing requests, one in red and one in green. Both routes go through edge 3, but in opposite directions. However, both edges will return true from the `isForward` method of EdgeIteratorState, despite going in opposite directions. Although GraphHopper knows that one of these is in reverse, the data is hidden from us.

In Figure 3.3, we can see why this may be an issue. When moving through the edges, we are unable to tell if we are travelling forwards or backwards based on the EdgeIteratorState by itself - the ID is the same and the `isForward` method returns true in both directions. Initially, I had thought a more complex solution than the boolean arrays would be required - perhaps some kind of 2D mapping from pairs of node IDs (or a base node and edge node) to the cell array. However, it is important to note that we don't actually need to know if GraphHopper internally stores an edge as forward or reverse so long as we are able to distinguish between the two cases shown above.

The technique I came up with to solve this uses the fact that the base node and adjacent node returned by the edge changes depending on direction. As such, we can define edges where the base node is greater than the adjacent node as 'forward' and edges where the base node is less than the adjacent node as

'backwards'. This allows us to reliably differentiate between the forward and backwards cases, and save the vehicles from crashing into each other.

The `CellGraph` class handles the storage for the cells, providing convenient getters and setters for edges at specific cells. It also transparently handles the forward and reverse edges, storing two boolean arrays (`boolean[][] cells` and `boolean[][] reverseCells`) and uses whichever one is appropriate for the current EdgeIteratorState.

3.3.2 Vehicle and Cell Iterators

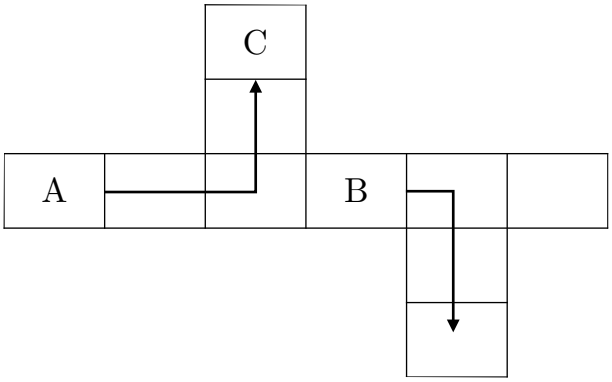


Figure 3.4: The Nagel-Schreckenberg Model across edge boundaries.

As we saw in Section 2.1.3, one of the key parts of the Nagel-Schreckenberg model requires vehicles to know how far they are from the next vehicle. In 3.4, we see three vehicles - A, B and C. Vehicle A is 2 cells from B and 3 cells from C. However, A is soon to turn left onto the edge with C, meaning it should not consider B as ahead of it.

However, each of these paths consists of multiple edges. We need a way of treating lists of edges as a single continuous array of cells. This is a good use case for the iterator pattern, providing us with an abstraction over the underlying arrays.

The `VehicleIterator` class is responsible for storing and moving through the vehicle's route. It stores the list of EdgeIteratorState objects and moves to the next element each time its `next` method is called. It implements the EdgeIteratorState API for full compatibility with GraphHopper. In addition to the usual EdgeIteratorState methods, it can return the road speed of an edge.

The `CellIterator` class stores the cell ID and the VehicleIterator, meaning it can traverse across edge boundaries by calling the VehicleIterator's `next` method. It also has a reference to the CellGraph so that it can return weather there is a vehicle in the current cell.

3.3.3 Vehicle Class

The Vehicle class now has five core methods that are used for running the simulation, rather than the single `calculateStep` function used before. The `accelerationStep`, `slowStep`, `randomStep` and `moveStep` all correspond to the four steps of the Nagel-Schreckenberg algorithm, whilst the `updateLocation` method interpolates the cell location into the edge geometry to find the vehicle's location.

The vehicle class stores two core things that make the implementation possible. The first is a VehicleIterator (named `route`) containing the list of edges each vehicle will take, as well as its current edge. The second is the current cell ID the vehicle is on. By duplicating the VehicleIterator and passing it to a

new CellIterator, the vehicle can find out if it is able to accelerate or must slow down - even if the vehicle in front is multiple edges ahead.

```
1  public void slowStep()
2  {
3      int j = 0;
4      CellIterator c = new CellIterator(new VehicleIterator(route), cg, cellId);
5
6      while (!c.next() && j <= v)
7          j++;
8
9      if (j <= v)
10         v = j;
11 }
```

Listing 3.1: The `slowStep` implementation making use of the CellIterator

Listing 3.1 shows how the CellIterator and VehicleIterator work in conjunction to implement the the slow step of the Nagel-Schreckenberg method. The variable `j` represents the distance to the next vehicle, whilst `v` is the vehicle's current velocity. Line 4 shows the initialisation of the CellIterator - note that `route` is a VehicleIterator being created with a copy constructor, meaning that the current location of the vehicle will not be changed from this CellIterator.

3.3.4 Results and Evaluation

<CREATE ARCHITECTURE DIAGRAM YAH>

At this point, the system was capable of simulating any number of vehicles with realistic traffic flow behaviour. However, there were still many key performance improvements that needed to occur before the system would be ready for algorithm development.

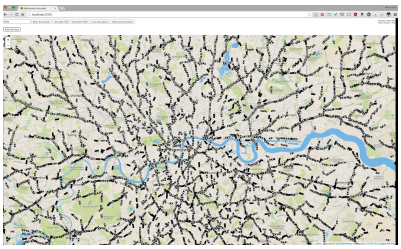
- The back end still waits one second per iteration.
- The back end architecture does not allow for vehicles with different behaviour.
- The back end does not make optimal use of the multiple threads and cores that modern computers have available to them.
- The front end has graphical glitches and poor performance when showing more than 16,000 vehicles.
- Metrics for later data analysis are not recorded.
- Additional vehicles could not be added to the simulation once it had started.
- The simulation cannot be paused or resumed.

3.4 Performance and Architecture Improvements

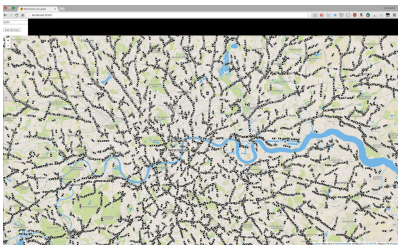
There were two core goals for the system at this stage. Firstly, improve performance such that at least 64,000 vehicles can be simulated and secondly, modify the architecture of the system to support multiple vehicle types, preferably with the ability to have different vehicle types running side by side.

3.4.1 Front-end Performance

Before this stage of the project, the front end had many performance issues. With enough vehicles, the entire page would become slow to respond and update. Even with the one second delay, it would sometimes fail to update before receiving the next set of data.



(a) Vehicles showing up as black squares rather than image icons.



(b) Large black blocks showing over parts of the screen.

Figure 3.5: Graphical glitches caused by displaying more than 16,000 images.

Marker Rendering

I had initially used the Leaflet.AnimatedMarker library to make it appear as though the vehicles are driving around the map in real time. However, this had a huge performance cost, and as such had to be disabled.

Additionally, the vehicle image I used was reasonably large and in colour. I created a much smaller vehicle image (from 15KB to 1KB.), which did improve performance a little, but did not raise the 16,000 vehicle limitation.

One of the core issues with the existing implementation was the use of `img` tags for displaying the vehicles. As each HTML tag is a full blown element in the DOM, there is a reasonably high performance cost associated with their use. There are two main alternatives for showing graphics in the browser - SVG and the HTML5 Canvas API.

Unlike the img tag, the Canvas API is designed for drawing and other graphical purposes. Instead of one tag per vehicle, A single `<canvas>` element would be able to render every vehicle. I had been concerned that there would be major challenges in extending the Leaflet Marker class to use an entirely different way of showing markers, but thankfully Leaflet provided the location to display the markers in pixels to marker subclasses. Using Canvas offered drastically improved performance with seemingly no upper limit on how many vehicles the front end could display with no glitches.

However, there were a few downsides to using Canvas. Firstly, the map correctly re-rendered all the markers when zooming in and out, but not update the markers when panning the map. Attempts at fixing this issue were unsuccessful. Additionally, the img tags were able to support a popup when mousing over a vehicle that showed its current speed and ID, which was useful for debugging. This would have to be implemented by hand to be supported with Canvas - manually detecting the current mouse position, checking which vehicle it was hovering over and then drawing a custom popup on top of the view.

Figure 3.6: SVG Rendered orange markers showing 30,000 vehicles

Instead, I decided to experiment with SVG (Scalable Vector Graphics), an XML based web API. One key advantage is that Leaflet has built in support for drawing certain types of SVG elements. The static image marker could simply be replaced with a `CircleMarker`, which used the same API as the Animated and normal image markers but instead shows a circle with customisable radius and colour.

SVG combined the performance of Canvas (rendering 64,000 vehicles whilst remaining responsive) and the interactivity of img tags (panning around the map worked flawlessly, and popups worked with no additional work). The only downside was that a circle is shown instead of a vehicle icon, meaning it is not possible to rotate the shape to indicate which direction the vehicles are travelling. This is a minor price to pay for the performance improvements, so the decision was made to use SVG for the front

end moving forwards - the result can be seen in Figure 3.6.

WebSocket Data Format

The back-end initially just sent down data in string format - for example, *10067|51.5306611887|0.1609468558|1* for vehicle with id 10067. This format has a number of issuses. Firstly, there is limited precision for the values, as they must be truncated to a certain number of decimal places. Secondly, the format is text based, meaning there is a much larger overhead of space compared to storing the values numerically. Finally, it takes additional time to convert the data into a string only to parse it back into numerical values on both the front end and back end.

The string data required for updating the locations of 1000 vehicles takes 33Kb. Encoding this as raw binary data requires 4 bytes for the vehicle id and speed each and 8 bytes for each of the latitude and longitude, requiring 24 bytes per vehicle and hence 24Kb for the total transfer. This is not only smaller, but also comes with a performance and accuracy improvement as well.

Thankfully, the WebSocket protocol supports the sending of binary data, which can then be efficiently processed by the front end using the DataView APIs. On the back end, we create a single reusable BinaryBuffer object and pass it to the Vehicles, which add their data into a specific offset. This is significantly more efficient than the string based method, although the change is primarily for improving network and front end performance.

3.4.2 Back-end Performance

Removing time-lock

The most necessary change was removing the added delay for the timestep from the Marmoset class. Instead of sending the data every second, the socket server waits for a 'next' message from the front end to start processing the next timestep. It then sends the data and continues to wait for the command to continue.

This drastically improved the speed of the system. For low numbers of vehicles, each timestep takes little more than a few milliseconds on both the front and back end. 1000 iterations with 1000 vehicles used to take at least 16 minutes - after making this change it took just 50 seconds.

Additionally, this allowed much larger numbers of vehicles to be simulated and visualised at the same time - the back end will only send data to the front end once it has rendered the previous set of changes.

This also made it easier to add the ability to pause the simulation - by simply ceasing to send the `next` message, the back end does no further work, leaving the user able to explore the current state of the simulation in the browser.

Exploiting Parallelism

Initial version of the system simply did all their work on a single thread. There were a number of places were task level parallelism made it easy to add more threads and cores to the system to improve performance.

```
public void timestep()
{
    vehicles.stream().forEach(Vehicle::accelerationStep);
    vehicles.stream().forEach(Vehicle::slowStep);
    vehicles.stream().forEach(Vehicle::randomStep);
    vehicles.stream().forEach(Vehicle::moveStep);
    vehicles.stream().forEach(Vehicle::updateLocation);

    vehicles.stream().filter(v -> !v.isFinished()).collect(Collectors.toList());
}
```

Listing 3.2: The single-threaded `timestep` function

In Listing 3.2 we can see the use of the Java 8 Stream API to run the Nagel-Schreckenberg functions on each vehicle. However, one of the core features of the API is built-in support for concurrency. By replacing the calls to `stream()` with `parallelStream()`, Java will automatically split the computation over multiple threads, whilst ensuring that all processes have completed when the next line is executed. Minor changes were made to ensure that the filter step for removing finished vehicles from the collection was still thread-safe.

When adding new vehicles to the simulation, their initialisation uses GraphHopper to find the route to their destination. This takes orders of magnitude longer than the timesteps themselves, and as GraphHopper is thread-safe for making routing requests is an easy way to further improve performance.

EXPLAIN THIS BIT FURTHER MAYBE???

3.4.3 Architecture Improvements

One of the issues with the system at this point was the lack of support for multiple vehicle types - although there is a Vehicle class that could have been be subclassed, it was not easy to modify its behaviour without having to rewrite large portions of the code. As such, I decided a refactor of this part of the system was required to improve the architecture of the system.

Vehicle Refactoring

Following the refactor, the Vehicle and VehicleIterator have been changed into interfaces with the public methods originally implemented in the Vehicles class. `BaseVehicle` and `BaseVehicleIterator` are abstract classes that implement most of the boilerplate functionality. BaseVehicle holds the implementation of the Nagel-Schreckenberg model, with routing behaviour defined by the VehicleIterator. A subclass of BaseVehicle must implement only a single method - `getVehicleIterator()`, which creates a VehicleIterator of the correct type and with the right routing information.

For the standard routing algorithm, new `DijkstraVehicle` and `DijkstraVehicleIterator` classes have been created. As a way of verifying that multiple vehicle types are possible, I also created a `RandomVehicle` and corresponding `RandomVehicleIterator` that simply drive around at random with no overarching behaviour.

3.4.4 Metric calculations

The initial engine only allowed for viewing the results of an algorithm by looking at the visualisation - it is also important to be able to perform offline analysis of the data.

Brief calculations showed that storing the full movement of 64,000 vehicles could take up to 10GB of storage, suggesting that it was better to calculate metrics at each timestep and store those instead. There are three main types of metric - vehicle, route and network metrics.

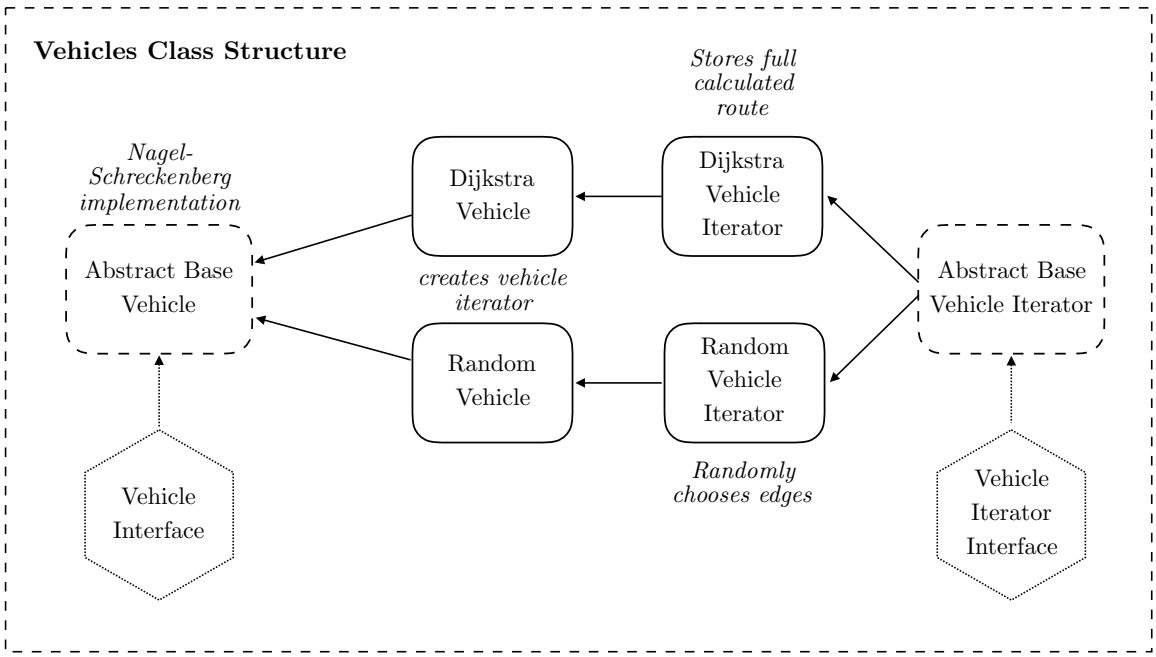


Figure 3.7: The Vehicle and VehicleIterator class structure

Vehicle Metrics

As their name suggests, vehicle metrics provide information about the state of one or more vehicles. They can be calculated at any time, so can be recorded and stored on each iteration. Vehicle metrics are the easiest way of getting a sense of the overall behaviour of the system at any point in time.

With the goal of understanding the levels of congestion, I tracked two main vehicle metrics: the number vehicles not moving at the maximum road speed, and the number of vehicles that slowed down due to a vehicle in front of them.

A new inner `Metric` class was added to MarmosetHopper, with simple data properties storing the average values for the two metrics mentioned above, as well as the total number of vehicles and the average speed (in cells per second) of the vehicles. The `toString` method has also been overridden to print the data in CSV format, whilst a static method returns the header for the CSV file to output.

Route Metrics

We can also better understand congestion by looking at how long a journey should take compared to how long it did take. The GraphHopper `GHResponse` class stores the length of time a route is expected to take. Although it does not include a realistic model of vehicle behaviour (so does not truly represent the correct time a journey would take, even on empty roads), the difference between expected and actual time is another metric that can be used to compare different vehicle behaviours.

Route metrics can only be recorded once the vehicle has reached its destination rather than whilst it's travelling. As such, I added a `printMetrics` function to BaseVehicle and provided implementations in DijkstraVehicle, which prints the expected time from GraphHopper and the actual number of iterations the vehicle took to reach its destination.

These metrics are output into a file that holds the id of the vehicle in question - each vehicle has its own file, meaning there is no need for centralised management of writing to disk.

Network Metrics

Network Metrics provide information about the roads themselves and how congested or occupied they are. Instead of providing numerical data for every edge (which provides very little information given how few cells/vehicles the average edge has), a visual approach was used, simply retaining the full set of vehicle positions and speed every 1000 iterations.

The code previously used to convert the Vehicle objects into strings was re-purposed and instead placed into an iteration file, meaning the data is human readable and easy to parse. Adding a simple input box with basic parsing code allows the data to be explored interactively after the simulation has finished, as can be seen in Figure 3.8.

3.4.5 Event System

Although the refactors mentioned above do allow for a large amount of flexibility, using new vehicle classes (or adding new behaviour during existing parts of the process) required modifying the source of the engine directly. Using a simple events system enables users of the engine to add code and functionality during key points of the programs execution without directly modifying the engine. Instead, users can call a `listenTo` method with a callback function that is executed when the event is triggered.

Event triggers were added in key locations so that this features would be useful. For example, an event is triggered at the start and end of each timestep, at the beginning and end of initialisation and when a new vehicle is added.

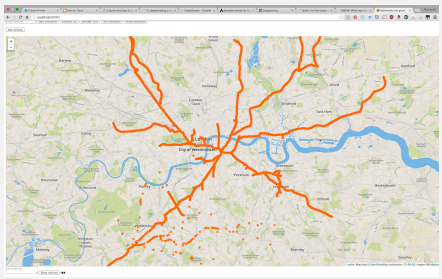


Figure 3.8: Post-simulation analysis of the 9,000th iteration of 15,000 vehicles

3.4.6 Offline Simulation

With the addition of metrics, it became clear that it would be useful to be able to run a simulation in the background and analyse the data later. One use case would be understanding how long it takes all vehicles to reach their destinations - another is for analysing very high density networks where it may not be desirable to view the data on screen.

A command line flag (`--file`) was added representing the number of vehicles to be simulated. The simulation creates a folder for the metrics including the number of vehicles and a Unix timestamp, allowing it to be uniquely identified.

However, the offline simulation appeared to be running slower than I had hoped given it was not constrained by the browser rendering. The VisualVM Java profiler was used to identify potential performance improvements whilst simulating. Interestingly, far more time was spent in the `updateLocation` step than I had expected - and given that the physical location is only used for display and not internal routing, a flag was added to disable the location updates for every timestep. Instead, the location is only updated when required (e.g for outputting the locations every 1000 iterations).

Hot Spots - Method	Self Time [%]	Self Time	Self Time (CPU)	Total Time	Total Time (CPU)
com.graphhopper.marmoset.vehicle.BaseVehicle.**updateLocation** ()		2,196 ms (24.7%)	2,196 ms	2,392 ms	2,392 ms
com.graphhopper.marmoset.vehicle.BaseVehicle.**addToBuffer** ()		603 ms (6.8%)	603 ms	703 ms	703 ms
com.graphhopper.marmoset.vehicle.DijkstraVehicleIterator.**duplicate** ()		279 ms (3.2%)	279 ms	279 ms	279 ms
com.graphhopper.marmoset.MarmosetHopper$$Lambda$15.1276042862.**ac**		102 ms (1.2%)	102 ms	2,494 ms	2,494 ms
com.graphhopper.marmoset.MarmosetHopper.**timestep** ()		93.3 ms (1.1%)	0.000 ms	2,587 ms	2,494 ms

Figure 3.9: VisualVM Profile of the most time consuming functions

Removing the location updates had a drastic improvement to offline performance, meaning simulations with large numbers of vehicles could be simulated to completion in a reasonably short amount of time.

3.5 Algorithm Design and Implementation

As a way of exploring the capability of the simulation engine, a multi-vehicle routing algorithm was designed, implemented and tested.

3.5.1 Algorithm Design

I chose to design a V2I algorithm, as there would be a substantial amount of additional code required to simulate realistic V2V communication. It is also beneficial that V2I simulation can apply to both high and low density situations as it is not limited by the distance to the nearest vehicle. Instead, access to a central system that knew the location and planned destination of every vehicle in a city was assumed. The algorithm would then provide routes for each vehicle in the system.

The initial implementation of the Marmoset algorithm is described below. It is important to note that this is not the final algorithm - the goal was to find a potentially effective and then optimise and improve it using the simulation engine. We will describe the behaviour of individual vehicles and the central system separately.

Vehicle Behaviour

Individual vehicles make their current route and position available to the central system at all times. The vehicles request routes from the system and then follow them directly. A vehicle requests a new route after a random interval (based on a predetermined parameter).

Central System Behaviour

The central system stores the number of vehicles that have been told to route along each edge, called the Expected Map. It is initialised with zero values for all edges on start-up.

At a fixed interval, the system updates the expected map by multiplying every edge by a damping factor that is less than 1. It then adds the edges in each vehicle's current route to the expected map.

When a route is requested, the data from the expected map is used in conjunction with a congestion function to modify the weight of edges based on their expected density. This will return a route that avoids high-congestion roads, which will be reflected in the expected map upon its next update.

A congestion function was chosen that was similar to the data found by <RESEARCHERS/CONGESTION FUNCTION STUFF HERE>

Design Justification

The goal of the expected map is to help vehicles avoid roads that are likely to have high levels of traffic. However, a naive approach to this would result in oscillatory behaviour between optimal and sub-optimal routes, as can be seen in Figure 2.2 in Section 2.1.2. As such, the expected map is retained for further requests. Updating the expected map results first multiplies each value by the damping factor. The goal of this is to stop the system from having too much of a memory (and hence over-penalising roads that will have many vehicles on them). This factor can be adjusted to define how much memory the system will have of the vehicle's locations.

Furthermore, the system can handle the expectation that most routes will change at some point whilst the vehicle is on the road. The random rerouting was chosen to ensure that the busy areas will not be avoided by all vehicles once the expected map has shown that they will be busy. If every vehicle was

rerouted simultaneously, the vehicles would completely avoid the busy roads and hence fail to use the network capacity available to them.

3.5.2 Implementation

<create a nice pretty diagram k>

The implementation of this algorithm made use of the new event system, and required a subclassing two GraphHopper types. A central self-driving vehicle controller class was also created that manages the behaviour of all the vehicles.

In keeping with the new system architecture, `SelfDrivingVehicle` and `SelfDrivingVehicleIterator` classes were created. The SelfDrivingVehicle class is similar to the DijkstraVehicle, but offers new methods for recalculating the route using the expected weighting. The SelfDrivingVehicleIterator is a subclass of the DijkstraVehicleIterator, but adds a simple method for replacing the list of edges once a new list has been calculated by the SelfDrivingVehicle class.

The expected map was implemented by creating a GraphHopper weighting class, `ExpectedWeighting` (see Section 2.2.2). It stores an array of floating point values representing the expected map (`double expectedMap[]`) and has a `updateExpectedMap` method that applies the damping factor and adds vehicle routes to the map. The weighting's `calcWeight` method uses the curve described in the previous section to return a weighting for an edge given the value in the expected map and the speed of the road.

This is all orchestrated by the `MultiSDVController` class, which stores a list of all SelfDrivingVehicles. It subscribes to the "vehicle:add" event to create its own list of vehicles, as well as the "timestep:end" event for triggering its rerouting and expected map recalculation functionalities.

The MultiSDVController was also optimised to exploit parallelism for the re-routing operations. As it was not a use case suited to the parallel Stream API, an `ExecutorService` is used to manage and shutdown the threads for routing as required.

3.5.3 Testing

Algorithmic Adjustments

Initial tests of the algorithm showed poor performance and many failed routes. Use of the visualisation aspect of the routing engine was crucial to identifying the casuses of this.

The first issue was caused by the congestion function. As the expected value for each edge represents how many vehicles will ever drive on that road (rather than at one time), the numbers are usually much larger than the number of vehicles that would be on the road at any given time. As such, the values returned by the congestion function will often be very close to (or will be exactly 0). The end result of this was that after a few recalculations of the expected map, any popular edge was completly removed from the graph, and hence connections to high-congestion areas of the map were removed entirely.

It is not entirely undesirable to fully remove roads that are very high congestion from the map. However, this would require accurate knowledge that a given road will be blocked - due to the non-deterministic nature of the vehicles (caused by the re-routing opreation), this cannot be guaranteed and hence edge removal is not appropriate for this routing algorithm. In response to this discovery, the congestion function was modified to have a lower bound of 25% of the original road speed, using the same curve shape as before.

The other issue was that many roads near a vehicle's destination would have very high values in the expected map, creating routes that avoided moving in the right direction only due to the fact that the vehicle was attempting to avoid penalties creating by its own routes. This was fixed by using a progress function - instead of simply incrementing the value at the edge by one, it is incremented by a

value determined from the progress function. The progress function takes in a percentage - the edges percentage in the route - and outputs a value that decreases as we reach the vehicle's destination. The justification for this behaviour is that a vehicle is much more likely to visit an edge nearer to it than further away, as it has a higher probability of having re-routed by then.

Additionally, it was found that random routing did not have the expected results - many vehicles never adjusted their routes, whilst others did it 7 times during a single simulation. This is problematic as the end result is that too many vehicles remain on the highly congested routes, even if it is known that they should be avoided.

Parameter Adjustments

The algorithm offers many parameters that can be adjusted, listed below. Some of these parameters are specific to the Marmoset algorithm, whilst others are general parameters of the simulation engine itself.

- **Congestion function** - can be modified to reduce penalties overall, behave differently for different types of road, have a longer or shorter 'tail', etc.
- **Progress function** - can be modified to decrease or increase values on nodes further away.
- **Re-routing percentage** - intially set to re-route 0.1% of vehicles each iteration, can be modified to change how quickly the vehicles react to high-congestion areas.
- **Cell size** - can increase or decrease number of vehicles each road can have, also affects max speed of roads.
- **Vehicle density** - overall number of vehicles can be adjusted to identify inflection points and understand interaction between vehicles on the road.
- **Vehicle ratios** - parameter for determining what proportion of vehicles are self driving, can be used to analyse the impact of 'selfish' drivers on congestion.
- **Vehicle destinations** - start and end location of vehicles can be adjusted to better model/understand traffic flow under different conditions.
- **Slow probability** - modifying the probablity a vehicle slows down (as described by the Nagel-Schreckenberg algorithm) can be adjusted to simulated different types of driving behaviour.

As part of the evaluation of the algorithm, each of these parameters was adjusted and a comparison was made between the outcome using DijkstraVehicles or SelfDrivingVehicles exclusively.

Evaluation

This section will discuss testing methodology, with the results of the algorithm and the overall performance of simulation engine discussed in Chapter 4 below.

Evaluating how two different routing algorithms would behave in any situation is a challenging task with a near unlimited scope, particularly with complex algorithms relying on the interactions between tens or even hundreds of thousands of separate entities. As such, the scope of the evaluation has been limited one key scenario in a particular location. London has been chosen for the location, due to the author's familiarity with its roads and expected congestion. The tests will be a simple simulation of rush hour, when 64,000 vehicles [**?**] travel into the city centre. Congestion during this period of time is often at its worse, in spite of attempts by TfL to reduce travel at peak times.

Tests will focus on a single parameter at a time. The tests for different cell sizes and vehicle density will be run with both the Marmoset and Dijkstra algorithms, whilst the tests for the Marmoset progress and congenstion functions will only be compared to other Marmoset tests.

Interestingly, when testing the rush hour simulation using Dijkstra's algorithm with more than around 30,000 vehicles found a strange bug - namely, the simulation would not terminate due to congestion in a closed loop around Elephant & Castle roundabout. All vehicles would slow to a halt along a fixed number of fully congested roads, as can be seen in Figure 4.3.

As such, new termination conditions were added. If every vehicle has slowed, is not at the road's maximum speed and the average speed of the vehicles is less than 0.01, the simulation terminates early. For 60,000 vehicles, early terminaton happens after approximately 21,000 iterations - with 30,000 vehicles this state is reached in around 12,000 iterations, whilst 20,000 vehicles terminates completely (with 0 vehicles yet to reach their destination) in a little over 9,000 iterations.

Chapter 4

Critical Evaluation

4.1 Marmoset Algorithm Evaluation

A simple model of rush hour was created for the purpose of evaluating the Marmoset algorithm. Each vehicle is given a random location and destination. The starting location is randomly distributed within the entirely of London, bounded by the M25. The destination is randomly distributed across the centre of London only, roughly covering Zone 1.

4.1.1 Vehicle Density Comparisons

The quantity of vehicles on the road clearly has the largest impact on congestion. Each algorithm was tested with 10,000 to 80,000 vehicles in increments of 10,000.

Dijkstra's Algorithm

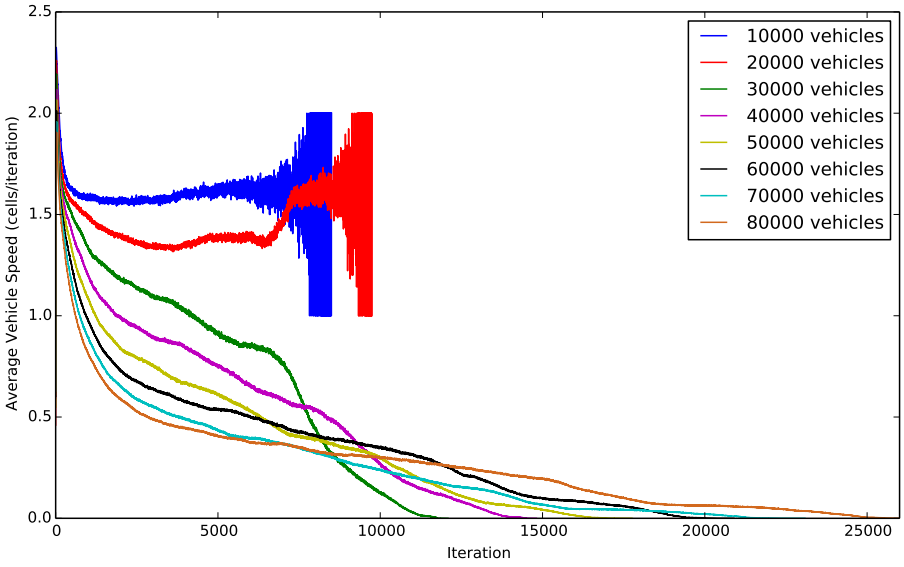


Figure 4.1: Average speed at each iteration for vehicles routing with Dijlkstra's Algorithm

The graph in Figure 4.1 shows two different cases for routing with Dijkstra's Algorithm. When simulating with 10,000 and 20,000 vehicles, we see the behaviour of the algorithm when all vehicles reach their destination and terminate successfully. The remaining six simulations show the behaviour of the algorithm when it fails to terminate and the vehicles slow to a halt.

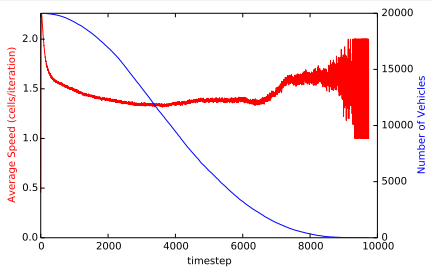


Figure 4.2: Comparision of speed an remaining number of vehicles using Dijkstra's algorithm with 20,000 vehicles.

In the successful termination cases, we see three stages. The first exhibits a slow decline in average speed as we reach the congested state. We then see a stage where the speed remains fixed, whilst the vehicles slowly move towards their destinations. Finally, we see a period with increased speed volatility. This is due to the decreased volume of vehicles causing the average to change much faster, as can be seen in Figure 4.2.

In the case of simulations that do not terminate normally, we see the same first two stages (pre-congestion and congestion respectively), but at a certain inflection point the average speed declines faster until it reaches zero. This is most notable for the 30,000 vehicle case, where the inflection point can be seen at around iteration 7,000, after which the average speed enters a steep decline.

The cause of the simulation failure can be seen in Figure 4.3 - a roundabout in central London becomes completely congestion, stopping any vehicle attempting to use the roundabout. As the cars continue to pile up, more and more main roads become completely full until no vehicles are capable of any movement.

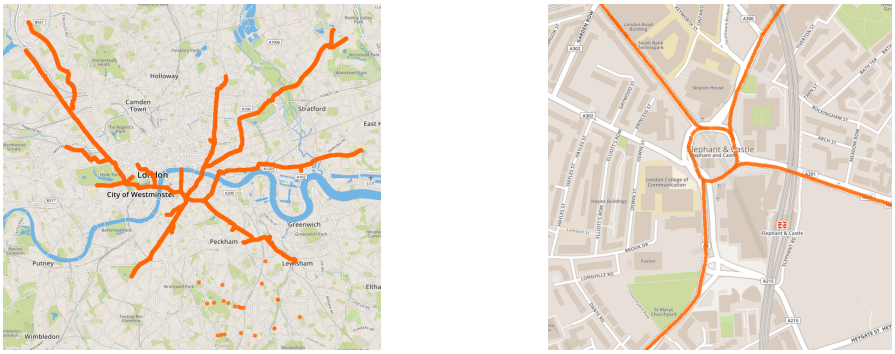


Figure 4.3: The system state shortly before termination

Marmoset Algorithm

We now compare this to the Marmoset routing algorithm. The most notable difference is that the Marmoset algorithm successfully terminates even with 80,000 vehicles attempting to enter the city centre (16,000 more than in rush hour).

Figure 4.4 shows that the Marmoset algorithm exhibits the same behaviour as Dijkstra's Algorithm on successful termination, but without the limitation on the number of vehicles that can be simulated. The simulation displays the three stage behaviour as before, with the congested stage elongating as the number of vehicles increases. We can also see a large difference in the amount of time it takes for the simulation to terminate, falling into three separate clusters - less than 40,000 vehicles, 50,000 to 70,000 vehicles and 80,000 vehicles. The reason for this is not clear from this graph alone.

Looking at the iteration data for the inflection point into the congested state in Figure 4.5, we can start to understand what the cause of this behaviour may be. At iteration 11,000, we see similar patterns of behaviour for both sets of vehicles. For the 50,000 vehicle simulation, we see three key areas of congestion (circle in green on both maps). For the lower density simulation, these three areas are distinct - once a

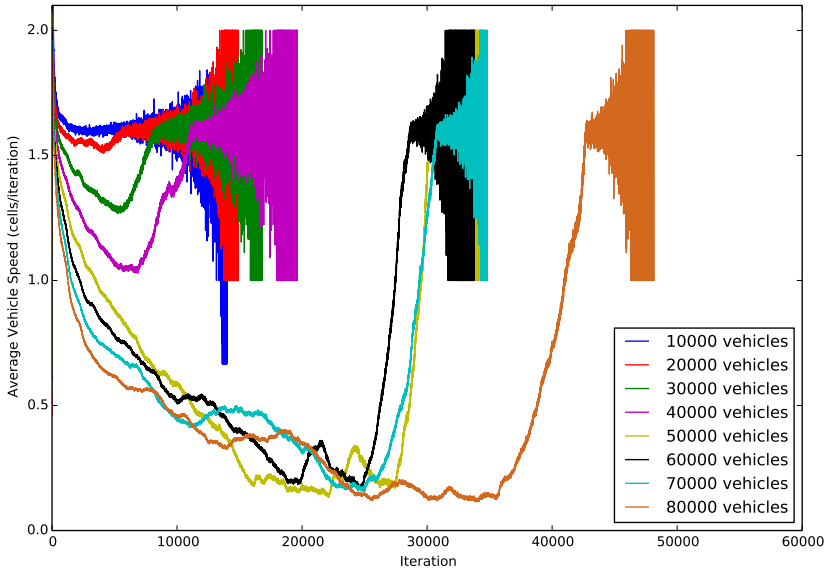


Figure 4.4: Average speed at each iteration for vehicles routing with the Marmoset Algorithm

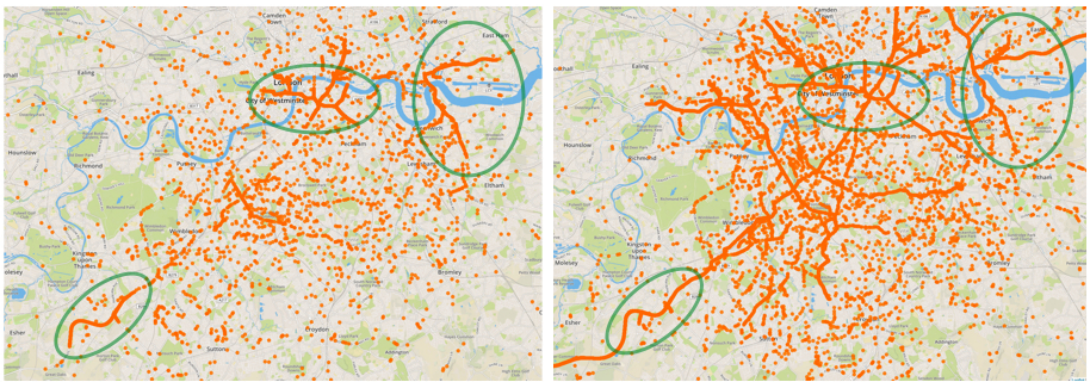
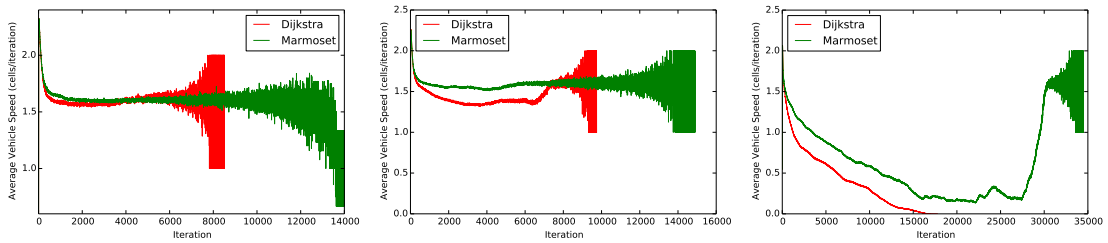


Figure 4.5: The 11,000th iteration of 50,000 and 80,000 vehicles respectively.

vehicle has left the congested roads it enters an area of low congestion. In the 80,000 vehicle simulation, this is not the case - instead, the highly congested roads are joint together, requiring significantly longer to clear. Hence we can conclude that the clustering of total travel time is a proprety of the map and routes that have been chosen to run on it - as the number of vehicles on the road increases, areas prone to congestion increase in size and connect, causing sudden increases in completion time with only a small increase in the number of vehicles.



(a) 10,000 vehicles (b) 20,000 vehicles (c) 50,000 vehicles

Figure 4.6: Comparison of average speed between Dijkstra's algorithm and the Marmoset algorithm

Finally, we look at a direct comparision between the Marmoset algorithm and Dijkstra's algorithm at different vehicle densities. In Figure 4.6, we see that when Dijkstra's algorithm does terminate, vehicles reach their destinations much faster than with the Marmoset algorith, despite a lower average speed. This is likely due to the 'selfish' behaviour of Dijkstra's algorithm allowing certain vehicles to reach their destinations earlier. With lower vehicles densities, this frees up the roads and enables other vehicles to reach their destinations sooner. However, with more vehicles on the road the congestion level becomes too high, and hence the vehicles are blocked from reaching their destination.

4.2 Marmoset Simulation Engine Evaluation

Chapter 5

Conclusion

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Appendix A

An Example Appendix