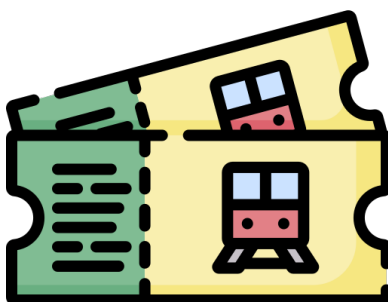




OLLSCOIL NA GAILLIMHE  
UNIVERSITY OF GALWAY

# Iompar: Live Public Transport Tracking



College of Science & Engineering  
Bachelor of Science (Computer Science & Information Technology)

## Project Report

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# Chapter 1

## Introduction

### 1.1 Project Overview

The purpose of this project is to create a useful & user-friendly application that can be used to track the current whereabouts & punctuality of various forms of Irish public transport, as well as access historical data on the punctuality of these forms of transport. In particular, this location-tracking takes the form of a live map upon which every currently active public transport service is plotted according to its current location, with relevant information about these services and filtering options available to the user.

The need for this project comes from the fact that there is no extant solution for a commuter in Ireland to track the current location and whereabouts of all the different public transport services available to them. There are some fragmented services that purport to display the live location of one particular mode of transport, such as the Irish Rail live map<sup>28</sup>, but this can be slow to update, displays limited information about the services, and only provides information about one form of public transport.

The need for an application that tracks the live location & punctuality of buses in particular is felt here in Galway, especially amongst students, as the ongoing housing shortage drives students to live further and further away from the university and commute in, with Galway buses often being notoriously unreliable and in some cases not even showing up, many commuters could benefit from an application that tells them where their bus actually is, not where it's supposed to be.

The name of the application, “Iompar” (IPA: /'ʊmˠpˠəɾ/), comes from the Irish word for “transport” but also can be used to mean carriage, conveyance, transmission, and communication<sup>32</sup>; it was therefore thought to be an apt name for an application which conveys live Irish public transport information to a user.

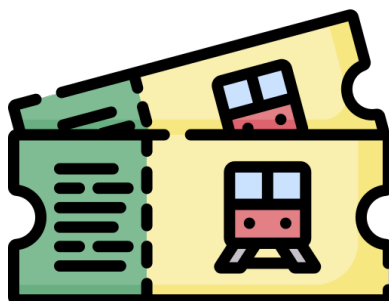


Figure 1.1: Iompar project icon<sup>37</sup>

## 1.2 Objectives

### 1.2.1 Core Objectives

The core objectives of the project are as follows:

- Create a live map of train, DART, bus, & Luas services in Ireland, which displays the real-time whereabouts of the service, relevant information about that particular service, and the punctuality of the service, to the extent that is possible with publicly-available data.
- Make the live map searchable to facilitate easy navigation & use, such as allowing the user to find the particular service in which they are interested.
- Provide an extensive array of filters that can be applied to the map to limit what services are displayed, including filtering by transport mode & punctuality.
- Collect & store historical data about services and make this available to the user as relevant, either via a dashboard or via relevant predictions about the punctuality of a service based off its track record.
- An easy-to-use & responsive user interface that is equally functional on both desktop & mobile devices.

### 1.2.2 Secondary Objectives

In addition to the core objectives, some secondary objectives include:

- Many of those who commute by bus don't have a specific service they get on as there are a number of bus routes that go from their starting point to their destination, and therefore it would be useful to have some kind of route-based information rather than just service-based information.
- A feature which allows the user to "favourite" or save specific services such as a certain bus route.
- Implement unit testing and obtain a high degree of test coverage for the application, using a unit testing framework such as PyUnit<sup>96</sup>.
- The ability to predict the punctuality of services that will be running in the coming days or weeks for precise journey planning.
- User accounts that allow the user to save preferences and share them across devices.
- User review capability that allows users to share information not available via APIs, such as how busy a given service is or reports of anti-social behaviour on that service.
- Make the web application publicly accessible online with a dedicated domain name.
- Port the React<sup>68</sup> application to React Native<sup>67</sup> and make the application run natively on both Android & iOS devices, and publish the native applications to the relevant software distribution platforms (Apple App Store & Google Play Store).

### 1.2.3 Additional Objectives

Some additional objectives beyond the objectives that were specified before beginning development of this project were added as the project was developed, including:

- Remember a user's preferences the next time they visit the page.
- Optimise the performance of the frontend to process data as fast and as efficiently as possible.
- Make the UI design comply with Nielsen's 10 Usability Heuristics<sup>88</sup>.
- Utilise the user's geographical location to allow them to filter results by proximity to them.
- Optimise the backend to stay within the limits of AWS Free Tier<sup>52</sup>.
- Create a CI/CD pipeline to automatically test and deploy new code.

### 1.3 Use Cases

The use cases for the application are essentially any situation in which a person might want to know the location or the punctuality of a public transport service, or to gain some insight into the historical behaviour of public transport services. The key issue considered was the fact that the aim of the project is to give a user an insight into the true location and punctuality of public transport: where a service actually is, not where it's supposed to be. The application isn't a fancy replacement for schedule information: the dissemination of scheduling information for public transport is a well-solved issue. Schedules can be easily found online, and are printed at bus stops and train stations, and displayed on live displays at Luas stops. Public transport users know when their service is *supposed* to be there, what they often don't know is where it *actually* is. The application is to bridge this gap between schedules and reality.



Figure 1.2: Photograph of a TFI display erroring due to the clocks going forward [Taken: 2025-03-30]

Furthermore, any existing solution that attempts to give public transport users live updates can be unreliable, slow to update, difficult to use, and only supports one type of transport which forces users to download or bookmark numerous different website and apps, and learn the different interfaces & quirks for each. Figure 1.2 above is a recent example of this: the few bus stops in Galway that actually have a live information display all displayed error messages on Sunday the 30<sup>th</sup> of March because the clocks went forward by an hour and the system broke. There is a need for a robust and reliable solution for public transport users who want to know where their service is.

With this being said, the main use cases that were kept in mind during the design process were:

- A bus user waiting for their bus that hasn't shown up when it was supposed to and needs to know where it actually is so they can adjust their plans accordingly;
- A train user waiting for their train that hasn't shown up;
- A train user on a train wondering when they will arrive at their destination;
- A Luas user who wants to catch the next Luas from their nearest stop.

### 1.4 Constraints

The primary constraint on this project is the availability of data. Different public transport providers have different APIs which provide different types of data: some don't provide location data, others don't provide punctuality data, and others don't have any API at all. Other constraints include:

- API rate limits & update frequencies;
- Cost of compute & storage resources;
- API security policies which limit what kind of requests can be made and from what origin;
- Availability of live data for certain geographical locations.

## Chapter 2

# Research & Planning

### 2.1 Similar Services

As background research for this project, a list of transport-tracking applications available online was compiled, with each application then being analysed to determine their positive characteristics from which inspiration should be taken and their negative characteristics which should be avoided or fixed.

#### 2.1.1 Irish Rail Live Map

The Irish Rail Live Map<sup>28</sup> displays the current location of Irish Rail intercity, commuter, & DART services, with clickable icons that display information about the selected service including the lateness of the train and its next stop.

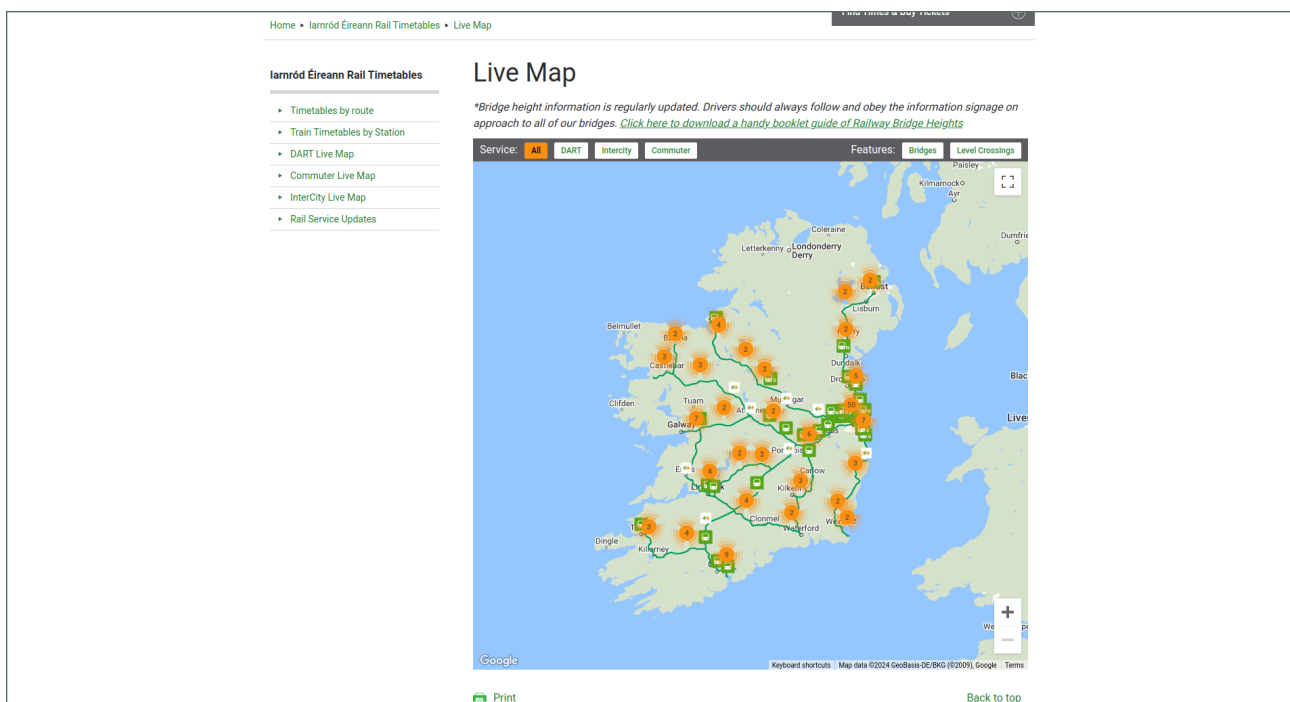


Figure 2.1: Irish Rail live map

Strengths of the Irish Rail live map that were identified include:

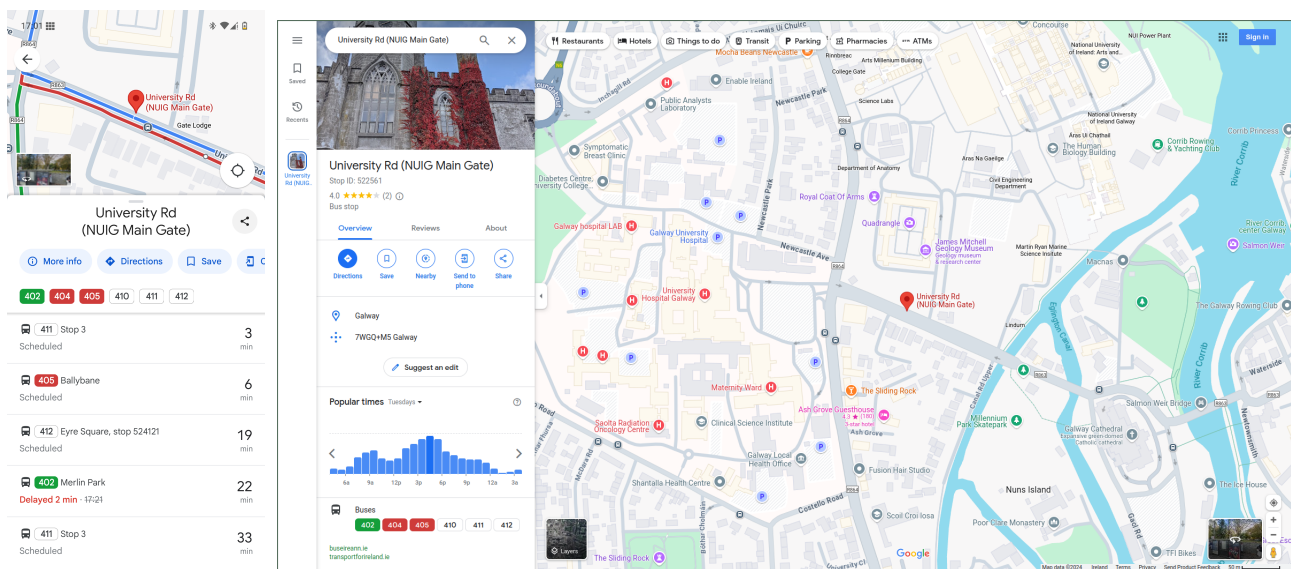
- Services can be clicked on to display a pop-up panel showing the punctuality of that service, the next stop of that service, and the stops on that service's route;
- There are basic filtering options to display a specific type of service such as DARTs;
- Bridges, level crossings, & stations are shown on the map. The stations can also be selected and information about them viewed.

Limitations of the Irish Rail live map that were identified include:

- The pop-up information panel covers the entire map and hides it;
- There is no search feature to find a specific service;
- The filtering options are greatly limited;
- The UI is slow and not particularly responsive;
- There is no visual distinction between the icons for different kinds of services.

### 2.1.2 Google Maps

Google Maps<sup>40</sup> is a common choice for finding the next the upcoming nearby services and route planning. It covers a number of different types of service, include buses & trains. The mobile UI has been included here alongside the desktop UI as there is no live service information available on the desktop version of Google Maps.



(a) Mobile view

(b) Desktop view

Figure 2.2: Google Maps mobile & desktop views

Strengths of Google Maps include:

- It facilitates route determination, and can tell the user about what services they need to take to get any arbitrary location;
- The mobile version lists when services are due and how long they are expected to be delayed.

Limitations of Google Maps include:

- There is no live service information on the desktop version;
- Vehicle locations are not plotted on the map and thus the user cannot tell where the service actually is;
- Specific services cannot be searched for, and there is no filtering to display only a certain type of service.

### 2.1.3 TFI Live Departures

The TFI Live Departures map<sup>73</sup> shows live departure information for both bus stops and train stations.

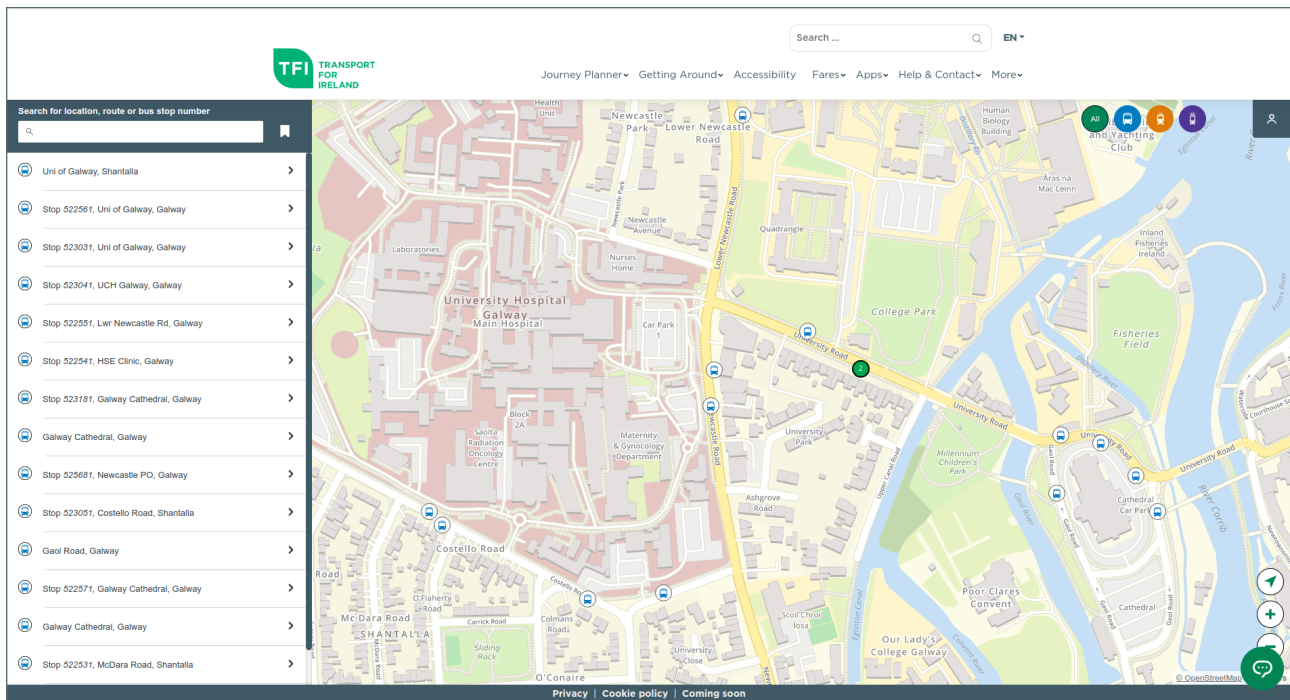


Figure 2.3: TFI Live Departures map

Strengths of the TFI Live Departures map include:

- A stop or a station can be clicked on to show a pop-up information panel that appears at the side of the screen and does not cover the map;
- There is a powerful search feature that allows the user to search by location, route, or stop number;
- If a specific route is selected, the route is highlighted on the map and its stops are plotted;
- The map is highly detailed, making it easier to find a particular location on the map and find nearby services.

Limitations of the TFI Live Departures map include:

- The map doesn't show the live locations of the services, it shows the stops or stations from which the services depart;
- The map has no filtering options beyond the search feature;
- The map has to be zoomed in very far to actually display the stations in that area, making the map more difficult to use & navigate;
- It doesn't say whether or not services will be delayed or where they currently are, only saying when they are scheduled for.

### 2.1.4 Flightradar24

Flightradar24<sup>2</sup> is a live-tracking application for monitoring aeroplane & helicopter flights; while not public transport and therefore not within the scope of this project, this application has nonetheless chosen to be included in this analysis as it is particularly good example of transport-tracking UI, and is highly successful



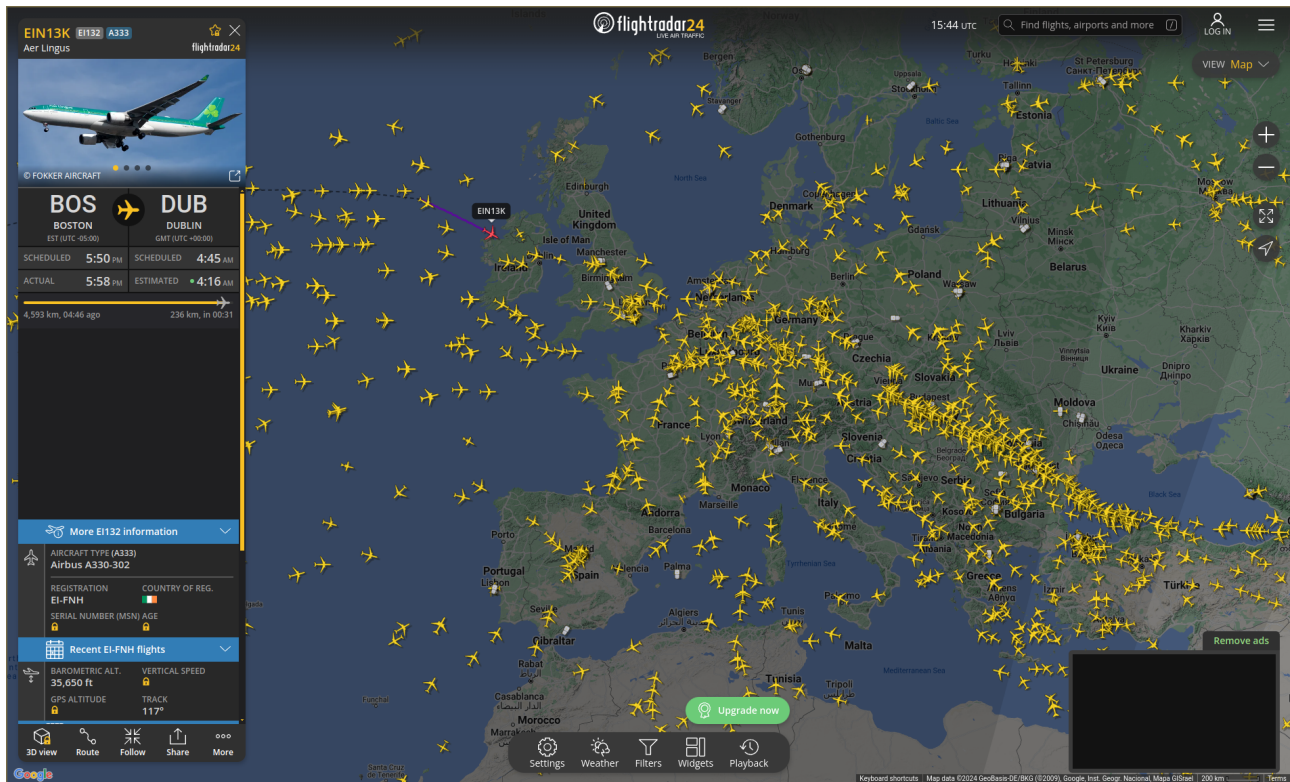


Figure 2.4: Flightradar24 UI

Strengths of Flightradar24 include:

- Ability to select a given service and open a pop-up panel that displays details about that service;
- Selected services are highlighted in red on the map;
- The information panel shows the scheduled departure time, the actual departure time, the scheduled arrival time, & the estimated arrival time;
- The information panel displays an image of the selected vehicle;
- Searching & filtering features;
- Larger planes have larger icons on the map and helicopters have distinct icons from planes.

Limitations of Flightradar24 include:

- Bookmarking a vehicle requires a paid account;
- The UI contains advertisements for free users.

## 2.2 Data Sources

### 2.2.1 Irish Rail API

Live train data, including DART information, can be sourced from the Irish Rail Realtime API<sup>29</sup>. This is a mostly RESTful-like API which seems to be a legacy hybrid between REST<sup>31</sup> (Representational State Transfer) and SOAP<sup>13</sup> (Simple Object Access Protocol): unlike SOAP, it accepts HTTP GET requests instead of a HTTP POST of an XML envelope containing the request, but it doesn't use resource-based URLs and returns a namespaced XML response instead of plain XML. Nonetheless, it can be interacted with in more or less the same way as one would a REST API to obtain data. It provides a number of endpoints, with the relevant endpoints to this project being:



- `/getAllStationsXML` and `getAllStationsXML_WithStationType?StationType=<A,M,S,D>` which returns information about Irish Rail stations including latitude & longitude.
- `/getCurrentTrainsXML` and `/getCurrentTrainsXML_WithTrainType?=<A,M,S,D>` which returns information about all the currently running trains (with latitude & longitude), including trains that are due to depart within 10 minutes of the query time.
- `/getStationDataByCodeXML?StationCode=<station_code>` which returns the trains due to serve the station in question in the next 90 minutes.

The documentation page for the API warns that some areas are not fully supported for real-time information due to the central signalling system being subject to “ongoing work to support this real-time facility” and that, in the case that a train is in an area of the rail system where real-time data is unavailable, the scheduled data for the train will be returned instead. The extent to which coverage of real-time data is available today is unclear, as the API documentation page has not been updated since the 8<sup>th</sup> of December 2015 at the very latest<sup>77</sup> (although a more realistic estimate would be 2011 based off example dates used in the documentation) and so is now likely nearly a decade out-of-date, but this does not affect how the data will have to be processed very much; since the scheduling information is just returned in the absence of real-time data, this can be treated as a best approximation of the real-time data and does not need to be handled differently.

### 2.2.2 Luas API

The Luas API<sup>74</sup> is an XML-over-HTTP API with a REST-like interface that provides real-time updates of expected Luas arrivals for a given Luas stop, based upon the location data of the trams from their Automatic Vehicle Location System (AVLS). No location data about individual trams is made publicly available; instead each stop must be queried individually using the `/get.ashx?action=forecast&stop=<stop_code>` endpoint, which returns an XML file with a list of all inbound & outbound trams due into that stop.

### 2.2.3 NTA GTFS API

The National Transport Authority (NTA) provides a General Transit Feed Specification (GTFS)<sup>25</sup> REST API named GTFS-Realtime<sup>8</sup> which provides real-time location data about buses operating in Ireland. GTFS is a standardised format for public transport schedules & associated geographic information that provides both static data (such as timetables, routes, & stop locations) and real-time data (such as live location data). The static GTFS feed is made up of comma-separated value files (as is standard) and the real-time data is returned in JSON format from the REST API endpoint `gtfsr/v2/Vehicles[?format=json]`. It is free to use, but requires an API key for access.

## 2.3 Technologies

### 2.3.1 Backend Technologies

#### Server-Based versus Serverless Architectures

The first choice to be made for the backend technologies for this project was whether the backend should be designed using a server-based or serverless architecture. A traditional server-based model was initially considered, either running on its own dedicated hardware or making use of a Virtual Private Server (VPS)<sup>112</sup> but was ultimately rejected. A server-based architecture requires extensive management of infrastructure, including the provisioning of hardware, system administration, and maintenance of the server application itself. Despite extensive personal experience with Linux-based and UNIX-like operating systems, the ongoing administration of a server would distract from the development of the application itself, and would be very difficult to scale to make the application available to a large number of users. While scaling issues could be partially mitigated with the utilisation of containerisation and a server-based microservices architecture<sup>47,103</sup> using technologies such as Docker<sup>61</sup>, it would nonetheless take a large amount of administrative effort to scale the application as usage demands grew.

In contrast, serverless architectures<sup>27,42,4</sup> abstract away these infrastructure concerns, allowing the focus of the project to be solely on the application logic. Since serverless functions are invoked on demand and billing for serverless models

is based solely upon the usage, serverless architectures are generally much more cost-effective for the workloads with variable or intermittent traffic that would be expected for a user-facing application such as this one. The serverless model lends itself especially well to a microservices architecture, which allows the system to be broken into small, independent services responsible for their own pieces of functionality, with each microservice being independently deployable and scalable. Instead of establishing or purchasing server infrastructure in advance, a serverless architecture can automatically scale up or down to meet the demand put upon it, preventing outages when large strain is put upon the service and preventing excessive financial or computational costs when there is low usage; the issue of over-provisioning or under-provisioning of compute resources is entirely circumvented, and the need for load balancers is eliminated entirely. Serverless functions support event-driven architecture, making them a natural fit for a system that must react to user demands as they occur. Furthermore, the fast time-to-production of serverless architectures results in faster iteration & experimentation, easier integration into CI/CD pipelines for continuous delivery, and simplifies rollbacks (should they be necessary) by deploying only small, isolated units, all without the need to spin up servers or configure deployment environment.

The ephemeral nature of serverless functions makes them highly fault-tolerant, as an error in a function execution will only affect that execution, whereas an improperly handled error in a server architecture could, in the very worst-case scenario, bring the entire system down and require a reboot. Moreover, although not especially relevant for this project as it does not handle sensitive data, the attack surface for a serverless architecture is much smaller and there is no need to manually configure server patches or firewall rules, as these are handled by the serverless provider. For these reasons, a serverless architecture was chosen for this project.

### Serverless Platforms

A number of serverless platforms were considered for this project, including Amazon Web Services (AWS)<sup>101</sup>, Google Cloud<sup>17</sup>, Microsoft Azure<sup>85</sup>, and Cloudflare<sup>60</sup>. While these platforms have innumerable differences, and are better and worse suited for different applications, a brief overview of their strengths & weaknesses as considered for this project is as follows:

- AWS has a mature & extensive ecosystem with broad service integration and a generous free tier, but its complexity can result in a steeper learning curve and a more complex initial set-up.
- Google Cloud has a simpler set-up, and tight integration with Firebase & Google APIs along with a similarly generous free tier, but fewer advanced features, less control over configuration, and a less extensive ecosystem.
- Microsoft Azure has a deep integration with the Microsoft ecosystem such as SQL server<sup>86</sup>, but less community support and a steep learning curve for non-Windows developers.
- Cloudflare has extremely low latency, excellent support for edge computing<sup>48</sup> (running on servers geographically close to users), and is great for lightweight apps, but has extremely limited memory and runtime, making it unsuitable for heavy backend logic. Its database & storage solutions are also not as mature or as scalable as comparable solutions.

AWS and Google cloud offer the most generous free tiers, while Cloudflare has very tight limits (CPU time is limited to 10ms maximum in the free tier<sup>59</sup>) and thus is only suitable for very lightweight tasks, not the kind of extensive data processing that this application will be engaging in. Therefore, AWS was chosen as the serverless platform for this project as it was deemed to be the most flexible & affordable option.

### Relational versus Non-Relational Databases

AWS offers a wide array of relational and non-relational database services, so the next choice was between a relational & non-relational database. **Relational databases** store data in tables using fixed schemata consisting of rows & columns, and use SQL for querying; relationships between tables are strictly enforced with the use of foreign keys. These rigid, pre-defined schemata are excellent for data integrity & relational consistency, and are suitable for applications in which relationships between entities are complex and querying across those relationships is common.

**Non-relational databases** store data in more flexible formats, such as key-value pairs, JSON documents, or graphs.

They are more suitable to scaling horizontally and for handling unstructured or semi-structured data. The simplified structure means that they can be very high performance for simple read/write patterns, and are ideal for applications that handle large volumes of fast-changing or unstructured data.

For this application, data is semi-structured and varies greatly by API source. The data is updated very frequently, which would require many **JOIN** operations or schema migrations for a normalised relational database. Non-relational databases, on the other hand, offer flexibility for heterogeneous transport data with different attributes, are more suitable for real-time data ingestion & retrieval due to low-latency reads & writes, and can support on-demand scaling without the need for the manual intervention required by relational databases to be scaled up; a non-relational database structure was selected for this reason.

AWS offers several non-relational database services, each of which is optimised for a different use case<sup>102</sup>:

- **Amazon DynamoDB**<sup>106</sup> is a fully-managed, serverless No-SQL database designed for low-latency, high-throughput workflows that supports storing data as key-value pair or as JSON-like documents. Key features of DynamoDB include the choice between on-demand or provisioned capacity, global tables for replication across multiple geographic regions, and fine-grained access control with Amazon Identity and Access Management (IAM).
- **Amazon DocumentDB**<sup>105</sup> is a fully-managed, document-based database using JSON-like BSON with MongoDB compatibilities, designed for applications using MongoDB APIs. However, unlike DynamoDB, it is not fully serverless, and is instead a managed cluster-based service that must be provisioned & scaled manually.
- **Amazon ElastiCache**<sup>107</sup> is an in-memory data store for extremely fast caching (sub-millisecond response times) and changing data, with data stored only per session. However, it cannot be used for persistent data storage, making it insufficient as a sole database service for this application.
- **Amazon Neptune**<sup>108</sup> is a managed database for storing & querying relationships using graph models, generally used for recommendation engines & knowledge graphs and therefore not suitable for this application.
- **Amazon Timestream**<sup>110</sup> is a time-series database that is purpose-built for the storage and analysis of time-series data, i.e., timestamped data. This would be a good choice for the historical analysis side of this application, but inappropriate for real-time data.
- **Amazon OpenSearch service**<sup>111</sup> is a distributed full-text search & analytics engine based upon Elasticsearch that supports advanced filtering, sorting, & ranking of query results on an *ad-hoc* basis by default and supports JSON document ingestion. However, the higher querying flexibility comes at the cost of higher-latency queries, making it less appropriate for real-time data.

DynamoDB was chosen for the database service due to its suitability for the data being processed, its scalability, and its low-latencies.

## Programming Language

AWS Lambda functions officially support many programming languages, including Node JS, Python, Java, C#, & Go; custom runtime environments can also be created, making practically any language usable within AWS Lambda functions with some effort. Due to previous experience with these programming languages, the main options considered for this project were Node JS, Python, & Java:

- Node JS<sup>33</sup> is a good choice for event-driven & real-time web applications because of its non-blocking IO, fast cold starts for latency-sensitive functions, and extensive library ecosystem. Asynchronous operations are supported out-of-the-box, making it a good choice for querying external APIs. However, it can become complex to manage for lengthy source files, and can be cumbersome to write compared to something like Python. An advantage of writing the backend in Node JS would be that both the frontend & the backend would utilise JavaScript code, meaning that the same tooling could be used for both.
- Python<sup>35</sup> is a good choice for polling of APIs & data ingestion due to its clean syntax, data parsing features, and extensive library ecosystem. Development & prototyping in Python is fast and easy to manage, but it does not

have built-in support for asynchronous programming. Python is generally slightly slower than Node JS, and start-up time for Python Lambda functions can be longer.

- Java<sup>92</sup> is a good choice for complex, enterprise-grade applications due to its strong typing & compile-time safety, and has a mature library ecosystem. However, it can be slower to write due to its verbose syntax, and development environments can be more complex to set up & configure. Despite having fast execution times, it can be slow to start up for Lambda functions as the JVM must be initialised each time, leading to ~1–2 seconds of delay.

Java was rejected on the basis that its slow start-up times made it unsuitable for this application, so the decision came down to whether the speed of execution for Node JS or the speed of development for Python should be favoured; ultimately, it was decided that Python would be a better choice for rapid prototyping & development, as the execution speed differences between the two languages are negligible (in this scenario), but the development speed differences are not.

### 2.3.2 Frontend Technologies

#### JavaScript Frameworks

While a web application like this could be developed using HTML and JavaScript alone, the complexity & dynamic nature of the application means that a JavaScript framework would more suitable for the benefits of re-usability & modularity, simplified application state management, optimised performance, and extensive library ecosystems. The main frameworks considered were React, Angular, & Vue due to their widespread popularity, good documentation, and extensive feature set:

- **React**<sup>68</sup> is the most popular choice of the three, with a large user community and a wide array of third-party libraries. It is component-based, making code easily re-usable and allowing the frontend design to be flexible for different design patterns & architectures. However, it can have a steep learning curve and can be needlessly complicated for simple applications. Technically speaking, it is not a full JavaScript framework, as it only provides built-in features for building UI components: it doesn't have built-in features for routing, data fetching, or tight integration with any backend services, although these can be added either with third-party libraries or by writing custom JavaScript code.

There is also a mobile development framework built on top of React called **React Native**<sup>67</sup>, which allows for native Android & iOS mobile application to be developed using JavaScript and React components. Instead of rendering to a DOM like vanilla React, React Native maps its UI components to native iOS/Android views (i.e., a button in React Native would use the operating system's native button component instead of being defined in HTML). This means that the same React Native codebase can be used to write an iOS and an Android application, and means that the performance will be superior to that of a webview application because of the utilisation of native components. However, React Native does not support any HTML or CSS, meaning that while a React web application is highly portable to React Native, it is not a simple drop-in solution, and a React web application would have to undergo extensive re-writing to use React Native.

- **Angular**<sup>39</sup> is a complete JavaScript framework for large-scale enterprise applications that comes with complete routing, state management, and a HTTP client out-of-the-box, therefore eliminating much of the need for third-party libraries. However, it has a rather steep learning curve, and takes a lot more development time to get up and running than other comparable JavaScript frameworks. It requires a lot of boilerplate code and complex configuration, with relatively simple features sometimes taking a great deal of set-up. It also rigidly enforces certain best practices, which is both a positive and a negative, as this ties the development into the Angular way of doing things.
- **Vue**<sup>123</sup> is a JavaScript framework known for its simplicity and ease-of-use, with very beginner-friendly syntax that is highly similar in appearance to standard HTML & JavaScript. Reactivity is baked into the framework, with the view updating automatically as data changes, reducing the need to manually update data values. All the HTML, CSS, & JavaScript for a Vue component is contained within a single component file, simplifying development. However, it has a far less mature library ecosystem than the other two discussed frameworks, and fragmentation between the Vue 2 version and the Vue 3 version means that the few plug-ins that do exist may

not be compatible with the version used. Vue’s automatic handling of reactivity, while simplifying development, can be a black box that is difficult to understand for debugging purposes.

It was decided that React would be the most suitable JavaScript framework for this project, as it has extensive library support, is flexible & lightweight, and it lends itself to porting the codebase to a native application if so desired in the future. Since the consideration of native applications is only a secondary objective of this project, the decision was made to focus only on React development and to make use of React-only functionality wherever suitable (such as using HTML + CSS), but to write the components in a clean & modularised fashion so that a React Native port would not be excessively difficult.

### CSS Frameworks

A **CSS framework** is a collection of pre-written styles, utility classes, or components that can be used to help build UIs quickly without reinventing basic functionality. CSS frameworks allow applications to be responsive by default on mobile devices, and maintain consistency throughout the application. The two CSS frameworks considered for this application were Tailwind CSS and Bootstrap CSS:

- **Tailwind CSS**<sup>70</sup> is a utility-first CSS framework in which the user interface is built by composing utility classes directly in HTML / React code; in this context, “utility first” refers to the fact that Tailwind does not provide any pre-built components, but instead provides pre-defined utility classes. Layout and styling are all done in-line via class names. This utility-based approach makes the framework very flexible & customisable, but comes at the cost of not providing any out-of-the-box re-usable components and require for components to be designed from scratch instead.
- **Bootstrap CSS**<sup>12</sup> is a component-first CSS framework designed to help developers build responsive, styled UIs quickly. It comes with many pre-built components such as buttons and navigation bars, and JavaScript plug-ins for drop-down menus and image carousels. This makes it very useful for fast prototyping and building of UIs, but can look generic due to its pre-built components and overriding the default component styles can be time-consuming.

Tailwind CSS was chosen for this project due to its flexibility & customisability, and because its utility-first approach means it integrates very well with React’s component-based approach as a component’s style can be contained entirely within that component.

## 2.4 Project Management

**Agile methodologies**<sup>7</sup> were employed throughout this project to facilitate iterative development with continuous feedback & adaptation: Agile is a development approach which divides work into phases, emphasising continuous delivery & improvement. Tasks are prioritised according to importance & dependencies, and are approached in a flexible manner so that approaches could be adjusted if something isn’t working as intended. Progress was reflected upon regularly, with areas for improvement being identified and plans adjusted accordingly. Automated CI/CD pipelines were employed to streamline development, and to ensure that new changes never broke existing functionality. Progress was tracked in a Markdown diary file, and a physical Kanban<sup>6</sup> board with Post-It notes was used to track planned work, in progress work, & completed work.

The principles of **clean coding**<sup>83</sup> (famously put forward by Robert “Uncle Bob” Martin) were also employed to ensure that all code written was easy to read, understand, & maintain. Key principles of clean coding involve ensuring that the code is readable with meaningful function & variable names, ensuring that the code is simple & concise with each function doing one thing only and doing that thing well, using consistent naming conventions, and employing the Don’t Repeat Yourself (DRY) principle which involves the avoidance of duplicated code by creating re-usable functions & modules. Code should be structured in a way that is meaningful, and should have proper comments & documentation where necessary; comments should only explain *why* something is done, not *what* it does as properly written clean code should be self-explanatory. Code should also be written in a way that lends itself easily to unit testing, and should be refactored to make testing as simple as possible rather than making the tests more complicated; if the code is decomposed into functions properly, it should be easier to test, upgrade, & maintain.

Proper functional decomposition also results in code that is less tightly coupled in to specific libraries, platforms, or services, making it more flexible & easier to port to different services if needs be. With proper separation of concerns, each function has a single responsibility and so dependencies can be isolated, and abstraction layers can prevent direct dependency on a specific implementation; if a function is abstracted properly switching libraries or services requires fewer changes and in fewer places. Isolated functions are also easier to test with mock functions, reducing reliance on real services during unit testing.

### 2.4.1 Version Control

Any software development project of substantial size should make use of version control software, and Git<sup>117</sup> was chosen for this project due to its ubiquitousness and extensive personal experience with the software. GitHub<sup>63</sup> was chosen as the hosting platform for the Git repository, again largely due to its ubiquitousness and extensive personal experience, but also because of its excellent support for CI/CD operations with GitHub Actions<sup>64</sup>. The decision was made to keep all relevant files for this project, including frontend code, backend code, and document files in a single monolithic repository (monorepo) for ease of organisation, a simplified development workflow, and easier CI/CD set-up. While this is not always advisable for very large projects where multiple teams are collaborating, or projects in which the backend and frontend are truly independent of one another and are developed separately, this works well for projects like this one where development is done by a single individual or a small team<sup>14</sup>, and is even used on very large projects where unified versioning and simplified dependency management are of paramount importance, such as at Google<sup>94</sup>.

Commits to this repository were made in adherence with the philosophy of *atomic commits*, meaning that each commit represents a single, logical change: commits are kept as small as reasonably possible, and are made very frequently. This makes the Git history easier to read, understand, & revert if needed, makes debugging easier, keeps changes isolated and understandable, and reduces merge conflicts. This is the generally accepted best practice, as bundling unrelated changes into a single commit can make review, reversion, & integration of these commits much more difficult<sup>26</sup>.

Meaningful commit messages are of great importance when using version control software, and even more so when making atomic commits as there will be a very large volume of commits & commit messages. For this reason, a custom scoped commit message convention was chosen, where each commit message follows the format `[scope]: Details of commit`, where the scope can be `[frontend]` for changes to frontend code, `[backend]` for backend code, `[report]` for changes to the  $\text{\LaTeX}$  project report files, and so on. This ensure consistency & clarity in commit messages, and the strict formatting of the messages make it easy to parse commit messages in a script should that be necessary. Recent examples of commit messages to the GitHub repository can be seen in Figure 2.5 below.

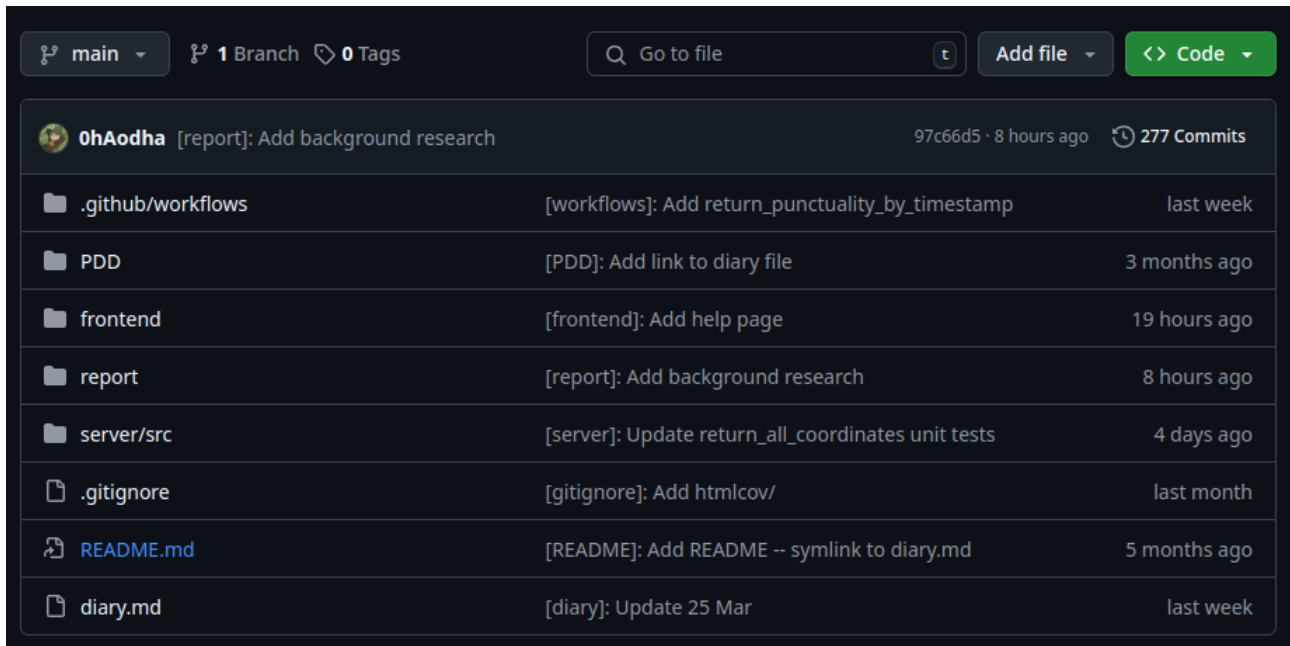


Figure 2.5: Screenshot of the repository files on GitHub

## Chapter 3

# Backend Design & Implementation

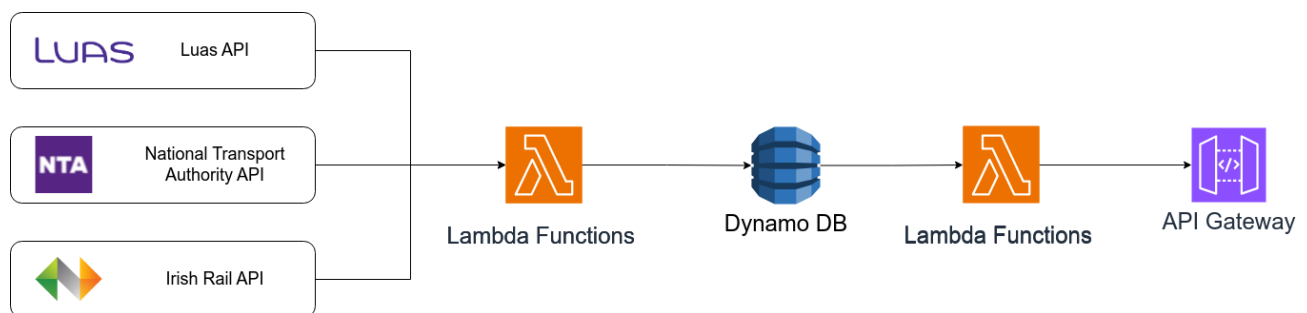


Figure 3.1: High-level backend architecture

### 3.1 Database Design

Since the chosen database system was DynamoDB, a No-SQL database, the question of how best to separate the data is more open-ended: unlike a relational database, there is no provably correct, optimised structure of separated tables upon which to base the database design. The decision was made that data would be separated into tables according to the type of data, how its used, and how its updated, thus allowing separation of concerns for functions which update the data and allowing different primary keys and indices to be used for different querying patterns.

#### Permanent Data Table

The permanent data table holds the application data which is unchanging and needs to be updated only rarely, if ever. This includes information about bus stops, train stations, Luas stops, and bus routes. This data does not need to be updated regularly, just on an as-needed basis. Since this data is not temporal in nature, no timestamping of records is necessary.

```
1  [
2    {
3      "objectID": "IrishRailStation-GALWY",
4      "objectType": "IrishRailStation",
5      "trainStationCode": "GALWY",
6      "trainStationID": "170",
7      "trainStationAlias": null,
8      "trainStationDesc": "Galway",
9      "latitude": "53.2736"
10     "longitude": "-9.04696",
11   },
12   {
13     "objectID": "BusStop-8460B5226101",
```



```

14     "objectType": "BusStop",
15     "busStopID": "8460B5226101",
16     "busStopCode": "522611",
17     "busStopName": "Eyre Square",
18     "latitude": "53.2750947795551"
19     "longitude": "-9.04963289544644",
20 },
21 {
22     "objectID": "BusRoute-4520_67654",
23     "objectType": "BusRoute",
24     "busRouteID": "4520_67654"
25     "busRouteAgencyName": "City Direct",
26     "busRouteAgencyID": "7778028",
27     "busRouteShortName": "411",
28     "busRouteLongName": "Mount Prospect - Eyre Square",
29 },
30 {
31     "objectType": "LuasStop",
32     "objectID": "LuasStop-STS",
33     "luasStopCode": "STS"
34     "luasStopID": "24",
35     "luasStopName": "St. Stephen's Green",
36     "luasStopIrishName": "Faiche Stiabhna",
37     "luasStopIsParkAndRide": "0",
38     "luasStopIsCycleAndRide": "0",
39     "luasStopLineID": "2",
40     "luasStopZoneCountA": "1",
41     "luasStopZoneCountB": "1",
42     "luasStopSortOrder": "10",
43     "luasStopIsEnabled": "1",
44     "latitude": "53.3390722222222",
45     "longitude": "-6.26133333333333",
46 }
47 ]

```

Listing 1: Sample of the various types of items stored in the permanent data table

As can be seen in Listing 1, two additional fields are included for each item beyond what is returned for that item by its source API: the `objectType` to allow for querying based on this attribute and the `objectID`, an attribute constructed from an item’s `objectType` and the unique identifier for that item in the system from which it was sourced, thus creating a globally unique identifier for the item. However (for reasons that will be discussed shortly), this attribute is *not* used as the primary key for the table; instead, it exists primarily so that each item has a unique identifier that does not need to be constructed on the fly on the frontend, thus allowing the frontend to treat specific items in specific ways. An example of a use for this is the “favourites” functionality: a unique identifier must be saved for each item that is added to a user’s favourites. Defining this unique identifier in the backend rather than the frontend reduces frontend overhead (important when dealing with tens of thousands of items) and also makes the system more flexible. While the “favourites” functionality is implemented fully on the frontend at present, the existence of unique identifiers for items within the table means that this functionality could be transferred to the backend without major re-structuring of the database.

There are two ways in which a primary key can be created for a DynamoDB table<sup>10</sup>:

- A simple primary key, consisting solely of a **partition key**: the attribute which uniquely identifies an item, analogous to simple primary keys in relational database systems.

- A composite primary key, consisting of a partition key and a **sort key**, analogous to composite primary keys in relational database systems. Here, the partition key determines the partition in which an item's data is stored, and the sort key is used to organise the data within that partition.

While the `objectID` could be used as a partition key and thus a simple primary key, it was decided not to use the attribute for this purpose as it was not the most efficient option. The primary function of the permanent data table is to provide data for a user when they want to display a certain type of object, such as bus stops, train stations, Luas stops, or some combination of the three. Therefore, the most common type of query that the table will be dealing with is queries which seek to return all items of a certain `objectType`. Partitioning the table by `objectID` would make querying by `objectID` efficient, but all other queries inefficient, and querying by `objectID` is not useful for this application. Instead, the permanent data table uses a composite primary key, using the `objectType` as the partition key and the `objectID` as the sort key. Thus, it is very efficient to query by `objectType` and return, for example, all the bus stops and Luas stops in the country.

Technically speaking, there is some redundant data in each primary key by using the `objectID` as the sort key when the partition key is the `objectType`: since the `objectID` already contains the `objectType`, it is repeated. However, the unique identifier for each item is different depending on the system from which it was sourced: for train stations, the unique identifier is named `trainStationCode`, while the unique identifier for bus stops is named `busStopID`. To use these fields as sort key, they would have to be renamed in each item to some identical title, thus adding overhead to the process of fetching data, and making the table less human-readable. Since the `objectID` was to be constructed regardless for use on the frontend, it is therefore more efficient to re-use it as the sort key, even if it does result in a few bytes of duplicated data in the primary key of each item.

### Transient Data Table

The transient data table holds the live tracking data for each currently running public transport vehicle in the country, including information about the vehicle and its location. Similar to the permanent data table, a unique `objectID` is constructed for each item. A sample of the data stored in the transient data table can be seen below in Listing 2:

```

1  [
2    {
3      "objectType": "IrishRailTrain",
4      "latenessMessage": "On time",
5      "timestamp": "1742897696",
6      "trainDirection": "Southbound",
7      "trainStatus": "R",
8      "trainDetails": "09:41 - Maynooth to Grand Canal Dock ",
9      "trainType": "S",
10     "objectID": "IrishRailTrain-P656",
11     "averagePunctuality": "0",
12     "trainUpdate": "Departed Pelletstown next stop Broombridge",
13     "trainStatusFull": "Running",
14     "longitude": "-6.31388",
15     "trainPublicMessage": "P656\\n09:41 - Maynooth to Grand Canal Dock (0 mins late)\\nDeparted
16     ↩ Pelletstown next stop Broombridge",
17     "trainPunctuality": "0",
18     "trainPunctualityStatus": "on-time",
19     "trainTypeFull": "Suburban",
20     "trainDate": "25 Mar 2025",
21     "latitude": "53.3752",
22     "trainCode": "P656"
23   },
24   {
25     "objectType": "Bus",

```

```

25 "busScheduleRelationship": "SCHEDULED",
26 "timestamp": "1742908007",
27 "busID": "V598",
28 "busRoute": "4538_90219",
29 "busRouteAgencyName": "Bus Éireann",
30 "objectID": "Bus-V598",
31 "busRouteLongName": "Galway Bus Station - Derry (Magee Campus Strand Road)",
32 "longitude": "-8.50166607",
33 "busDirection": "1",
34 "busStartDate": "20250325",
35 "busRouteShortName": "64",
36 "latitude": "54.2190742",
37 "busTripID": "4538_114801",
38 "busStartTime": "10:30:00"
39 },

```

Listing 2: Sample of the various types of items stored in the transient data table

There are only two types of objects stored in the transient data table: Irish Rail Trains and Buses. There is no per-vehicle data provided in the Luas API, and thus no way to track the live location of Luas trams. For the two types of objects stored in the transient data table, additional fields are added beyond what is returned by their respective APIs (and beyond the `objectType` & `objectID` fields) to augment the data.

The following additional pieces of data are added to each `IrishRailTrain` object:

- The `trainStatus` & `trainType` fields are single-character codes returned by the API, representing longer strings; for example a `trainStatus` of "R" indicates that the train is *running*. To avoid having to construct these strings on the frontend, the fields `trainStatusFull` & `trainTypeFull` are automatically added to the record when the data is retrieved.
- The Irish Rail API compacts much of its interesting data into a single field: `trainPublicMessage`. This field contains the `trainCode` (which is also supplied individually in its own field by the API), a string containing details about the train's origin & terminus, a string describing how late the train is, a string containing an update about the train's current whereabouts, all separated by `\\n` characters. This string is parsed into several additional fields to prevent additional computation on the frontend, including:
  - `latenessMessage`: a human-readable string which describes whether a train is early, late, or on time.
  - `trainDetails`: a string describing the train service itself, its start time, origin, & terminus.
  - `trainUpdate`: a string containing an update about the current whereabouts of the train, such as what station it last departed and what station it will visit next.
  - `trainPunctuality`: an integer which represents how many minutes late the train is (where a negative number indicates that the train is that many minutes early).
  - `trainPunctualityStatus`: a whitespace-free field which gives the same information as `latenessMessage` but for use in filtering rather than information presentation to the user. While one of these fields could be derived from the other on the frontend, the extra computation necessary when repeated for multiple trains and multiple users dwarfs the few extra bytes in the database to store the data in the machine-readable and human-readable forms.
- The `averagePunctuality` field is a field which contains the average recorded value of the `trainPunctuality` for trains with that `trainCode` in the database, thus giving a predictor of how early or late that particular train usually is.

The following additional pieces of data are added to each `Bus` object:

- `busRouteAgencyName`.

- busRouteShortName.
- busRouteLongName.

These details are not included in the response from the GTFS API, but can be obtained by looking up the given busRoute attribute in the permanent data table to find out said information about the bus route. In a fully-normalised relational database, this would be considered data duplication, but storing the data in both places allows for faster querying as no “joins” need to be performed.

Since the primary role of the transient data table is to provide up-to-date location data about various public transport services, each item in the table is given a timestamp attribute. This timestamp attribute is a UNIX timestamp in seconds which uniquely identifies the batch in which this data item was obtained. Each train & bus obtained in the same batch have the same timestamp, making querying for the newest data in the table more efficient. Because the data is timestamped, old data does not have to be deleted, saving both the overhead of deleting old data every time new data is fetched, and allowing an archive of historical data to be built up over time.

Since the primary type of query to be run on this table will be queries which seek to return all the items of a certain objectType (or objectTypes) for the latest timestamp, it would be ideal if the primary key could be a combination of the two for maximum efficiency in querying; however, such a combination would fail to uniquely identify each record and thus would be inappropriate for a primary key. Instead, the primary key must be some combination of the timestamp attribute and the objectID attribute. It was decided that the partition key would be the objectID and the sort key to be the timestamp so that all the historical data for a given item could be retrieved efficiently. Equivalently, the partition key could be the timestamp and the sort key could be the objectID which would allow for queries of all items for a given timestamp, but this was rejected on the basis that such scenarios were covered by the introduction of a Global Secondary Index.

A **Global Secondary Index (GSI)** allows querying on non-primary key attributes by defining an additional partition and sort key from the main table<sup>56</sup>. Unlike a primary key, there is no requirement for a GSI to uniquely identify each record in the table; a GSI can be defined on any attributes upon which queries will be made. The addition of GSIs to a table to facilitate faster queries is analogous to **SELECT** queries on non-primary key columns in a relational database (and the specification of a sort key is analogous to a relational **ORDER BY** statement); the structured nature of a relational database means that such queries are possible by default, although an index must be created on the column in question for querying on that column to be *efficient* (such as with the SQL **CREATE INDEX** statement). In a No-SQL database like DynamoDB, this functionality does not come for free, and instead must be manually specified.

To facilitate efficient querying of items in the table by objectType and timestamp, a GSI was created with partition key objectType and sort key timestamp, thus making queries for the newest data on a public transport type as efficient as querying on primary key attributes. The downside of creating a GSI is the additional storage requirements, as DynamoDB implements GSIs by duplicating the data into a separate index: efficient for querying, but less so in terms of storage usage.

### Average Punctuality by objectID Table

To give the user punctuality predictions based off the historical data stored for a given service, it's necessary that the average punctuality be calculated. The most obvious way to do this would be to calculate the average of the punctuality values for a given objectID in the transient data table every time data a new data item with that objectID is added to the transient data table. However, this would be greatly inefficient, as it would require scanning the entire table for each item uploaded to the table, greatly slowing down the fetching of new data and consuming vast amounts of DynamoDB read/write resources. It is also intractable, as the historical data archive in the transient table grows, it will become linearly more expensive to compute the average punctuality for an item.

Instead, it was decided that the average punctuality for an item would be stored in a table and updated as necessary. By storing the objectID, the average\_punctuality, and the count of the number of records upon which this average is based, the mean punctuality for an item can be updated on an as-needed basis in an efficient manner. The



```

1  [
2    {
3      "average_punctuality": "0.8823529411764706",
4      "timestamp": "1742908007"
5    },
6    {
7      "average_punctuality": "1.0625",
8      "timestamp": "1742905796"
9    }
10 ]

```

Listing 4: Sample of items from the average punctuality by timestamp table

The partition key for this table is the `timestamp` value, and there is no need for a sort key or secondary index.

## 3.2 API Design

To make the data available to the frontend application, a number of API endpoints are required so that the necessary data can be requested as needed by the client. AWS offers two main types of API functionality with Amazon API Gateway<sup>49</sup>:

- **RESTful APIs:** for a request/response model wherein the client sends a request and the server responds, stateless with no session information stored between calls, and supporting common HTTP methods & CRUD operations. AWS API Gateway supports two types of RESTful APIs<sup>53</sup>:
  - **HTTP APIs:** low latency, fast, & cost-effective APIs with support for various AWS microservices such as AWS Lambda, and native CORS support<sup>a</sup>, but with limited support for usage plans and caching. Despite what the name may imply, these APIs default to HTTPS and are RESTful in nature.
  - **REST APIs:** older & more fully-featured, suitable for legacy or complex APIs requiring fine-grained control, such as throttling, caching, API keys, and detailed monitoring & logging, but with higher latency, cost, and more complex set-up & maintenance.
- **WebSocket APIs:** for real-time full-duplex communication between client & server, using a stateful session to maintain the connection & context.

It was decided that a HTTP API would be more suitable for this application for the low latency and cost-effectiveness. The API functions needed for this application consist only of requests for data and data responses, so the complex feature set of AWS REST APIs is not necessary. The primary drawback of not utilising the more complex REST APIs is that HTTP APIs do not natively support caching; this means that every request must be processed in the backend and a data response generated, meaning potentially slower throughput over time. However, the fact that this application relies on the newest data available to give accurate & up-to-date location information about public transport means that the utility of caching is somewhat diminished, as the cache will expire and become out of date within minutes or even seconds of its creation. This combined with the fact that HTTP APIs are  $3.5\times$  cheaper<sup>50</sup> than REST APIs resulted in the decision that a HTTP API would be more suitable.

It is important to consider the security of public-facing APIs, especially ones which accept query parameters: a malicious attacker could craft a payload to either divert the control flow of the program or simply sabotage functionality. For this reason, no query parameter is ever evaluated as code or blindly inserted into a database query; any interpolation of query parameters is done in such a way that they are not used in raw query strings but in **parameterised expressions** using the `boto3` library<sup>54</sup> (the official AWS SDK for Python). This means that query parameters are safely bound to named

<sup>a</sup>**Cross-Origin Resource Sharing (CORS)** is a web browser security feature that restricts web pages from making requests to a different domain than the one that served the page, unless the API specifically allows requests from the domain that served the page<sup>121</sup>. If HTTP APIs did not natively support CORS, the configuration to allow requests from a given domain would have to be done in boilerplate code in the Lambda function that handles the API requests for that endpoint, and duplicated for each Lambda function that handles API requests.

placeholder attributes in queries rather than inserted into raw query strings and so the parameters have no potential for being used to control the structure or logic of the query itself. The AWS documentation emphasises the use of parameterised queries for database operations, in particular for SQL databases which are more vulnerable, but such attacks can be applied to any database architecture<sup>55</sup>. This, combined with unit testing of invalid API query parameters means that the risk of malicious parameter injection is greatly mitigated (although never zero), as each API endpoint simply returns an error if the parameters are invalid.

Figure 3.2: CORS configuration for the HTTP API

The Cross-Origin Resource Sharing (CORS) policy accepts only GET requests which originate from `http://localhost:5173` (the URL of the locally hosted frontend application) to prevent malicious websites from making unauthorised requests on behalf of users to the API. While the API handles no sensitive data, it is nonetheless best practice to enforce a CORS policy and a “security-by-default” approach so that the application does not need to be secured retroactively as its functionality expands. If the frontend application were moved to a publicly available domain, the URL for this new domain would need to be added to the CORS policy, or else all requests would be blocked.

### 3.2.1 API Endpoints

**`/return_permanent_data[?objectType=IrishRailStation,BusStop,LuasStop]`**

The `/return_permanent_data` endpoint accepts a comma-separated list of `objectType` query parameters, and returns a JSON response consisting of all items in the permanent data table which match those parameters. If no query parameters are supplied, it defaults to returning *all* items in the permanent data table.

**`/return_transient_data[?objectType=IrishRailTrain,Bus]`**

The `/return_transient_data` endpoint accepts a comma-separated list of `objectType` query parameters, and returns a JSON response consisting of all the items in the transient data table which match those parameters *and* were uploaded to the transient data table most recently, i.e., the items which have the newest `timestamp` field in the table. Since the timestamp pertains to the batch of data uploaded to the table in a single run, each item in the response will have the same timestamp as all the others. If no `objectType` parameter is supplied, it defaults to returning all items from the newest upload batch.

**`/return_historical_data[?objectType=IrishRailTrain,Bus]`**

The `/return_historical_data` endpoint functions in the same manner as the `/return_transient_data` endpoint, with the exception that it returns matching items for *all* timestamp values in the table, i.e., it returns all items of the given `objectTypes` in the transient data table.

**`/return_luas_data?luasStopCode=<luas_stop_code>`**

The `/return_luas_data` returns incoming / outgoing tram data for a given Luas stop, and is just a proxy for the Luas real-time API. Since the Luas API returns data only for a queried station and does not give information about individual vehicles, the Luas data for a given station is only fetched on the frontend when a user requests it, as there is no

information to plot on the map beyond a station's location. However, this request cannot be made from the client to the Luas API, as the Luas API's CORS policy blocks requests from unauthorised domains for security purposes; this API endpoint acts as a proxy, accepting API requests from the localhost domain and forwarding them to the Luas API, and subsequently forwarding the Luas API's response back to the client.

This endpoint requires a single `luasStopCode` query parameter for each query to identify the Luas stop for which incoming / outgoing tram data is being requested.

**`/return_station_data?stationCode=<station_code>`**

The `return_station_data` returns information about the trains due into a given station in the next 90 minutes. This data is only shown to a user if requested for a specific station, so it is not stored in a DynamoDB table. Like the `/return_luas_data` endpoint, it too is just a proxy for an (Irish Rail) API, the CORS policy of which blocks requests from any unauthorised domain for security purposes. It requires a single `stationCode` query parameter for each query to identify the train station for which the incoming train data is being requested.

**`/return_punctuality_by_timestamp[?timestamp=<timestamp>]`**

The `/return_punctuality_by_timestamp` returns the contents of the `punctuality_by_timestamp` DynamoDB table. It accepts a comma-separated list of timestamps, and defaults to returning the average punctuality for *all* timestamps in the table if no timestamp is specified.

**`/return_all_coordinates`**

The `/return_all_coordinates` endpoint returns a JSON array of all current location co-ordinates in the transient data table for use in statistical analysis.

### 3.3 Serverless Functions

All the backend code & logic is implemented in a number of **serverless functions**<sup>45</sup>, triggered as needed. Serverless functions are small, single-purpose units of code that run in the cloud and reduce the need to manage servers & runtime environments. In contrast to a server program which is always running, serverless functions are event-driven, meaning that they are triggered by events such as API calls or invocations from other serverless functions and do not run unless triggered. Each serverless function is *stateless*, which means that each function invocation is independent and that no state data is stored between calls; they are also *ephemeral*, starting only when triggered and stopping when finished, running only for a short period of time. This means that they automatically scale up or down depending on usage, and because they only run when they need to, they are much cheaper in terms of compute time than a traditional server application.

AWS Lambda<sup>57</sup> is a serverless compute service provided by Amazon Web Services that allows for the creation of serverless functions without provisioning or managing servers. A Python AWS Lambda function typically consists of a single source code file with specified entrypoint function, the name of which can vary, but is typically called `lambda_handler()`. They can be created and managed via the GUI AWS Management Console<sup>58</sup> or via the AWS CLI tool<sup>51</sup>. Each Lambda function can be configured to have a set memory allocation, a timeout duration (how long the function can run for before being killed), and environment variables.

Often, when a serverless application replaces a legacy mainframe application, the time & memory needed to perform routine tasks is drastically reduced because it becomes more efficient to process events individually as they come rather than batching events together to be processed all at once; the high computational cost of starting up a mainframe system means that it's most efficient to keep it running and to batch process events. For this reason, serverless functions often require very little memory and compute time. This application, however, is somewhat unusual as it requires the processing of quite a large amount of data at once: status updates for public transport don't come from the source APIs individually for each vehicle on an event-by-event basis, but in batches of data that are updated regularly. Therefore, the serverless functions for this application will require more memory and more compute time to complete. In this



context, memory and compute time have an inversely proportional relationship: more memory means more items can be processed quickly, thus reducing computational time, and less memory means that fewer items can be processed quickly, thus increasing the computational time.

One common approach to tuning the configuration of AWS Lambda functions is to use **AWS Lambda Power Tuning**<sup>15</sup>, an open-source tool that is designed to help optimise the memory & power configurations for AWS Lambda functions. It works by invoking the function to be tuned multiple times across various memory allocations, recording metrics such as execution duration and cost for each configuration, and visualises the trade-off between cost and performance for each tested memory configuration, allowing the user to decide the most suitable memory allocation based on minimising cost, maximising speed, or balancing the two. While this is a very powerful & useful tool for Lambda function optimisation, it was not used in this project in order to (somewhat ironically) manage costs and remain with the AWS Free Tier: running the tuner involves several invocations of the target Lambda function at various memory levels, and a typical tuning run involves dozens of Lambda invocations. With the amount of data being written to the database per Lambda run (thousands of items), this would quickly exceed the free tier and begin incurring costs. While these costs would not be prohibitively high, doing so would change the nature of the project from researching & implementing the optimal approach for this application to paying for a faster & more performant application. The tuner *could* be run with database writes disabled, but this would not generate meaningful results for the functions as writing to the DynamoDB database is the critical choke point for functions in this application.

Instead, each function was manually tuned to consume the least amount of resources (reasonably) possible by gradually incrementing the memory allocation until the function could run to completion in what was deemed to be a reasonable amount of time (somewhat subjectively) for this application; for this reason, the functions could almost certainly achieve superior execution times if they were allocated more resources, but this would bring the application closer and closer to exceeding the free tier limit of 400,000 GB-seconds (allocated memory in GB  $\times$  execution time in seconds).

### fetch\_permanent\_data

The `fetch_permanent_data` Lambda function is used to populate the permanent data table. As the data in question changes rarely if ever, this function really need only ever be triggered manually, such as when a new train station is opened or a new bus route created. However, for the sake of completeness and to avoid the data being out of date, a schedule was created with **Amazon EventBridge** to run the function every 28 days to ensure that no changes to the data are missed. Like all other schedules created for this application, the schedule is actually disabled at present to avoid incurring unnecessary AWS bills, but can be enabled at any time with the click of a button.

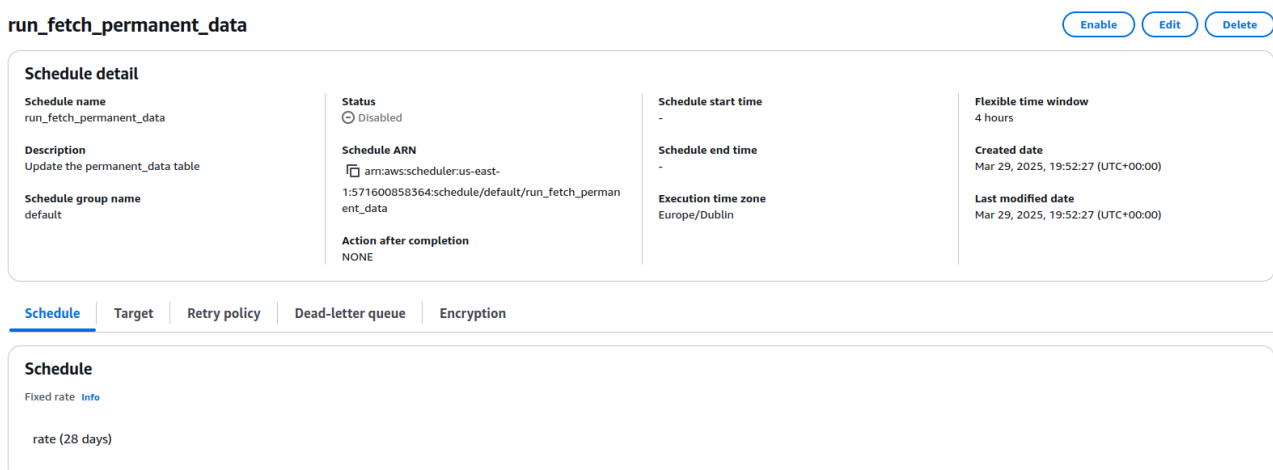


Figure 3.3: Screenshot of the Amazon EventBridge schedule to run the `fetch_permanent_data` Lambda function

The `fetch_permanent_data` function retrieves Irish Rail Station data directly from the Irish Rail API, but Luas stop data and bus data are not made available through an API; instead, the Luas stop data is made available online in a tab-separated TXT file, and the bus stop & bus route data are available online in comma-separated TXT files distributed as a single ZIP file. This makes little difference to the data processing however, as downloading a file from a server

and parsing its contents is little different in practice from downloading an API response from a server and parsing its contents. The function runs asynchronously with a thread per type of data being fetched (train station data, Luas stop data, and bus stop & route data), and once each thread has completed, batch uploads the data to the permanent data table, overwriting its existing contents.

User testing conducted at the end of the development phase for this project revealed that the frontend's live map was missing several Luas stops, and inspection of the permanent data database revealed that these stops were not present in the database either. Under further investigation, it transpired that the official Luas stop datasets distributed by Transport Infrastructure Ireland and by `data.gov.ie` are missing several Luas stops on the Green Line<sup>76,75</sup>: these datasets have not been updated since 2015, and the Green Line was extended in 2017<sup>9</sup>. Because this is the only official Luas dataset publicly available online, these additional stops were manually added to this Lambda function so that the live map could be accurate & useful. In the unlikely event that this dataset does eventually get updated by those responsible for it, the function will not duplicate any entries as they will have the same `objectID` and so only one will be uploaded to the database, preventing any inconsistencies.

### **fetch\_transient\_data**

The `fetch_transient_data` function operates much like the `fetch_permanent_data` function, but instead updates the contents of the transient data table. It runs asynchronously, with a thread per API being accessed to speed up execution; repeated requests to an API within a thread are made synchronously to avoid overloading the API. For example, retrieving the type (e.g., Mainline, Suburban, Commuter) of the trains returned by the Irish Rail API requires three API calls: the Irish Rail API allows the user to query for all trains or for trains of a specific type but it does not return the type of the train in the API response. Therefore, if a query is submitted for all trains, there is no way of knowing which train is of which type. Instead, the function queries each type of train individually, and adds the type into the parsed response data.

Additionally, the `return_punctuality_by_objectID` function is called when processing the train data so that each train's average punctuality can be added to its data for upload. Somewhat unintuitively, it transpired that the most efficient way to request this data was to request all data from the punctuality by `objectID` data table rather than individually request each necessary `objectID`; this means that much of the data returned is redundant, as many of the trains whose punctualities are returned are not running at the time and so will not be uploaded, but it means that the function is only run once, and so only one function invocation, start-up, database connection, and database query have to be created. It's likely that if bus punctuality data were to become available in the future, this approach would no longer be the most efficient way of doing things, and instead a `return_punctuality_by_objectType` function would be the optimal solution.

The bus data API doesn't return any information about the bus route beyond a bus route identifier, so the permanent data table is queried on each run to create a dictionary (essentially a Python hash table<sup>34</sup>) linking bus route identifiers to information about said bus route (such as the name of the route). As the bus data is being parsed, the relevant bus route data for each vehicle is inserted. Once all the threads have finished executing, the data is uploaded in a batch to the transient data table, with each item timestamped to indicate which function run it was retrieved on.

This function is run as part of an **AWS Step Function** with a corresponding Amazon EventBridge schedule (albeit disabled at present). A step function is an AWS service which facilitates the creation of state machines consisting of various AWS microservices to act as a single workflow. The state machine allows multiple states and transitions to be defined, with each state representing a step in the workflow and the transitions representing how the workflow moves from one state to another and what data is transferred. Step functions have built-in error handling and retry functionality, making them extremely fault-tolerant for critical workflows.

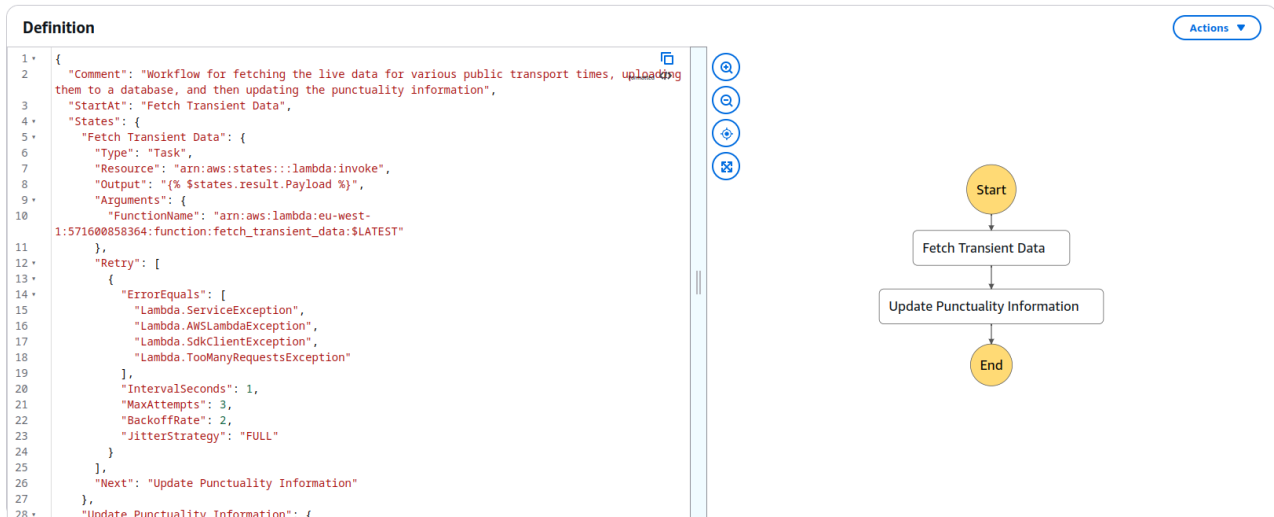


Figure 3.4: Screenshot of the get\_live\_data step function definition

The step function runs the `fetch_transient_data` function and then runs the `update_average_punctuality` function, if and only if the `fetch_transient_data` function has completed successfully. This allows the average punctuality data to be kept up to date and in sync with the transient data, and ensures that they do not become decoupled and therefore incorrect. This step function is triggered by a (currently disabled) Amazon EventBridge schedule which runs the function once a minute, which is the maximum frequency possible to specify within a cron schedule, and suitable for this application as the APIs from which the data is sourced don't update much more frequently than that. Furthermore, the data from which bus data is sourced will time out if requests are made too frequently, so this value was determined to be appropriate after testing to avoid overwhelming the API or getting timed-out. It is possible to run EventBridge schedules even more frequently using the *rate-based schedule* schedule type instead of the *cron-based schedule* schedule type but a more frequent schedule would be inappropriate for this application.

### update\_average\_punctuality

The `update_average_punctuality` function runs after `fetch_transient_data` in a step function and populates the average punctuality by objectID and average punctuality by timestamp tables to reflect the new data collected by `fetch_transient_data`. For each item in the new data, it updates the average punctuality in the average punctuality by objectID table according to the aforementioned formula:

$$\bar{x}_{\text{new}} = \frac{(\bar{x}_{\text{old}} + c) + x}{c + 1}$$

As the function iterates over each item, it adds up the total punctuality and then divides this by the total number of items processed before adding it to the average punctuality by timestamp table, where the timestamp in question is the timestamp that the items were uploaded with (the timestamp of the `fetch_transient_data` run which created them).

There are a number of concerns that one might reasonably have about using the mean punctuality for the average displayed to users:

- Means are sensitive to outliers, meaning that if, for example, a train is very late just once but very punctual the rest of the time, its average punctuality could be misleading.
- The punctuality variable is an integer that can be positive or negative, which could have the result that the positive & negative values could cancel each other out for a train that is usually either very late or very early, giving the misleading impression of an average punctuality close to zero.
- Considering the entire history of a train for its average punctuality may not be reflective of recent trends: a train may historically have been consistently late, but become more punctual as of late and therefore the average punctuality may not be reflective of its recent average punctuality.

These questions were carefully considered when deciding how to calculate the average punctuality, but it was decided that the mean would nonetheless be the most appropriate for various reasons:

- The mean lends itself to efficient calculation with the  $O(1)$  formula described above. No other average can be calculated in so efficient a manner: the median requires the full list of punctualities to be considered to determine the new median, and the mode requires at the very least a frequency table of all the punctualities over time to determine the new mode, which requires both additional computation and another DynamoDB table.
- Similarly, considering only recent data would destroy the possibility for efficient calculation: the mean could not be updated incrementally, and instead a subset of the historic punctualities would have to be stored and queried for each update.
- The outlier sensitivity is addressed by the sheer number of items that are considered for the mean: since this will be updated every minute of every day, an outlier will quickly be drowned out with time.
- Finally, the average is being calculated so that it can be shown to the user and so that they can make decisions based off it. The average person from a non-technical or non-mathematical background tends to assume that any average value is a mean value, and so it would only serve to confuse users if they were given some value that did not mean what they imagined it to mean. While calculating additional different measures of averages would be possible, displaying them to the user would likely be at best not useful and at worst confusing, while also greatly increasing the computation and storage costs. This aligns with the second of Nielsen's famous *10 Usability Heuristics for User Interface Design*, which were consulted throughout the design process: **“Match between the System and the Real World:** The design should speak the users' language. Use words, phrases, and concepts familiar to the user, rather than internal jargon”<sup>88</sup>.

For these reasons, it was decided that the mean was the most suitable average to use.

#### **return\_permanent\_data**

The `return_permanent_data` function is the Lambda function which is called when a request is made from the client to the `/return_permanent_data` API endpoint. It checks for a comma-separated list of `objectType` parameters in the query parameters passed from the API event to the Lambda function, and scans the permanent data table for every item matching those `objectTypes`. If none are provided, it returns every item in the table, regardless of type. It returns this data as a JSON string.

When this function was first being developed, the permanent data table was partitioned by `objectID` alone with no sort key, meaning that querying was very inefficient. When the table was re-structured to have a composite primary key consisting of the `objectType` as the partition key and the `objectID` as the sort key, the `return_permanent_data` function was made  $10\times$  faster: the average execution time was reduced from  $\sim 10$  seconds to  $\sim 1$  second, demonstrating the critical importance of choosing the right primary key for the table.

#### **return\_transient\_data**

The `return_transient_data` function is the Lambda function which is called when a request is made from the client to the `/return_transient_data` API endpoint. Like `return_permanent_data`, it checks for a comma-separated list of `objectType` parameters in the query parameters passed from the API event to the Lambda function, and scans the permanent data table for every item matching those `objectTypes`. If none are provided, it returns every item in the table, regardless of type.

Similar to `return_permanent_data`, when this function was originally being developed, there was no GSI on the transient data table to facilitate efficient queries by `objectType` and `timestamp`; the addition of the GSI and updating the code to exploit the GSI resulted in an average improvement in run time of  $\sim 8\times$ , thus demonstrating the utility which GSIs can provide.

**return\_punctuality\_by\_objectID**

The `return_punctuality_by_objectID` function is invoked by the `fetch_transient_data` function to return the contents of the punctuality by objectID table. It accepts a list of objectIDs and defaults to returning all items in the table if no parameters are provided.

**return\_punctuality\_by\_timestamp**

The `return_punctuality_by_timestamp` function is similar to `return_punctuality_by_objectID` but runs when invoked by an API request to the `/return_punctuality_by_timestamp` endpoint and simply returns a list of JSON objects consisting of a timestamp and an `average_punctuality`. It is used primarily to graph the average punctuality of services over time.

**return\_all\_coordinates**

The `return_all_coordinates` function is used to populate the co-ordinates heatmap in the frontend application which shows the geographical density of services at the present moment. It accepts no parameters, and simply scans the transient data table for the newest items and returns their co-ordinates.

**return\_historical\_data**

The `return_historical_data` function operates much like the `return_transient_data` function, accepting a list of objectTypes or defaulting to all objectTypes if none are specified, with the only difference being that this function does not consider the timestamps of the data and just returns all data in the transient data table. This function, along with its corresponding API endpoint exist primarily as a debugging & testing interface, although they also give a convenient access point for historical data analysis should that be necessary.

**return\_luas\_data**

The `return_luas_data` function is a simple proxy for the Luas API which accepts requests from the client and forwards them to the Luas API to circumvent the Luas API's restrictive CORS policy which blocks requests from unauthorised domains. It simply accepts a `luasStopCode` parameter, and makes a request to the Luas API with said parameter, parses the response from XML into JSON, and returns it.

**return\_station\_data**

Like `return_luas_data`, the `return_station_data` is a proxy for the Irish Rail API so that requests can be made as needed from the client's browser to get data about incoming trains due into a specific section without running afoul of Irish Rail's CORS policy. It also accepts a single parameter (`stationCode`) and makes a request to the relevant endpoint of the Irish Rail API, and returns the response (parsed from XML to JSON).

## 3.4 CI/CD Pipeline

### 3.4.1 Unit Tests

As the code for each Lambda function was written, so too were corresponding PyUnit<sup>96</sup> (based on the Java unit testing framework JUnit<sup>43</sup>) unit tests for that function to ensure that the function was working as expected, that edge cases were covered, and to indicate if functionality was broken when updates were made. Indeed, this often proved invaluable, as the unit tests revealed on multiple occasions edge cases that were not handled properly, such as the handling of the API responses when only a single item was returned. Without the utilisation of unit testing, it's likely that these issues would have gone unnoticed in the codebase until they caused an error in deployment, which could have lead to Lambda function crashes, inconsistent database data, and wasted developer time spent on debugging the application.

These PyUnit tests are run using `pytest`<sup>79</sup> which automatically discovers Python test files in a given directory and can generate code coverage reports. While PyUnit tests can be run with `python -m unittest`, `pytest` makes it easier to run the tests and can generate coverage reports automatically. `pytest` also allows for unit tests to be specified in its own

non-standard format alongside to the standard PyUnit format, but this was not used in an effort to keep the tests as standard and as homogeneous as possible. The coverage percentage is calculated as:

$$\text{Coverage (\%)} = \frac{\text{Number of lines executed}}{\text{Total number of executable lines}} \times 100$$

A line coverage of 70% was selected to be aimed for when writing tests for this application; this is a high degree of test coverage, but allows the tests to focus on testing the core logic of the application rather than boilerplate code and allows for interactions with third-party services that cannot be fully covered by testing and instead have to be mocked<sup>36</sup>. The actual total coverage achieved is 85%, which exceeds this minimum value and ensures that the application is well-covered with test cases.

server/src/test/fetch_transient_data/test_fetch_transient_data.py	35	1	0	97%
server/src/test/return_all_coordinates/test_return_all_coordinates.py	60	1	0	98%
server/src/test/return_historical_data/test_return_historical_data.py	60	1	0	98%
server/src/test/return_luas_data/test_return_luas_data.py	25	0	0	100%
server/src/test/return_permanent_data/test_return_permanent_data.py	60	1	0	98%
server/src/test/return_punctuality_by_objectID/test_return_punctuality_by_objectID.py	37	1	0	97%
server/src/test/return_punctuality_by_timestamp/test_return_punctuality_by_timestamp.py	56	1	0	98%
server/src/test/return_transient_data/test_return_transient_data.py	57	1	0	98%
server/src/test/update_average_punctuality/test_update_average_punctuality.py	99	1	0	99%
<b>Total</b>	<b>1071</b>	<b>164</b>	<b>0</b>	<b>85%</b>

Figure 3.5: Screenshot of (some of) the results from the HTML coverage report generated

### 3.4.2 CI/CD

To run the unit tests automatically, a GitHub Workflow<sup>62</sup> was created. This workflow is triggered when a pull request to merge code into the main Git branch is opened, or when code is pushed to the main branch. Since the Git repository used for this project is a monorepo containing all code files for the project, not just the backend Python files, many of the commits to this repository will not require re-running the unit tests, as the Python code will not have changed; therefore, the workflow only runs if the changes have been made to a \*.py file.

```

1 name: Continuous Integration / Continuous Deployment
2
3 on:
4   pull_request:
5     branches:
6       - main
7   paths:
8     - "**.py"
9   push:
10    branches:
11      - main
12    paths:
13      - "**.py"

```

Listing 5: Snippet of the ci.yml workflow file

The workflow consists of two “jobs”:

- The test job installs the necessary dependencies and runs the unit tests, generating coverage reports in both XML and HTML and uploading these as artifacts<sup>65</sup> (a way to share data from a GitHub workflow run).
- The deploy job runs only on pushes to main (including direct pushes and merges of pull requests), and only runs if the test job completed successfully: if any of the tests fail, the code will not be deployed and an email will be

sent to the administrators of the GitHub repository. It installs AWS CLI<sup>51</sup> and sets the AWS credentials using GitHub Secrets<sup>66</sup> which allow for sensitive information such as environment variables to be stored privately for a repository, even if that repository is public, and avoids having to hard-code these values. It then iterates over each Lambda function in the repository, installs the necessary Python libraries to a temporary directory, and bundles these along with the function source code into a ZIP file for deployment via the AWS CLI.

## Chapter 4

# Frontend Design & Implementation

The frontend design is built following the Single-Page-Application (SPA)<sup>98</sup> design pattern using the React Router<sup>97</sup> library, meaning that the web application loads a single HTML page and dynamically updates content as the user interacts with the application, without reloading the webpage. Since there is just one initial page load, the content is dynamically updated via the DOM using JavaScript rather than by requesting new pages from the server; navigation between pseudo-pages is managed entirely using client-side routing for a smoother & faster user experience since no full-page reloads are necessary.

The web application is split into three “pages”:

- The home (or map) page, which is the main page that displays live location data & service information to the user. This page is where the user will spend the majority of their time, and where the majority of the functionality is delivered.
- The statistics page, which is used to deliver statistical insights about the data to the user. This page is for providing deeper insights into the stored data on a collective basis, rather than on a per-service basis.
- The help page, which gives some basic usage information on how to complete basic tasks within the application, in keeping with Nielsen’s usability heuristic of “Help and Documentation”<sup>88</sup>.

The web application follows the Container/Presentational Pattern<sup>44</sup>, which enforces separation of concerns by separating the presentational logic from the application logic. This is done by separating the functionality into two classes of components:

- **Container Components:** those which fetch the data, process it, and pass it to the presentational components which are contained by their container components, i.e., the presentational components are children of the container components.
- **Presentational Components:** those which display the data it receives from the container components to the user as it is received. This makes the components highly re-usable, as there isn’t specific data handling logic within them.

React components are reusable, self-contained pieces of the UI which act as building blocks for the application<sup>115</sup>; they can receive properties from their parent components, manage their own internal state, render other components within themselves, and respond to events.

The Container/Presentational pattern can be contrasted with other design patterns for UI design such as the Model-View-Controller (MVC) pattern<sup>95</sup>: in many ways, the containers of the Container/Presentational pattern as a collective can be thought of as analogous to the controller of the MVC pattern, and the presentational components as analogous to the view. The key difference between the two patterns is that the Container/Presentational pattern defines only the architecture of the frontend layer, and does not dictate how the backend ought to be laid out; the MVC pattern defines the architecture of the entire application and so the backend (the model) is necessarily *tightly coupled*<sup>84</sup> with the frontend layer (the view) by means of the controller. Therefore, updating the backend code will most likely



necessitate updating the frontend code (and vice-versa). For this reason, MVC is most commonly used for applications in which the backend & the frontend are controlled by the same codebase, and especially for application in which the frontend rendering is done server-side. The Container/Presentational pattern, however, is *loosely coupled*<sup>84</sup> with the backend and therefore the frontend & the backend can be updated almost independently of one another as long as the means & format of data transmission remain unchanged, thus making development both faster & easier, and mitigating the risk of introducing breaking changes. The Container/Presentational pattern lends itself particularly well to React development, as React code is rendered client-side and makes extensive use of components: the Container/Presentational pattern just ensures that this use of components is done in a way that is logical & maintainable.

In keeping with the Agile principle of continuous improvement<sup>11</sup>, the frontend design has been updated in accordance with user feedback to address issues as they become known.

## 4.1 Main Page

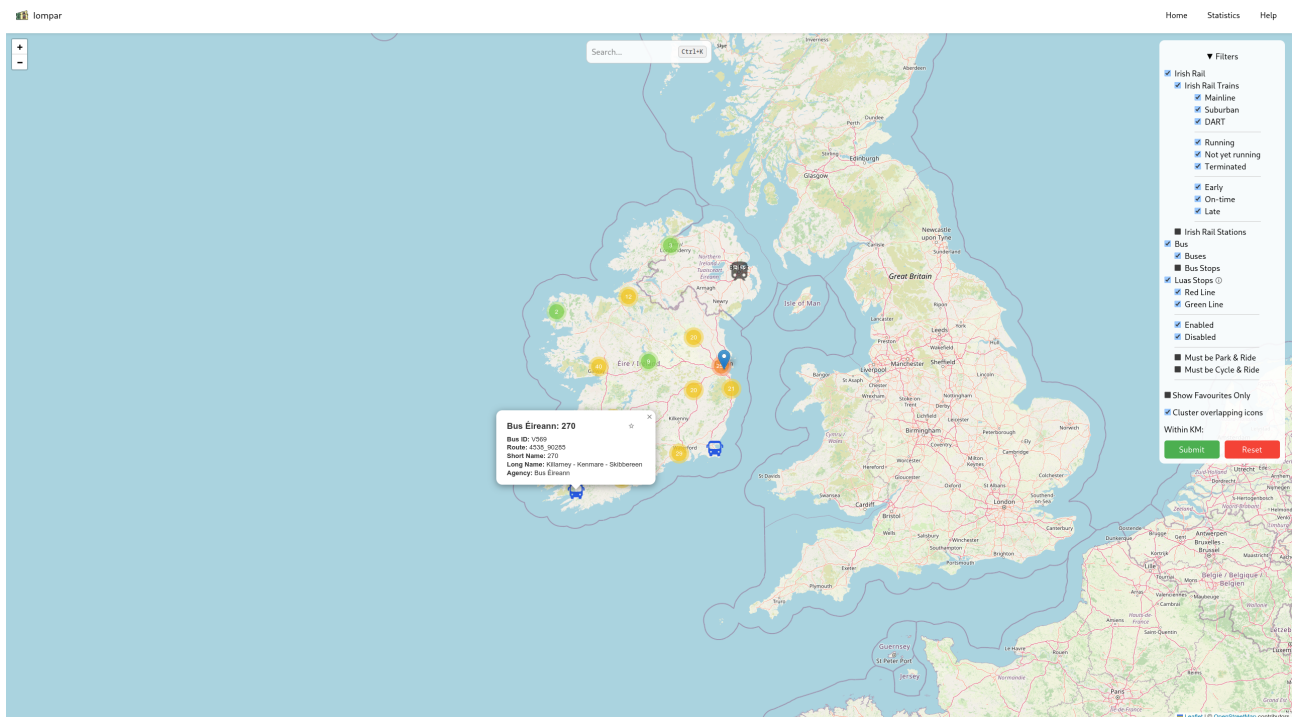


Figure 4.1: Screenshot of the front page of the web application

The main page of the application contains a map upon which the live location of each public transport object is marked, a navigation bar, a search bar to filter the vehicles shown on the map, and a filters side-panel which allows the user to select what kind of objects the user wants displayed on the map. The location markers for each item are clickable, and when clicked, display a pop-up with relevant information about the selected item. In line with Container/Presentational pattern, the main `App.jsx` file contains the data retrieval & processing logic, and passes the processed data to presentational components for display.

### Data Retrieval & Processing

The data is retrieved and processed in a function named `fetchData()`. When the “Submit” button is clicked in the filters side-panel, the function is triggered and sends asynchronous API requests to the `/return_permanent_data` and `/return_transient_data` API endpoints as necessary. The `App.jsx` file contains a JavaScript object which identifies what checkboxes in the side-panel pertain to `objectTypes` in the backend, and which API endpoint they can be sourced from. When the function is fetching data, it constructs a comma-separated list of selected `objectTypes` to send to each API endpoint, thereby making only one request to each API endpoint to avoid unnecessary repeated queries. In order to avoid unnecessary GET requests, this function was originally only run when the user clicked “Submit”, but this was

changed due to user feedback as users were confused as to why no data appeared when they first opened the application; now, this function is automatically executed on page load.

Originally, the returned data was processed using JavaScript functional array methods<sup>21</sup> (very superficially similar to the Java `Stream`<sup>24</sup> interface), which allow for the creation of chained operations on arrays, not dissimilar to chained shell operations using the pipe (`|`) operator on UNIX-like systems<sup>46</sup>. Methods like `.map()`, `.reduce()`, etc. are some of the methods covered in JavaScript functional array methods which allow data processing pipelines to be specified in a clean, elegant, & readable manner. However, the price of this elegance is slower and less efficient execution: these array methods add extra layers of abstraction, invoke a new function per element, create intermediate arrays for each result, and (unlike their Java counterparts) do not support short-circuiting and therefore cannot break early (with the exception of the `.some()` & `.many()` methods)<sup>99</sup>. The modern JavaScript engine also is less efficient at optimising these array methods than simple **for**-loops<sup>91</sup>. Indeed, re-writing the function to use a simple **for** loop resulted in an average loading speed increase of  $\sim 2$  seconds when all data sources were selected.

While the data is loading, a loading overlay with a “spinner” icon is displayed on-screen which prevents the user from interacting with the UI, keeps the user informed of what’s going on (in keeping with the first of Nielsen’s 10 usability heuristics<sup>88</sup>), prevents the user from changing any settings as the data is loaded that may cause inconsistent behaviour, and gives the perception of a smoother loading experience. Studies have shown that displaying a loading screen to the user instead of just waiting for the UI to update gives the impression of a faster loading speed, so much so that even longer load times with a loading screen feel faster than shorter load times without one<sup>22,93,120</sup>.

Once the JSON response is received, each item in the response is iterated over, as described above, and the marker for each item is constructed. The map plotting is done with Leaflet<sup>3</sup>, and each marker on the map consists of an array of co-ordinates, some HTML pop-up content when the marker is clicked, an icon depending on the transport type, a Boolean display variable which dictates whether or not the marker is displayed, and some markup-free `markerText` which is not part of the Leaflet API<sup>3</sup> but added to each icon to give it some text to which the search text can be compared. This `markerText` is never displayed to the user, and is used solely for search & filtering purposes; it is created as an additional variable instead of just using the pop-up content for searching as the pop-up content contains HTML mark-up which would have to be removed at search time to make searching possible, leading to a large number of unnecessary & costly string-processing operations. Each item has a colour-coded icon depending on the type of data it represents:












 41	On-time & early, running Irish Rail trains
 41	Late, running Irish Rail trains
 41	Not-yet running & terminated Irish Rail trains
 38	On-time & early, running DARTs
 38	Late, running DARTs
 38	Not-yet running & terminated DARTs
 87	Irish Rail stations
 1	Buses
 30	Bus stops
 5	Red line Luas stops
 5	Green line Luas stops

Table 4.1: Marker icons &amp; their descriptions

The value of the Boolean `display` variable for each function is calculated before any pop-up content or `markerText` is generated, so as not to waste computational time generating information that will not be shown to the user. Each `objectType` has its own Boolean formula that determines whether or not an item should be shown to the user, depending on what filters they have selected. Each formula is constructed in such a way that expensive computations are avoided if they are unnecessary, by taking advantage of JavaScript's ability to **short-circuit** logical expressions, that is, return immediately if the left-hand side of a Boolean `AND` is false<sup>19</sup> or if the left-hand side of a Boolean `OR` is true<sup>20</sup>.

$$\begin{aligned}
 \text{display}_{\text{train}} = & (\text{latitude} \neq 0) \wedge (\text{longitude} \neq 0) \\
 & \wedge ((\text{showMainline} \wedge (\text{trainType} = \text{Mainline})) \\
 & \quad \vee (\text{showSuburban} \wedge (\text{trainType} = \text{Suburban})) \\
 & \quad \vee (\text{showDart} \wedge (\text{trainType} = \text{DART}))) \\
 & \wedge ((\text{showRunning} \wedge (\text{trainStatus} = \text{Running})) \\
 & \quad \vee (\text{showNotYetRunning} \wedge (\text{trainStatus} = \text{Not yet running})) \\
 & \quad \vee (\text{showTerminated} \wedge (\text{trainStatus} = \text{Terminated}))) \\
 & \wedge (((\text{trainStatus} = \text{Running}) \wedge \\
 & \quad ((\text{showEarly} \wedge (\text{trainPunctualityStatus} = \text{early})) \\
 & \quad \vee (\text{showOnTime} \wedge (\text{trainPunctualityStatus} = \text{On time})) \\
 & \quad \vee (\text{showLate} \wedge (\text{trainPunctualityStatus} = \text{late})))) \\
 & \quad \vee ((\text{trainStatus} = \text{Not yet running}) \wedge \text{showNotYetRunning}) \\
 & \quad \vee ((\text{trainStatus} = \text{Terminated}) \wedge \text{showTerminated})) \\
 & \wedge ((\text{withinDistance} \wedge \text{userLocationAvailable}) \Rightarrow \\
 & \quad \text{haversineDistance}(\text{userLocation}, [\text{latitude}, \text{longitude}]) < \text{withinDistance}) \\
 & \wedge (\text{showFavouritesOnly} \Rightarrow \text{trainCode} \in \text{favourites})
 \end{aligned}$$

$$\begin{aligned}
 \text{display}_{\text{station}} = & (\text{latitude} \neq 0) \wedge (\text{longitude} \neq 0) \\
 & \wedge ((\text{withinDistance} \wedge \text{userLocationAvailable}) \Rightarrow \\
 & \quad \text{haversineDistance}(\text{userLocation}, [\text{latitude}, \text{longitude}]) < \text{withinDistance}) \\
 & \wedge (\text{showFavouritesOnly} \Rightarrow \text{trainStationCode} \in \text{favourites})
 \end{aligned}$$

$$\begin{aligned}
 \text{display}_{\text{bus}} = & (\text{latitude} \neq 0) \wedge (\text{longitude} \neq 0) \\
 & \wedge ((\text{withinDistance} \wedge \text{userLocationAvailable}) \Rightarrow \\
 & \quad \text{haversineDistance}(\text{userLocation}, [\text{latitude}, \text{longitude}]) < \text{withinDistance}) \\
 & \wedge (\text{showFavouritesOnly} \Rightarrow \text{busRoute} \in \text{favourites})
 \end{aligned}$$

$$\begin{aligned}
 \text{display}_{\text{bus stop}} = & (\text{latitude} \neq 0) \wedge (\text{longitude} \neq 0) \\
 & \wedge ((\text{withinDistance} \wedge \text{userLocationAvailable}) \Rightarrow \\
 & \quad \text{haversineDistance}(\text{userLocation}, [\text{latitude}, \text{longitude}]) < \text{withinDistance}) \\
 & \wedge (\text{showFavouritesOnly} \Rightarrow \text{busStopID} \in \text{favourites})
 \end{aligned}$$

$$\begin{aligned}
 \text{display}_{\text{Luas stop}} = & (\text{latitude} \neq 0) \wedge (\text{longitude} \neq 0) \\
 & \wedge ((\text{showGreenLine} \wedge (\text{luasLine} = \text{Green Line})) \\
 & \quad \vee (\text{showRedLine} \wedge (\text{luasLine} = \text{Red Line}))) \\
 & \wedge ((\text{showEnabled} \wedge (\text{luasStopIsEnabled} = 1)) \\
 & \quad \vee (\text{showDisabled} \wedge (\text{luasStopIsEnabled} = 0))) \\
 & \wedge (\neg \text{showCycleAndRide} \vee (\text{showCycleAndRide} \wedge (\text{luasStopIsCycleAndRide} = 1))) \\
 & \wedge (\neg \text{showParkAndRide} \vee (\text{showParkAndRide} \wedge (\text{luasStopIsParkAndRide} = 1))) \\
 & \wedge ((\text{withinDistance} \wedge \text{userLocationAvailable}) \Rightarrow \\
 & \quad \text{haversineDistance}(\text{userLocation}, [\text{latitude}, \text{longitude}]) < \text{withinDistance}) \\
 & \wedge (\text{showFavouritesOnly} \Rightarrow \text{luasStopID} \in \text{favourites})
 \end{aligned}$$

Although the formulae may appear excessively complex at first glance, they're relatively easy to understand when broken down: each line is essentially a conjunction of a variable that dictates whether or not a filter is applied and a check to see if that condition is fulfilled, e.g.,  $(\text{showMainline} \wedge (\text{trainType} = \text{Mainline}))$  checks if the "Show Mainline" filter is applied and if the item in question fulfils that criterion. Each line of logic is either in conjunction or disjunction with the preceding line depending on whether or not that the filter is a *permissive filter* (that is, it increases the number of items shown) or if it is a *restrictive filter* (that is, it decreases the number of items shown).

As can be seen in the preceding formulae, if the user location is available and the user has specified that all items must be within a certain distance of their location, each marker is checked to see if it's within range by using **Haversine distance**, which calculates the shortest distance between two points on the surface of a sphere. The Haversine distance formula is defined as follows<sup>16</sup>:

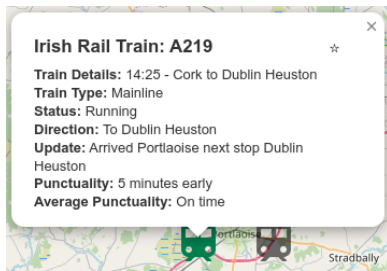
$$d = 2r \cdot \arcsin \left( \sqrt{\sin^2 \left( \frac{\Delta\phi}{2} \right) + \cos(\phi_1) \cos(\phi_2) \sin^2 \left( \frac{\Delta\lambda}{2} \right)} \right)$$

where:

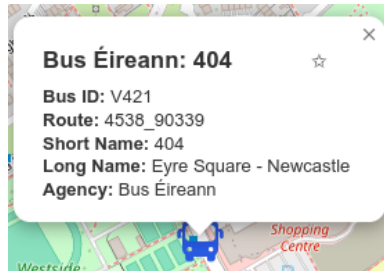
- $d$  is the distance between the two points,
- $r$  is the radius of the Earth ( $\sim 6,371$  kilometres<sup>118</sup>),
- $\phi_1, \phi_2$  are the latitudes of each point in radians,
- $\lambda_1, \lambda_2$  are the longitudes of each point in radians,
- $\Delta\phi = \phi_2 - \phi_1$ , and
- $\Delta\lambda = \lambda_2 - \lambda_1$ .

This formula was chosen as a good middle ground between accurate distance calculations and efficient computation. There are other distance formulae, such as Vincenty's formula<sup>119</sup> which is more accurate (because it considers the Earth to be an oblate spheroid rather than sphere) but slower to compute, or Euclidean distance<sup>114</sup> which is fast to compute, but inaccurate for points on the surface of the Earth (because it considers the points to be on flat 2D grid). Arguably, one could get away with using Euclidean distance, as the distances considered in this application are relatively short (covering only the island of Ireland) and in general, a user will be specifying only short distances to see services in their immediate vicinity. However, this approach cannot be scaled if the application scope was increased to include a broader geographical area as inaccuracies would rapidly build up, and even over the island of Ireland alone, there is potential for inconsistent behaviour due to measurement inaccuracies. Haversine distance is not too computationally expensive, and guarantees a reliable degree of accuracy for the user.

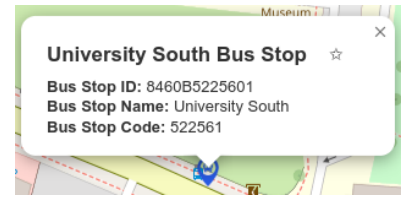
## Marker Pop-Ups



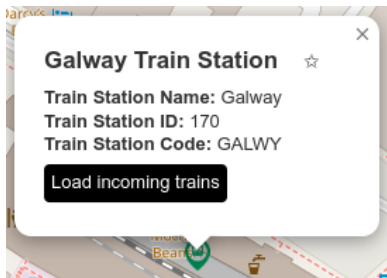
(a) IrishRailTrain pop-up



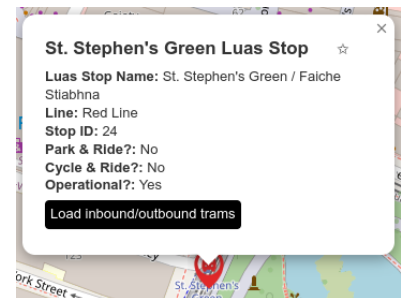
(b) Bus pop-up



(c) BusStop pop-up



(d) IrishRailStation pop-up

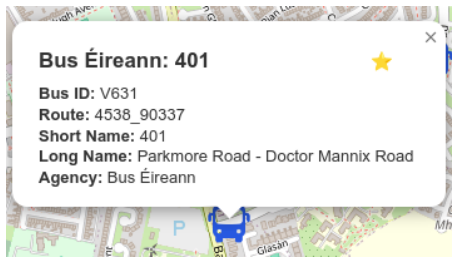


(e) LuasStop pop-up

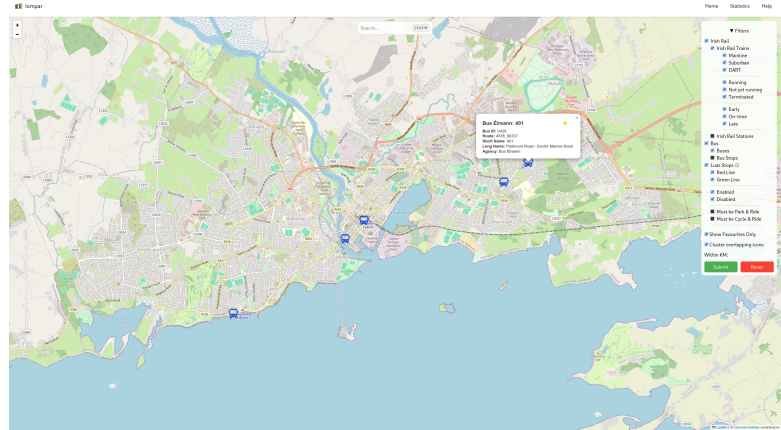
Figure 4.2: The 5 pop-up types

When the data is being fetched, a pop-up is created for each new marker collected, to be displayed when the marker is clicked. For each objectType, there is a separate React component for its pop-up to which the item's data is passed so that it can be rendered differently depending on the service type. The IrishRailTrain pop-up, Bus pop-up, & BusStop are the most similar and the simplest, as they simply display information passed into their respective components, the only variance being that different objectType have different fields to display. On mouse-over of a marker icon, a tool-tip displays the item's title, as user feedback expressed that it would be useful for the item's title to be displayed on mouse-over so that the user doesn't have to click into the pop-up to see the service to which a marker belongs.

Each pop-up has a "star" button which, when clicked, adds the selected item to a list of the user's "favourite" services, which is stored as a cookie in the user's browser. This cookie is loaded when the main page is loaded and updated every time an item is toggled to be "starred" or not. This list of favourites is used to determine whether or not the item is displayed when the user selects "Show favourites only", as can be seen in the Boolean display formulae previously outlined. Favouriting behaves differently depending on the objectType of the item being favourited: notably, buses are favourited not on a per-vehicle basis using the item's objectID, but on a per-route basis. This means that if a user favourites, for example, a 401 Bus Éireann bus, every bus on this route will appear when the user applies the "Show favourites only" filter. This makes the favourites feature far more useful than it would be otherwise: users are generally interested not in a specific bus vehicle, but a specific bus route.



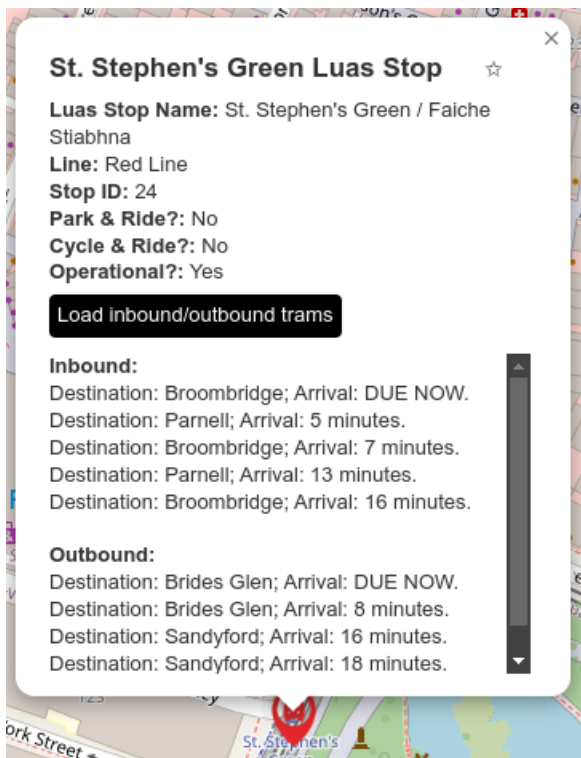
(a) Bus pop-up with bus “favourited”



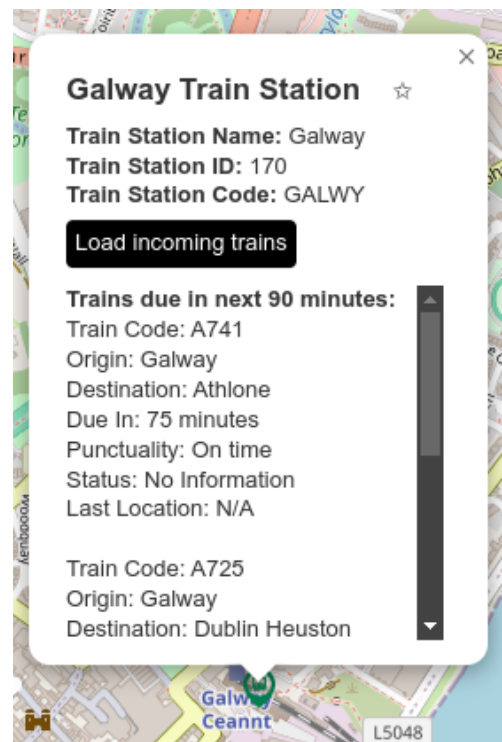
(b) Buses of the same route appearing when “favourites only” filter applied

Figure 4.3: Demonstration of the “favourite” functionality with buses

Train station pop-ups & Luas stop pop-ups also have an additional button which, when clicked, fetches data about the services relating to that station. This is necessary for Luas stops, as Luas data is only available on a per station basis, and just an extra feature for train stations, as train data is plotted on the map regardless. The “Load inbound/outbound trams” button on the Luas stop pop-up fetches data from the `/return_luas_data` API endpoint which contains the inbound and outbound trams due into that stop. The “Load incoming trains” button on the train station pop-up fetches data from the `/return_station_data` API endpoint which contains the trains due into that station in the next 90 minutes. This information is then displayed in the pop-up itself, with a scrollbar if the information is too long to display in the pop-up without it becoming unmanageably long.



(a) Results of clicking “Load inbound/outbound trams”



(b) Results of clicking “Load incoming trains”

Figure 4.4: Demonstration of the “favourite” functionality with buses

## Filters Side-Panel

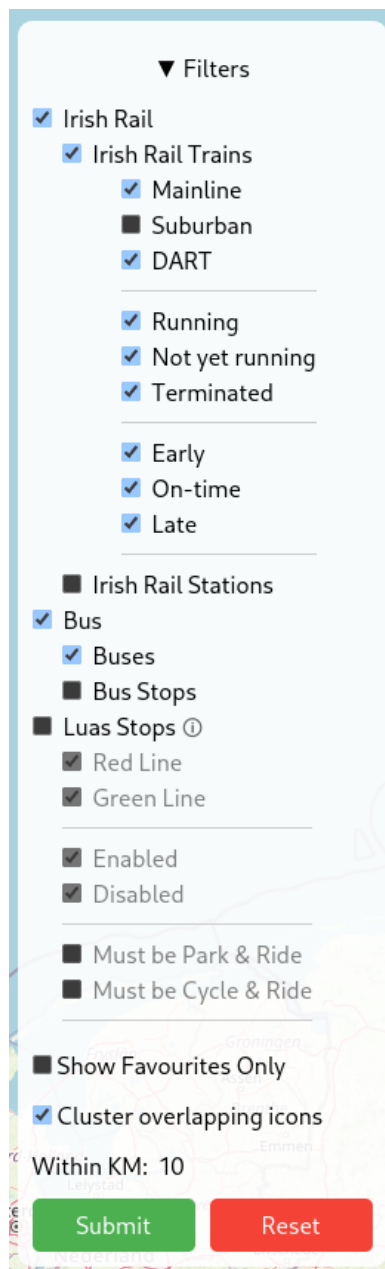


Figure 4.5: Screenshot of the filters side-panel

The Boolean filter variables mentioned in the display formulae above are selected by the user in the filters side-panel, implemented as a separate (presentational) component. The component appears in the top-right hand corner of the screen, and can be minimised while browsing the map. When a user clicks “Submit”, the `fetchData()` function is invoked with the selected filters, and these selected filters are saved as a cookie to the user’s browser; this cookie is loaded when the main page is first loaded, so that a user’s last used filters are pre-selected for them when they open the application. Even the value of the “Within KM” number is stored as a cookie and loaded in with page load so that a user’s experience is as seamless as possible between uses. These saved filters are applied automatically when the data is first being fetched as the page loads so as to reduce the user’s workload and need to interact with the application.

The first three top-level filters determine what data sources are used: Irish Rail, Bus, and/or Luas Stops. If a top-level or second-level filter is deselected, all its child filters are greyed out and cannot be interacted with until all its parents are selected. Initially, if no cookie was stored for a user, the top-level filters would all be deselected and all of their children would be selected, in an effort to allow the user to only include the filters that they wanted to include; however,



user feedback indicated that this was annoying & cumbersome, so the panel was updated to default to displaying all the live data available on page load, with “Irish Rail Trains”, “Bus”, and “Luas Stops” selected and all of their children. The only exception to this are the “Must be Park & Ride” and the “Must be Cycle & Ride” filters underneath “Luas Stops”: these filters are more restrictive, and hide any item that does not match them, and so are not selected by default.

In the initial design, any checkbox could be de-selected as the user pleased but this had the negative side-effect of there being filter selection combinations that would necessarily display no data, for example if “Mainline”, “Suburban”, and “DART” were de-selected then there would be no Irish Rail Train fulfilling the criteria of being not one of those three train types, and so no train data could be displayed; this caused confusion and frustration in users. There was also no indication of which filters shared these dependencies: all the child filters of a filter were just listed vertically. To address these issues, functionally dependent filters were grouped together with the use of horizontal rules to indicate groupings in a subtle yet intuitive manner. Then, in keeping with Nielsen’s usability heuristic of “Error Prevention”, the panel was updated so that it was no longer possible to de-select every filter in a dependent group; if a user attempts to do so, a notification will appear to inform them that they must have at least one filter from that group must be selected (also in keeping with the Nielsen’s heuristic of “Visibility of System Status” and “Help Users Recognise, Diagnose, & Recover from Errors”. For example, if a user de-selects the “Terminated” and “Not yet running” filters for Irish Rail Trains, they will be prevented from de-selecting the “Running” filter, as a train must be in at least one of those three states.

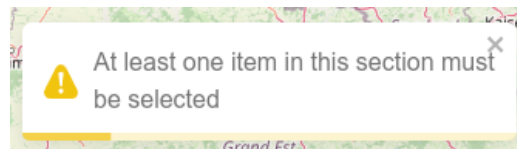


Figure 4.6: Notification displayed to user if they attempt to deselect all filters in a dependent group

Another addition that was made in response to user feedback was the addition of an information icon & an information tooltip that appears on mouse-over, which explains how to see live tram data: some users expressed confusion about the unavailability of live tram location data, and suggested that the information be made more readily accessible to the user than in a help page that the user has to click into themselves. The addition of this tooltip makes the information easily & readily accessible, without excessively cluttering up the user interface. This is in keeping with Nielsen’s heuristic of “Help & Documentation”, which suggests that documentation (should it be required) ought to be presented in context right at the moment that the user requires it.

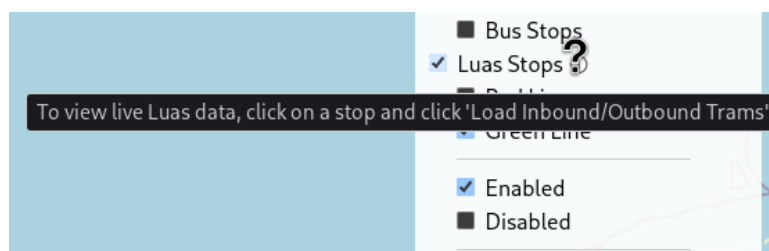


Figure 4.7: Information tooltip which is displayed on mouse-over of the Luas Stops filter

The “Cluster overlapping icons” option does not change what data is shown, but how it is shown; by default, any items whose icons overlap one another’s at the current zoom level are *clustered* into a single icon that displays the number of items which are contained within it using a Leaflet plug-in called `Leaflet.markercluster`<sup>80</sup>. This option toggles this behaviour, which may be desirable depending on the user’s preferences, especially when only few items are being displayed in a small geographical area.



Figure 4.8: Effects of enabling/disabling clustering

The “Within KM” option accepts a number input value of the range within which an item must be for it to be displayed. This option only appears if the user’s geographical location is available: if their browser does not support the option, or if they have rejected location access to the application, the option will not appear. The option can be reset to showing all items regardless of range by deleting the input to the textbox; if the user enters a value that doesn’t make sense, such as a number  $\leq 0$ , the application defaults to displaying all items regardless of distance, on the assumption that the user is either attempting to reset the filter by entering “0” or that they have accidentally entered a nonsensical value.

A subject of much deliberation in the design process was the behaviour of the “Submit” button. It’s important that the map only updates when the user asks it to so as to avoid situations where the user is looking at an item, the page refreshes automatically, and it disappears from view; therefore, fetching new data had to be a manually-specified process, rather than occurring automatically. The question of whether or not the filters should be applied as soon as they are selected or only upon a “Submit” also received much consideration: automatically updating them would minimise the amount of user interactions necessary, but to re-calculate the display value for every item when there are many being displayed could take a few seconds, and make the application unresponsive as the user makes many changes to the selected filters. Therefore, it was decided that the filters should only be applied when the user requests that they be applied, so that they can decide what filters to apply in a convenient & usable way. Finally, there was the question of optimisations: if the data sources selected did not change but a display filter did (for example, the user didn’t change that they wanted to look at Irish Rail Trains, but added a selection to specify only Mainline trains), should another request be made to the API endpoints? Not requesting new data would mean a faster loading time and a more responsive program, at the cost of showing the user potentially out-of-date data. It was decided that each new click of “Submit” should always fetch new data, to align the program as much as possible with the user’s mental model of the program, in keeping with the HCI principle of **conceptual model alignment**<sup>90</sup>: the behaviour of the application should match how the user imagines it to behave. Users are familiar with the “make selections, then confirm” paradigm, and will expect the submit button to do the same thing each time (which aligns with Nielsen’s usability heuristic of “Consistency & Standards” and of “speaking the user’s language”<sup>88</sup>).

In keeping with Nielsen’s heuristic of “User Control & Freedom” (which suggests that there should be a clearly accessible “undo” button to allow users to back out of a process to foster a sense of freedom & confidence, and to allow them to avoid getting stuck), a “Reset” button was added to the panel which resets the selected filters to the last saved selection for the user (or the default selection if there is no last saved selection); this means that if a user makes or mistake or wants to backtrack, they can do so easily.

The initial design for this application had the filters panel minimised by default for a clean & minimalist aesthetic, but user testing & feedback showed that the panel should be maximised by default so that users can easily see how they are supposed with the application and know where to look for controls.

## Search Bar

The search bar allows the user to further refine the displayed items beyond what is possible with the filters side-panel by specifying text that should be present in the marker. The search is based upon a `markerText` variable that is constructed for each marker as the data is fetched, consisting of the pop-up content without any formatting, upper-case characters, or non-alphanumeric characters. Similarly, entered search terms are made lower-case and stripped of non-alphanumeric characters to facilitate searching, and an item is deemed to match the search term if the search term occurs in the `markerText`. This approach is relatively simplistic as search algorithms go, but is fast & efficient, and more than suitable for this application.

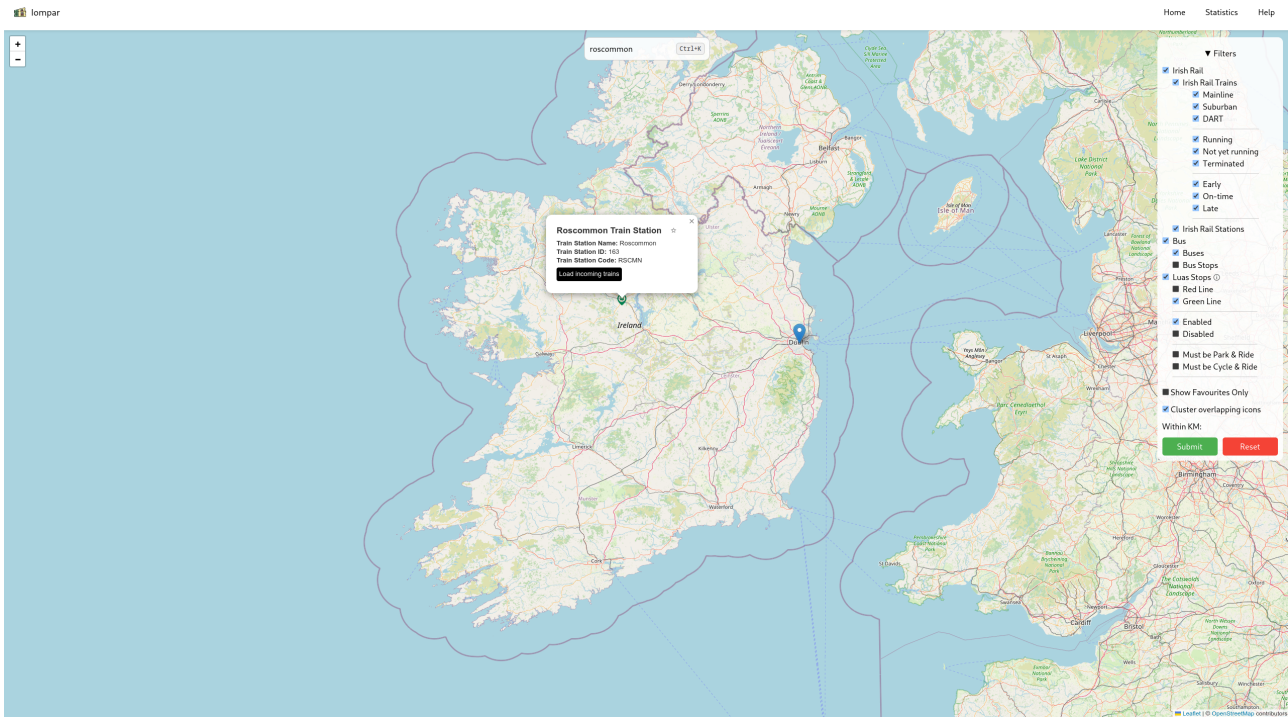


Figure 4.9: Screenshot of the search bar being used

Unlike the filters panel, the displayed items are automatically filtered as the user enters text, which is facilitated by the search-based filtering being separated from and less computationally complex than the side-panel based filtering. This allows the results to be quickly filtered in a responsive manner by the user, and makes the completion of tasks generally faster & more responsive. However, updating the filtered items for every keystroke that the user enters would be wasteful, as each key entry further refines their search and they would type it regardless, and constantly re-computing which items match the search term for each keypress would result in the application becoming less responsive. To prevent this, the search bar employs a **debounce function**<sup>78</sup> which waits for a very short interval after the user's last keypress to start searching for the entered text; the search will only commence once the user has finished typing. Experiments with different values on different users indicated that 300 milliseconds is the ideal value for this application: long enough that it won't be triggered until the user pauses typing, but short enough that the gap between the user stopping typing and the search being applied is nearly imperceptible.

However, if very large amounts of data are being displayed, such as in the event that the user has selected all data sources, the search can take a noticeable amount of time and make the UI sluggish & unresponsive as the search is executed. To address this, if the number of items being displayed is so high that it will induce noticeably slow loading times, the debounce time is increased to 400 milliseconds to be more careful in avoiding unnecessary computations, and the loading overlay is displayed as the filtering is performed to prevent the user from being exposed to a sub-optimally performant UI.

The search function makes use of the `useMemo`<sup>116</sup> React hook to cache the results of filtering the markers based off the search text, and making it so that it will only be re-calculated if the search term changes or if the markers change.

Without `useMemo`, every re-render of the page would cause the filter function to run even if nothing had changed, which would be a huge waste of computational resources.

Finally, the keyboard shortcut `CTRL + K` was added to allow advanced users to speed up search interactions and focus the search bar without having to remove their hands from the keyboard, in keeping with Nielsen’s heuristic of “Flexibility & Efficiency of use” which says that shortcuts can speed up interactions for expert users so that the design can cater to both experienced & inexperienced users: inexperienced users can focus the search bar the simple & intuitive way using the mouse, and experienced users can do it in a faster manner using the keyboard.

## Map

The map component itself is the presentational component in which all of the mapping & plotting functionality is performed, implemented using the `Leaflet`<sup>3</sup> mapping library and map tiles from `OpenStreetMap`<sup>23</sup>; this option was chosen as it is lightweight & performant, free to use, and is flexible & customisable. It is also by far the most popular mapping library, and has comprehensive documentation and a wide range of plug-ins. Other mapping options exist, such as `Mapbox`<sup>82</sup> and the `Google Maps API`<sup>40</sup>, but these have limited free tiers compared to the completely free & open-source option of `Leaflet` with `OpenStreetMap`. It receives the markers to be displayed, a Boolean determining whether clustering is enabled, and the geolocation of the user, if available. If the user’s geolocation is available, a “You are here” marker is added to the map and the map is centered on those co-ordinates; otherwise, the map centers on the geographical centre of the island of Ireland<sup>72</sup> and displays no marker.

Each marker variable component passed to the map component is added to the map, and if clustering is enabled, is wrapped in a `MarkerClusterGroup` to cluster the icons together if they overlap.

## 4.2 Statistics Page

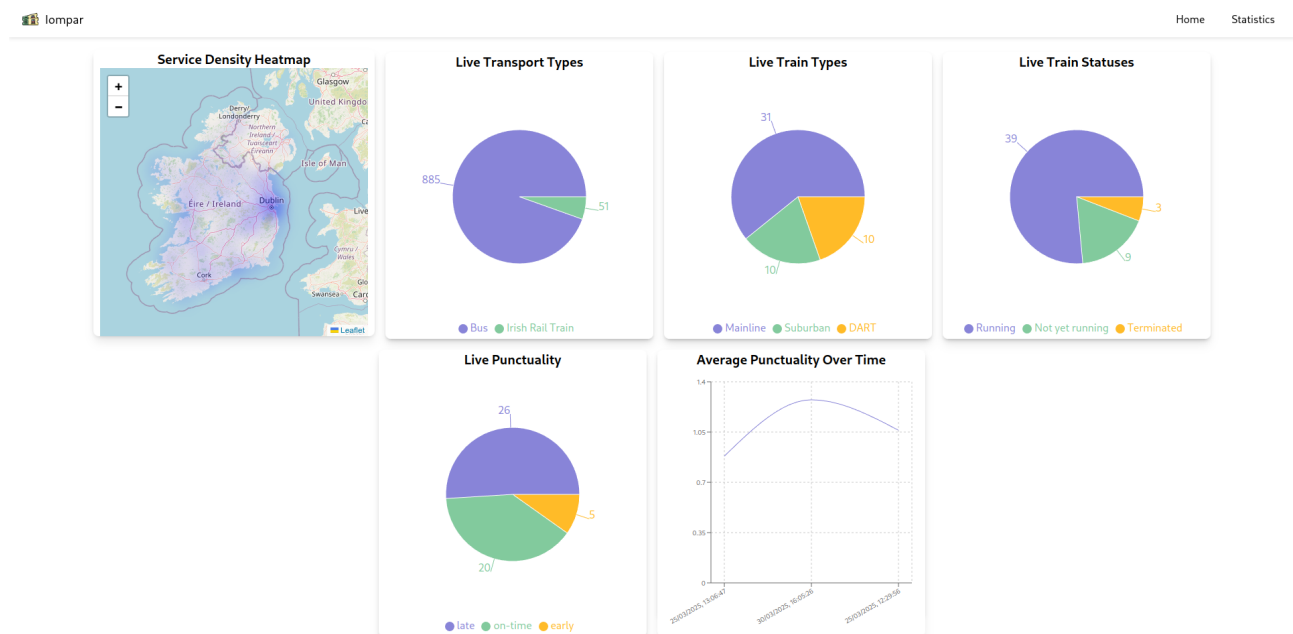


Figure 4.10: Screenshot of the statistics page

The statistics page of the application exists to give the user a deeper insight into the data than simply live data. The grid layout is achieved with the use of Tailwind CSS flexbox<sup>69</sup>. It consists of 6 graphs, each displaying a different statistical insight about the application data:

- The Service Density Heatmap displays a heatmap depicting the geographical distribution of currently-running public transport services on the island of Ireland;
- The Live Transport Types pie chart displays the proportion of objectTypes for which there is currently live location data;
- The Live Train Types pie chart displays the proportion of mainline, suburban, & DART Irish Rail Trains currently in operation;
- The Live Train Statuses pie chart displays the proportion of running, not yet running, & terminated trains at the present moment;
- The Live Punctuality pie chart displays the proportion of late, on-time, & early services at the present moment.
- The Average Punctuality Over Time line graph displays how the average punctuality of services varies per collected timestamp.

Each pie chart uses the same re-usable presentation component which accepts some data and displays it. Pie charts are somewhat controversial in the realm of data visualisation and are often rejected in favour of bar charts, and are only recommended to be used under certain particular situations: when the data being illustrated is a part-to-whole representation, when there is no more than 5 categories in the pie chart, and when there are not small differences between the categories<sup>122,18,81</sup>. Since the data for this application fulfils these criteria, and because testing with bar charts resulted with more difficult to understand results (as part of the proportion), pie charts were deemed suitable for this purpose.

### 4.3 Help Page

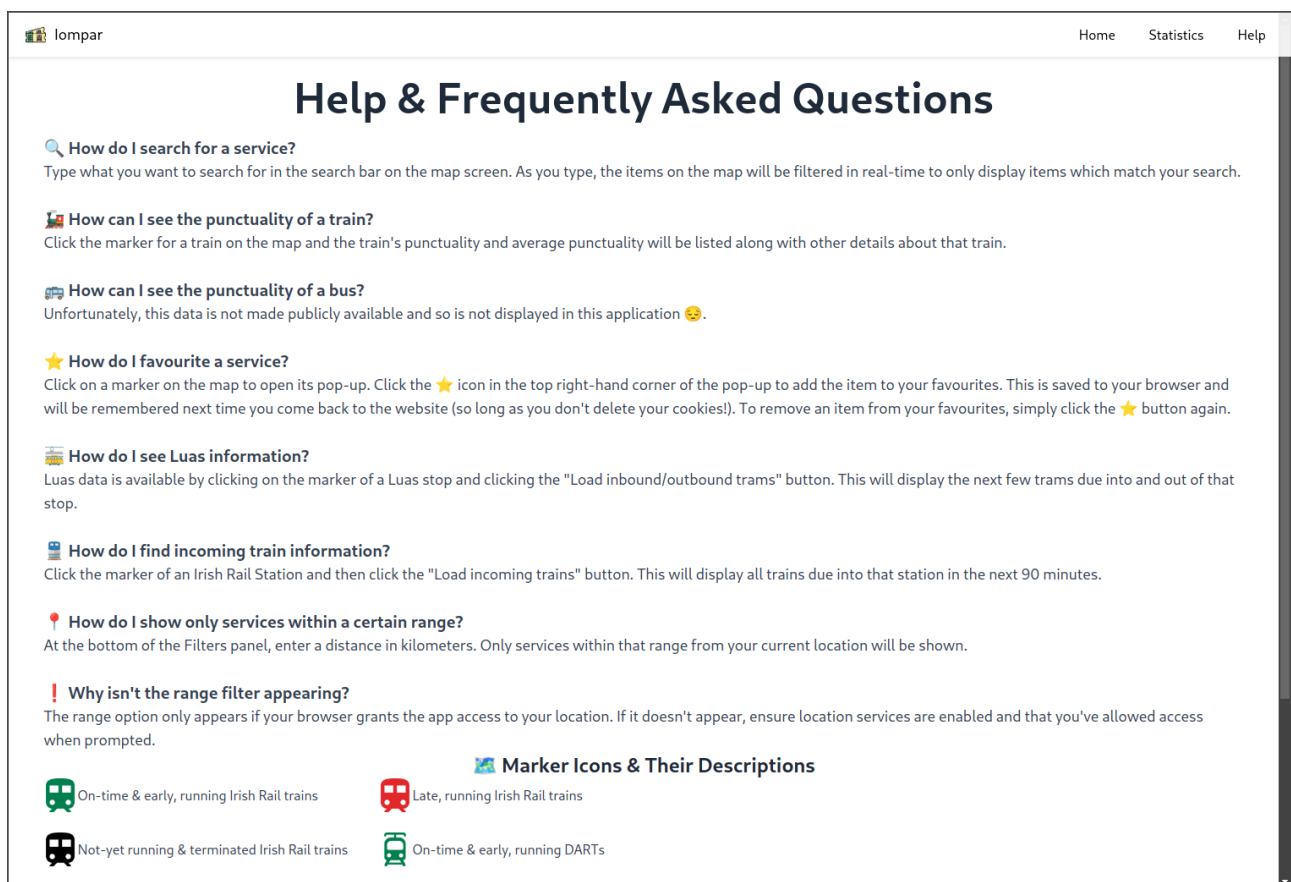


Figure 4.11: Screenshot of the help page

The help page is a very simple web page that just contains questions and answers on how to perform basic tasks, such as favouriting an item or viewing real-time Luas information. It is intended to be user-friendly and easy to search through; this is in part facilitated through its minimalist design (achieved with TailwindCSS) which attempts to prevent the user from having to sift through irrelevant information to find out how to perform a basic task. A legend of the icons used & their meanings was added in response to a user request for a legend.

# Chapter 5

## Evaluation & Conclusion

### 5.1 Evaluation

#### 5.1.1 Objectives Completed

Each of the core objectives set out for this project were completed:

1. A live map of train, DART, bus, & Luas services in Ireland was created which displays the real-time whereabouts about the service, relevant information about that particular service, and the punctuality of the service, to the extent that is possible with publicly-available data.
2. The live map was given a powerful search tool which facilitates easy navigation & use, such as allowing the user to find the particular service in which they are interested.
3. A side-panel was created with an extensive array of filters that can be applied to the map to limit what services are displayed, including filtering by transport mode & punctuality.
4. A historical database was created in which historical data about public transport services is collected, with the insights gained from the historical data being made available to the user via relevant predictions about the punctuality of a service based off its track record.
5. The interface is responsive and is equally functional on both desktop & mobile devices.

Many additional objectives beyond the core objectives were also completed:

1. The application does not just have vehicle-based information, but also route-based information, allowing users to search for a particular bus route or service.
2. A feature was created to allow the user to “favourite” or save specific services, such as a particular bus route or Luas stop.
3. Cookies were employed to recall a user’s selected filters and favoured items when they re-visit the page.
4. The user’s geographical location is obtained via their browser’s API and plotted on the map, and this information is used to allow users to filter results by proximity to themselves by specifying a radius.
5. The UI design complies with Nielsen’s 10 Usability Heuristics.
6. The frontend performance was optimised and tuned to increase the loading speed of the application by several seconds.
7. The backend was cost-optimised to stay within the limit’s of the AWS free tier.
8. Unit tests were written for each piece of backend code, with a line coverage of 85% achieved, exceeding the minimum target value.
9. A CI/CD pipeline was created which automatically tests and deploys new code.



However, not all of the secondary objectives which were set out at the beginning of the project were completed:

1. No user account feature was added. The primary reason for this was just that it was quite low on the list of priorities, and so time wasn't made for it before the project deadline, although research was done into how it could be executed, and it likely would not be overly difficult. **Amazon Cognito**<sup>104</sup> provides a user directory, authentication server, and authorisation service, and therefore circumvents the need to create a sign-up process for the application and secure the database from scratch. It integrates into React with the `aws-amplify` library<sup>100</sup> which comes with a pre-built login/sign-up UI, and so practically no work would need to be completed to add an accounts system to the application: just enable the service and add some boilerplate React code. The only aspect that would require any substantial development effort would be the creation of a DynamoDB table with the primary key being the user's Cognito ID which stores the user's filters preferences; since these are already stored in JSON format on the user's machine, the structure would not have to be changed at all to add the information to the No-SQL database, and all that would need to be done would be to add a method for uploading the data.
2. No user review capability was added to allow users to report issues such as anti-social behaviour. This is primarily because of this feature being very low priority, and being dependent on the creation of a user account feature first to work; theoretically, a review system could be implemented without a user account system by just allowing anyone to POST some data to an API which adds it to a database and displays it on the website, but this would be a very bad idea in practice both from a security point of view and from a spam & vandalism prevention point of view. However, some research and planning was nonetheless carried out: a new DynamoDB table could be created with an item's objectID as its partition key, and `userID#timestamp` as the sort key, where `userID` is the Cognito ID of the logged-in user and the `timestamp` is the time the review was made. A form could be added to the frontend which uses `aws-amplify` to make authorised POST requests to an API endpoint. Then, when a user loads information about a given service, this table could be queried to display relevant user feedback about that service. In practice, there would need to be some kind of moderation of this review system to prevent spam, vandalism, & to remove unhelpful reviews.
3. The web application was not made available online with a dedicated domain name. The first reason for this is simply to avoid the cost of acquiring a dedicated domain name, but the site nonetheless could be made available online using an AWS S3 bucket<sup>109</sup> (essentially serverless flat file storage) to store the website's build files, and accessed using the auto-generated S3 static endpoint URL; the second reason is that this would expose the application more fully to the open Internet, which could increase the number of API calls made, Lambda functions triggered, and risk pushing the application out of the free tier, although the risk of this is really quite low. The third and primary reason why this was not implemented is that its low priority led it to being sidelined in favour of more mission-critical work.
4. The React application was not ported to React native to run natively on Android & iOS devices, nor was it published to relevant software distribution programs. In retrospect, this was a wildly over-optimistic goal to even consider for this project: while React Native greatly simplifies mobile application development, it is not a magic solution that completely removes the need for platform-specific development, and Android & iOS knowledge would almost certainly be needed for debugging platform-specific issues or to utilise any native modules that don't have a React Native wrapper. Moreover, such development would require a development & testing environment using Xcode and Android Studio, and would in doing so require at least a basic understanding of the two operating systems. Porting a web application as substantial as this one to React Native is non-trivial, as there are quite significant differences between the two, and would in itself constitute several months of work.

Overall,  $\frac{14}{18} = 77.7\%$  of the specified objectives were completed, including 100% completion of the core objectives, and completion of the majority of the secondary objectives; objectives that were not completed were nonetheless researched and planned.

### 5.1.2 Heuristic Evaluation: Nielsen's 10

Nielsen's 10 usability heuristics for user interface<sup>88</sup> design are a commonly-applied evaluation framework used by UX professionals to identify common usability issues, and so the application was defined with these heuristics in mind. Nielsen's 10 usability heuristics provide a comprehensive, research-backed framework for evaluating the usability of user interfaces and are widely accepted in the field of Human-Computer Interaction, in particular for their general yet



actionable nature which makes them applicable to nearly any user interface.

In a business setting, this heuristic-based analysis would be carried out by a disinterested, third-party HCI professional or expert; in the absence of such an evaluation, I have attempted to provide a reasonably & fair heuristic-based analysis below, that is as unbiased as is possible for an evaluation of an application done by the developer of said application. It is my opinion that, as a result of development having been carried out with these heuristics in mind, that the application fulfils each of Nielsen's 10 usability heuristics to a high degree, with some room for marginal improvements in some areas.

### Visibility of System Status

*The design should always keep users informed about what is going on, through appropriate feedback within a reasonable amount of time*

The system status of the application at any given time is displayed clearly to the user, in an intuitive manner:

- The live location of each service is plotted on the map, clearly indicating the geographical state of each item.
- Each item has a colour-coded icon that tells the user the type of service it is, and specific information about that particular service beyond type, e.g., if the train is late or if the Luas stop belongs to the green line.
- The details of each item plotted on the map are displayed in a clear format and are readily available: a tooltip which appears on mouse-over tells the user the service to which a marker belongs, and clicking on a marker displays a pop-up where the information about the service is laid out clearly in text form. This pop-up is pre-generated as the live data is fetched & parsed, so it loads as quickly as the DOM can be updated.
- Whenever data is being fetched, a loading screen is displayed with variable text that changes depending on what's being loaded: for example, when the user's location is being determined it says "Attempting to determine the current location..." (subtly informing the user that it may not successfully determine the location if, say, GPS data is disabled on the user's device), and when the data is being fetched it says "Loading data...". Individual graphs on the Statistics page that may take longer to load than other graphs have their own loading overlays, for example, the heatmap has an overlay that says "Loading heatmap...".
- Whether or not an item is "favourited" is clearly indicated in the top right-hand corner of the item's pop-up, which updates instantly as the item is toggled as a favourite.
- When a user is prevented from taking an action that would produce undesired behaviour, such as when the user is prevented from de-selecting all the filters in a single group such as "Mainline", "Suburban", & "DART" (because any train must be at least one of those three), a notification is displayed telling the user what happened and how they can avoid it in the future.
- The filters panel uses the widely-recognisable & widely-understood checkbox to indicate whether or not a filter is applied, which updates as soon as the checkbox is clicked.

Potential for improvement in this domain could include displaying the timestamp of when the data displayed was obtained in a status bar at the bottom of the screen, along with other pieces of information like the number of items displayed.

### Match Between the System & the Real World

*The design should speak the users' language. Use words, phrases, and concepts familiar to the user, rather than internal jargon. Follow real-world conventions, making information appear in a natural and logical order.*

The application seeks to match the user's expected meaning for any term, symbol, or value displayed and avoids any technical terminology or jargon that is not immediately obvious in its meaning.

- As detailed in §3.3 **update\_average\_punctuality**, the average calculation employed was carefully considered to be as intuitive and immediately understandable as possible to the user; while it is a design flaw if a user doesn't know what is meant by a term used, it is an even worse design flaw if the user thinks they know what is meant by a term used but it doesn't actually mean what they expect it to mean. Therefore, it was of great importance that the average value shown to users was easily understood and what they expected it to be.
- Each filter is named in such a way so that it is immediately obvious how it affects what results are displayed; each filter that is a sub-filter applied to items selected in another filter is displayed visually below and indented to make it clear that the filter in question is a child filter or subordinate to the parent filter, i.e., in a natural & logical order. Filters that are naturally grouped together in the real world, like the different punctuality filters are delimited with a horizontal rule to make it clear that they are grouped together. This natural mapping<sup>113</sup> makes it easier for users to learn & remember how the interface works, and to build an experience that feels intuitive.
- As detailed in §4.1 **Filters Side-Panel**, much thought was put into making the behaviour of data fetching align with the user's conception of how the data fetching should work, and it was decided that the optimal way to do this would be with the "make selections, then confirm" paradigm.
- Nowhere in the UI is esoteric or unusual technical jargon used to describe an aspect of the application; familiar transport terms like "stop" and "route" are used, and no technical reference is made to the internal operation of the software. To a non-technical user, it has the appearance of "just working".
- As previously mentioned, each icon has a unique icon that depicts the public transport type it represents, which utilises familiar imagery to convey a message to users quickly Icons are colour-coded to imply meaning: for example, a black semi-transparent train is not active at the moment, a green train is on time or early, and a red train is late.
- The term "favourites" was chosen for the list of services that the user has marked as being of interest to them; a more technically precise term would be something like "Saved objectID list", but "favourites" is much more quickly understood and is not confusing for non-technical users.

### User Control & Freedom

*Users often perform actions by mistake. They need a clearly marked "emergency exit" to leave the unwanted action without having to go through an extended process.*

The application emphasises user control, allowing users to specify whatever combination of filters they see fit (that will return results), and supporting a diverse range of navigation styles such as searching the map with the search bar for a specific service, looking for the service manually on the map, or limiting down the displayed results with filters. In addition to these user controls, the application gives greater control to users with:

- The "Reset" button in the filters side-panel which can be used to reset the filters to the last saved state if the user has accidentally made a wrong selection or has changed their mind about something (similar to the "undo" button of which Nielsen speaks).
- The browser forward & back buttons are supported with the use of React Router, something that is not guaranteed for single page applications; if a user visits the statistics or the help page, they can return to the map page by using their browser back buttons, where the application will still be displaying the results of their last search and the filters / search terms used.

There is potential scope for future improvements for this heuristic: a button to cancel the fetching of new data on the loading screen could be used to allow the user to change their mind after clicking "Submit", especially if they've selected filters that will produce a large number of items to be displayed or if they're on a weak network connection. However, the loading speed of the application is fast enough on a moderately fast network that loading a normal selection of filters takes a few seconds at worst, so this is not a particularly critical feature to have. Other possible future work includes storing the full history of filters applied by the user so they can skip back through them with dedicated forward & back buttons, and to store the user's search history so that it appears as suggestions in the search bar as the user types.

## Consistency & Standards

*Users should not have to wonder whether different words, situations, or actions mean the same thing. Follow platform and industry conventions.*

Re-inventing the wheel has been consistently avoided throughout the design of this application: if there is a standard and well-understood way of doing something, it was applied in the UI design to make it as simple & intuitive to use as possible.

- As mentioned previously, the “Submit” is designed to behave in a way that is consistent & understandable.
- The map interactions with Leaflet & OpenStreetMap support standard & well-established navigation controls: zoom in/out buttons in the top left-hand corner, scroll to zoom, +/- keys to zoom, panning by dragging, panning by arrow keys.
- The keyboard shortcut to focus the search bar (Ctrl+K) is a commonly used keyboard shortcut for
- The navigation bar component was deliberately designed to be as unsurprising as possible.
- The means for displaying additional information about a marker by clicking on it is standard across many mapping applications, such as Google Maps<sup>40</sup>.
- The checkbox filters used in the filters panel are easily understood & recognised, and are well-established web features.
- As mentioned previously, consistent & standard terms are used throughout the application.
- The layout & theming of the application is consistent throughout the entire application.

## Error Prevention

*Good error messages are important, but the best designs carefully prevent problems from occurring in the first place. Either eliminate error-prone conditions, or check for them and present users with a confirmation option before they commit to the action.*

User feedback was used to identify error-prone conditions and prevent them from happening. There were some situations in the application that were identified as never being something that a user with perfect knowledge would deliberately do, such as submitting the filters with none selected.

- It is impossible to de-select all of the filters in a dependent group where at least one filter must be selected for there to be matching results.
- It is impossible to apply the filter “Show favourites only” if the user has no favourited items.
- If the user enters an invalid number ( $\leq 0$ ) for the “Within KM:” filter, the application treats it as if no number has been specified in the assumption that the user either mistakenly entered that value or that the user was deliberately selecting an invalid value to disable the filter.

## Recognition Rather than Recall

*Minimize the user’s memory load by making elements, actions, and options visible. The user should not have to remember information from one part of the interface to another. Information required to use the design (e.g. field labels or menu items) should be visible or easily retrievable when needed.*

All relevant information to a user’s task should be available to them at all times:

- The filters panel is always available on the home page, and is only minimised when the user specifies, so it is always ready to be used. The user can look at the map and the filters panel at the same time to hone their filters.

- A design consideration that was made was whether or not the sub-filters of a de-selected filter should be hidden or just greyed out: in order to prevent the user from having to try and remember what filters are available to them, they are just greyed out and remain visible for ease of use.
- The help information on how to view Luas data is delivered in-context as the user is looking at the Luas section of the filters panel.
- The search bar can be used to look for items based on human-readable information like a route description, rather than a route number.

### **Flexibility & Efficiency of Use**

*Shortcuts — hidden from novice users — may speed up the interaction for the expert user so that the design can cater to both inexperienced and experienced users. Allow users to tailor frequent actions.*

Flexibility & efficiency of use in the application are achieved in the following ways:

- Any meaningful combination of filters can be selected by a user, allowing them to filter the results however they please.
- The search bar can be used for maximum flexibility & efficiency by immediately narrowing down the results.
- The statistics page allows for users to gain deeper insights into the data, if interested.
- As previously mentioned, a number of keyboard shortcuts work within in the application including `Ctrl+K` to search and arrow keys to navigate the map.
- The “favourites” functionality allows for users to display just specific services in which they are interested, and once selected they will never have to be faced within non-favourite data again if they are not interested.

### **Aesthetic & Minimalist Design**

*Interfaces should not contain information that is irrelevant or rarely needed. Every extra unit of information in an interface competes with the relevant units of information and diminishes their relative visibility.*

An aesthetic & minimalist design is achieved in the following ways:

- Clean, minimalist UX achieved with Tailwind CSS.
- Only the bare minimum information is displayed in the main page to help the user navigate it; in-depth help information is kept in a separate area.
- The filters panel can be minimised when not in use.
- Each item’s pop-up contains only data that could be relevant to the user, and is kept simple & logically organised.
- Colour-coding of icons both enhances the aesthetic appearance of the application and its usability.

### **Help users Recognise, Diagnose, & Recover from Errors**

*Error messages should be expressed in plain language (no error codes), precisely indicate the problem, and constructively suggest a solution.*

- All error messages displayed to the user clearly indicate the issue (e.g., no favourites selected) and appear with a clear warning symbol notification pop-up.
- Error messages are kept simple & short, and only display user-relevant information. Errors in the application logic are never displayed to users. No technical jargon is used in error messages.
- The application prevents users from ending up in common error states, and so recovery information is not necessary (e.g., the user cannot de-select the last filter in a dependent group).

## Help & Documentation

*It's best if the system doesn't need any additional explanation. However, it may be necessary to provide documentation to help users understand how to complete their tasks.*

Help and documentation is provided in the form of the help page, which is quite comprehensive, and the tool-tip pop-up in the filters panel instructing the user how to see live Luas data. This could potentially be augmented with the use of a user demo or tutorial the first time the user visits the page, that takes them through the steps to complete some basic tasks.

### 5.1.3 User Evaluation

User evaluation was carried out towards the end of development of the program, with feedback taken on board from each user evaluation being applied to update the application and improve areas that caused users difficulty. The user evaluations were conducted in a one-on-one fashion, usually lasting in the range of 10–30 minutes. At the beginning of each evaluation, the user was asked for their informed consent to participate in this data collection process, including informing the user what the evaluation is about, what participation in the evaluation involves, their right to withdraw and have their data destroyed at any time, and how their data will be used and processed, including anonymisation of any identifying information.

Each user evaluation session consisted of the user being asked to perform a number of basic tasks such as finding a specific train or bus, or finding Luas information if they were travelling from a certain location in Dublin. Users were asked to use the Think Aloud Protocol (TAP)<sup>89</sup> which involves the user verbalising their thoughts, feelings, & reasoning while interacting with the application. This allows a better picture to be drawn of what the user's mental models & cognitive processes are, and where they do not align with the design. Notes were taken throughout the user evaluation on points of interest that were expressed by the user, and they were asked to complete a survey at the end. The users were offered no help throughout the process, and instead had to figure out how to use the application themselves based off the information presented to them. The primary drawback of this approach is that it's very time-consuming, and requires an interviewer to be present to observe or record the user's thought process; a take-home survey would be much faster, but also likely much less in-depth.

There are a number of limitations associated with the approach to user evaluation that was taken:

- The interviews were not conducted by a disinterested third party, but by the developer of the application; bias is inherent here, and cannot be eliminated regardless of best efforts made.
- In the absence of access to large-scale, industrial user evaluations, the sample population for the user evaluation was selected from people whom I know personally, which presents three key issues:
  - The sample population is not a representative random selection of the general population; many of the users came from more technical backgrounds and there was limited age range sampled.
  - The sample population is not unbiased: they personally know the developer of the application, and therefore cannot be considered fully impartial regardless of how much they try to remain impartial.
  - The sample population is small: ideally, hundreds of users would be surveyed for their feedback, but it was not possible to find that many willing participants within the project deadline.
- After each user evaluation, the highlighted flaws or areas for improvement in the program were addressed, meaning that no two user evaluations were on the same version of the application. This allowed for quick iteration & improvement, at the cost of not having one canonical dataset. The user ratings generally improved with each evaluation as issues were addressed & the program refined, which is a positive indicator that the feedback was useful & the attempts to address it worked, but casts some doubt on how comparable each evaluation is with its predecessors.

Overall, a total of 7 user evaluations were conducted, with the users surveyed being in the age range of early teens to late sixties, disproportionately from technical backgrounds, leaning to a male majority, and predominately Irish; English was the first language of every user surveyed. One user surveyed works as a professional feature tester, and another user

suffers from deuteranomaly<sup>71</sup> (common red-green colourblindness), so the population was relatively diverse despite its small size.

The questions asked in the survey, and a summary of user answers to each of these questions can be seen below. For each question, users were given the optional to elaborate further on their answers in a text box.

### Question 1: How easy was it to use the application?

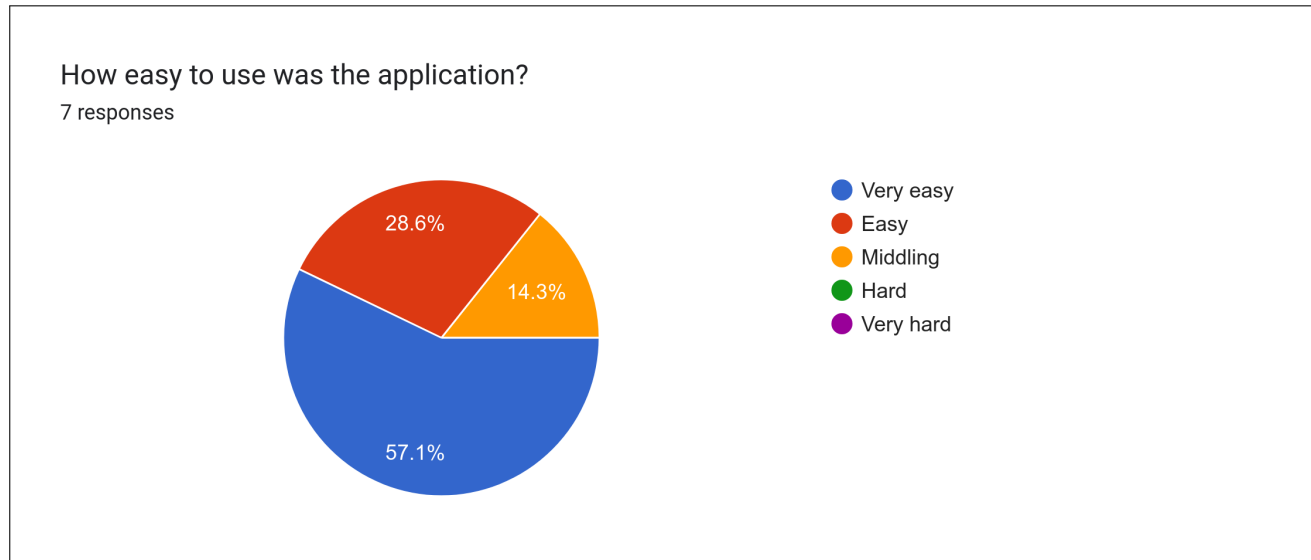


Figure 5.1: Question 1 responses

The responses to the first question were overwhelmingly positive, with no users finding it “Hard” or “Very hard” to use the application. User comments on this question include:

- *“Easy to use. Was impressed with the willingness of the developer to take on feedback and rapidly develop prototypes for discussion.”;*
- *“Self explanatory, just worked”;*
- *“When I had a lot of bus and train data loaded, the performance could be quite slow.”.*

The final comment came from a user who selected all filters for displaying results, which took a non-negligible time to load. The main culprit for this is the bus stops, as there are almost 14,000 bus stops alone in the country. How best to address this issue remains an open question: the Lambda functions which return the data could be given more memory to allow them to process it more quickly, or perhaps some solution could be employed to only query bus stops from the database if they are within a certain range or on a certain tile; most users will likely not be interested in far away bus stops regardless.

The colourblind user described the greens & reds of the Green & Red line Luas stops as “sufficiently distinguishable”, but struggled to tell the yellow from green in icon clusters (where the colour indicates how many items are in that cluster). A potential future task here would be to provide colourblind-friendly accessibility options to the application.

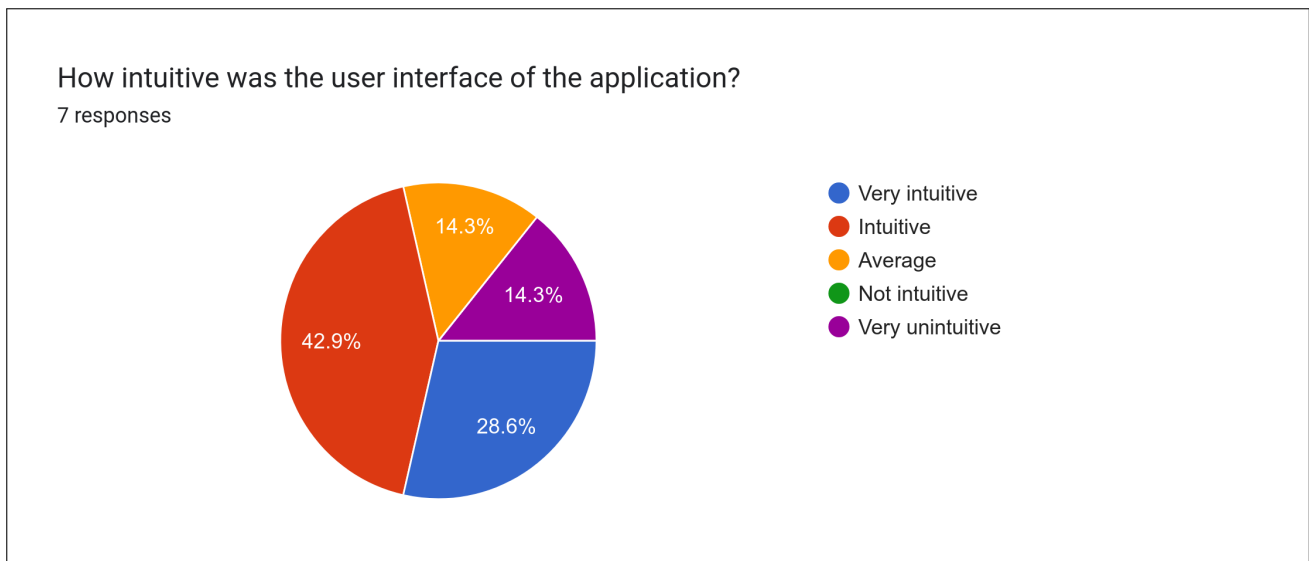
**Question 2: How intuitive was the user interface of the application?**

Figure 5.2: Question 2 responses

This question received more mixed results, with the majority of users describing the interface as “Intuitive”, followed by “Very intuitive”, one “Average”, and one “Very unintuitive”. The primary reason for the discrepancy in the results is that the user who said “Very unintuitive” was the first user who performed an evaluation, and the system UI underwent quite a substantial UI change after their evaluation, including a complete re-structuring of the filters side-panel, the addition of the “Reset” button, and the addition of user error warnings & preventions. In particular, that particular user struggled with the fact that the application didn’t display any useful information on page load: the map was blank, and the filters panel minimised, so the natural first port of call was the search bar which only acts on displayed data, which the user found greatly frustrating. To address this, the map was updated to automatically load markers based off the default or last saved filters of the user, and to automatically maximise the filters panel to draw users to it naturally.

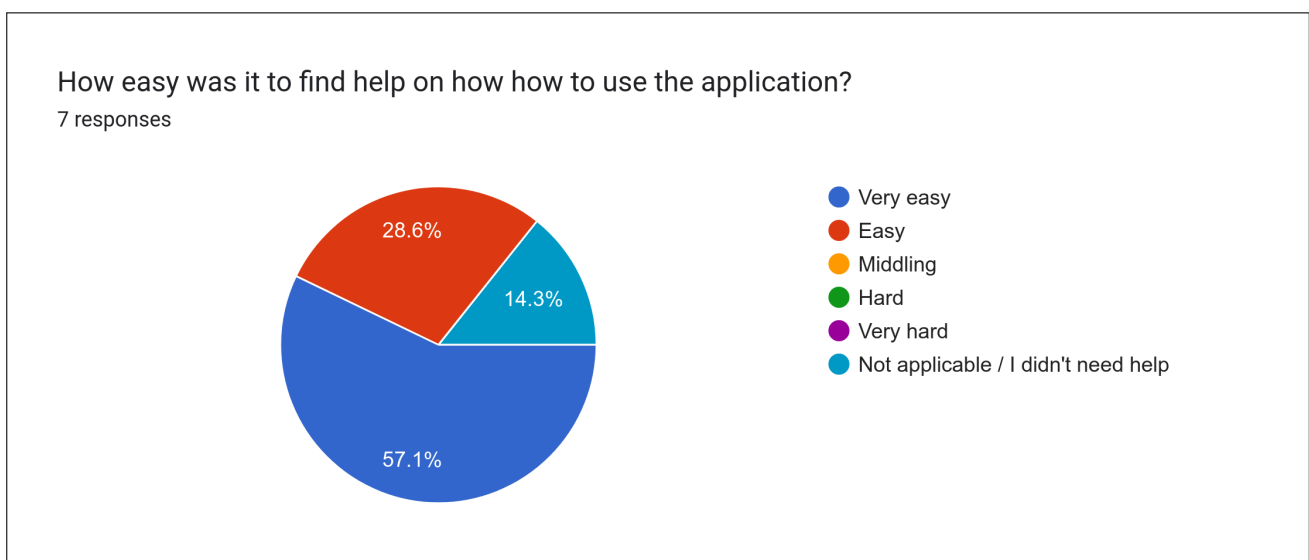
**Question 3: How easy was it to find help on how to use the application?**

Figure 5.3: Question 3 responses

The feedback on how easy it was to find help in the application was overwhelmingly positive, with the majority considering it very easy & easy, and one user not requiring any help at all (the most positive feedback to this question).

Users seemed to understand the Help page well, and it was where they looked for it. At the request of the users, a legend was added to the help page to definitively say which icons were which, and a mouse-over tool-tip was added to the filters side-panel to instruct users on how to view Luas data, as the unavailability of Luas location caused confusion for many users. User comments included:

- *“Very good. Most information is available at point of use, with some further info on the FAQ page.”*;
- *“The help tab was there, I would say the button might be better if it was a one time pop up suggestion of where to access it”*;
- *“The website was clearly laid out, and the Help/FAQ section provided me with all necessary information.”*;
- *“Application was very intuitive and self-explanatory.”*

**Question 4: How would you say the application compares to other existing application?**

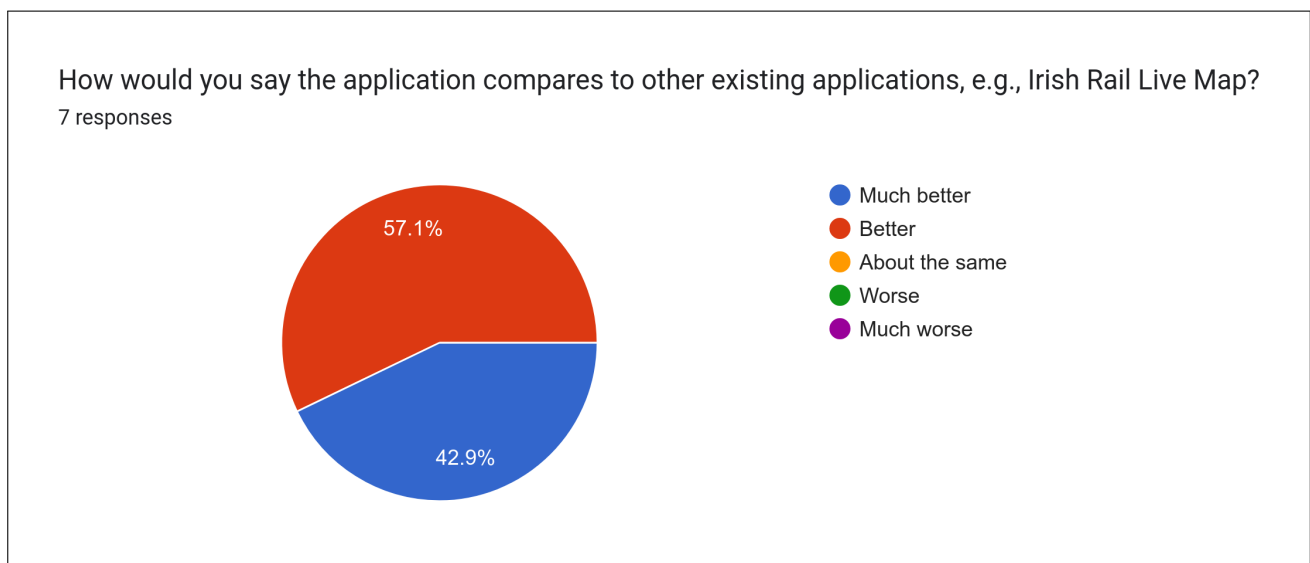


Figure 5.4: Question 4 responses

Users overwhelmingly preferred the Iompar application to comparable alternatives, with no users thinking that the application was of similar quality or worse than the existing solutions. Users cited the UI/UX and aggregation of all public transport information into one place as reasons for their responses. Some comments in response to this question include:

- *“The integration of multiple transport services makes for a better overall user-centric experience.”*;
- *“It feels less clunky and more transparent in what it provides.”*;
- *“As stated in my answer to previous questions, I found the User Interface to be much smoother and seamless than other applications I have previously encountered.”*



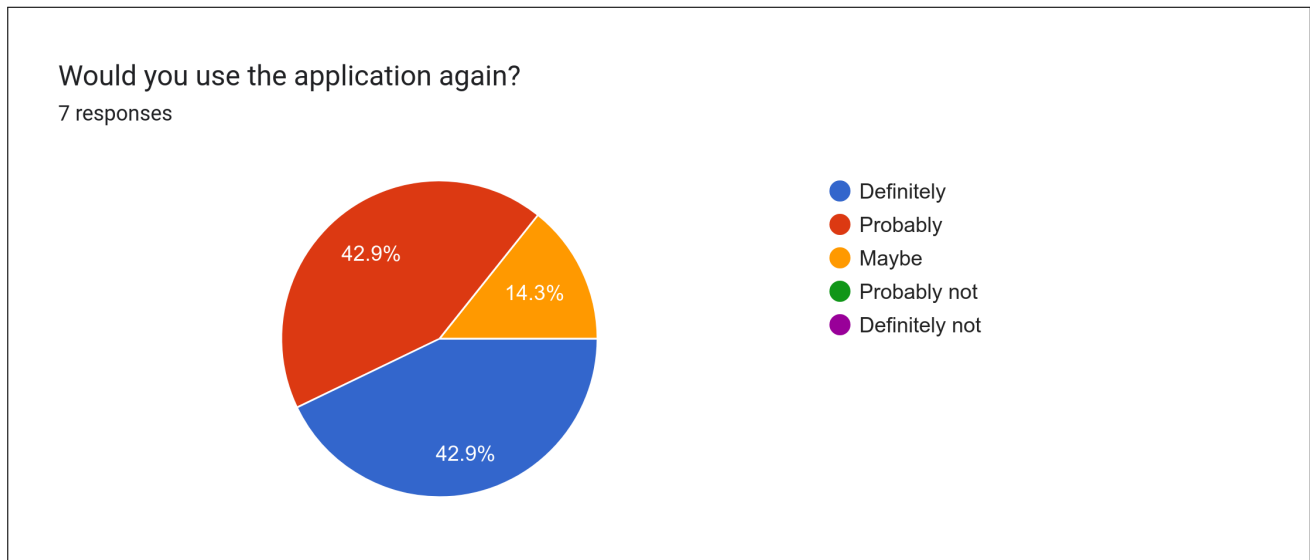
**Question 5: How would you say the application compares to other existing application?**

Figure 5.5: Question 5 responses

Users generally were positively inclined to using the application again in the future, with equal numbers saying “Definitely” and “Probably”, and one “Maybe”. Comments in response to this question included:

- *“It gives me a lot of context on where my train or bus actually is, and I am not relying on information boards that can be inaccurate.”;*
- *“Really good application, easy to use and gives data on all the forms of transport so I would not have to use multiple trackers if I was using more than one form of transport that day.”.*

**Question 6: What did you like about the application?**

Users generally cited speed, the UI, filtering options, and the aggregation of public transport data into a single place as reasons they liked the application. Some responses include:

- *“It was very fast, despite the potentially large amount of data to be fetched and processed.”;*
- *“I can view everything I want, when I want. Particularly you can set it to view only a certain local area, as to not load irrelevant data.”;*

**Question 7: What did you dislike about the application?**

Users generally had little negative to say about the application, beyond requests for additional feature. Some responses include:

- *“Would like satellite tiles option.”;*
- *“Half of my Luas line being missing”* (this user discovered the missing Green Line Luas stops, which have since been added into the database);
- *“I found very little if anything wrong with the application. Although, I believe an introduction of Northern Irish transport services could be useful, due to the slight overlap of routes.”;*
- *“Couldn’t really say. It seemed to have all the features that I personally would need.”;*

**Question 8: Was there a feature that you expected to find that you didn't?**

Two users answered “No” to this question, but the rest of the users expressed that they expected some different functionalities. Some responses include:

- *“I thought there could be an icon for parking etc. at Luas stops.”*: this would certainly be do-able, with the *“is-park-and-ride”* field for each Luas stop and a custom icon;
- *“The bus lines being drawn for a route”*: I believe this response refers to a desire to be able to see the routes taken thus far by a bus or train. This likely would not be impossible, but it would require supplying all past co-ordinates for a bus with that bus data when it’s being loaded so that a trail could be drawn, which would likely increase loading times by quite a bit. This functionality could also be implemented by storing the trail for a given bus route, and drawing the line up to the location of the given bus to display its past trail, but this would involve presenting misleading, arguably fake data to the user, and would not be particularly useful;
- *“Bus schedule information for a stop”*: one user expressed an interest in bus schedule information being available on a per-stop basis, which is certainly possible to implement as bus schedule information is available online;
- *“Live locations for Luas trams”*: unfortunately, this data is not publicly available and so cannot be displayed in the application, although it would greatly improve it.

**User Evaluation Conclusion**

Overall, users seemed to think the application would prove useful in their daily lives, and gave quite positive reviews, especially those who saw the later versions of the application which had been updated to address the concerns of other users.

**5.1.4 Future Work**

There are a number of potential expansions & improvements to the application, including:

- Addition of user accounts to store user information, as previously outlined;
- Addition of a user review capability;
- Making the web application available online with a dedicated domain name;
- Running AWS Power Tuner to obtain maximally performant configurations for the Lambda functions;
- Port the application to React Native and publish it for download on iOS & Android devices;
- Add accessibility options, such as colourblindness options or screen-reader friendly content for visually impaired users;
- Add a dark theme to the website;
- Make bus schedule information available on a per-stop basis, as per user request;
- Adding a “Cancel” button to loading screens;
- Expand in scope to other countries or other transport services;
- Multilingual support, such as for Irish;
- Alternate map tile options, such as satellite images as per user request;
- Indicate parking for Luas stops in the Luas stop icons on the map.

### 5.1.5 Conclusion

In conclusion, all the core objectives that were set out were achieved, and many additional objectives on top of those. Non-trivial speed optimisations were made throughout the development of the project, including  $10\times$  and  $8\times$  speed increases. User evaluation revealed that users thought highly of the application, preferred it to existing alternatives, and would use it again in the future.

Personally, this project has been a tremendous learning opportunity for me; generally speaking, I have always favoured backend development and have a substantial amount of experience with Linux-based servers. To undertake a project with such an emphasis on HCI was greatly outside my comfort zone, and I have learned a massive amount about the field that I didn't know before. I have also learned a great deal about AWS and React, both technologies with which I had minimal contact before embarking on this project. It would have been much easier for me to do a Linux-based project with my previous experience, but the nature of the application lent itself best to a serverless architecture, which ended up being an incredible learning opportunity, with some of the most intensive upskilling I have ever undergone in such a short time frame.

It is my opinion that this project has been a great success, with many objectives achieved, glowing user reviews, and a huge amount learned about HCI, serverless computing, & modern web development.

## **Appendix A**

### **Source Code**

All files related to the source code of this project, including frontend source, backend source, diary files, and L<sup>A</sup>T<sub>E</sub>X files for the project deliverables can be found in the project Git repository: <https://github.com/0hAodha/fyp>.

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