**Capstone Project Final Report**

**TTC Delay**

# **Capstone Project- BIA-5450-0GB**

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**Executive Summary**

The Toronto Transit Commission (TTC) serves as the backbone of Toronto’s public transportation system, facilitating the daily commute of approximately 1.7 million individuals. As Toronto experiences rapid population growth, its transit infrastructure is under increasing strain. In 2024, delays across subways, buses, and streetcars became a recurring concern, affecting commuter satisfaction, urban mobility, and environmental goals. This project leverages data-driven techniques to analyze delay trends within the TTC system, aiming to identify root causes, high-impact locations, and patterns over time.

By focusing on factors such as mechanical failures, operational inefficiencies, and external conditions like weather or traffic congestion, this research offers actionable insights to improve service reliability. The findings support broader objectives, including reducing greenhouse gas emissions, easing urban congestion, and promoting economic productivity. Moreover, the analysis aligns with Toronto’s vision of becoming a smart city by emphasizing the strategic use of data to optimize public services. Ultimately, this project offers a roadmap for enhancing transit efficiency, informing infrastructure investment, and establishing best practices that can be shared with transit agencies globally.

**Introduction**

Toronto’s public transit system, operated by the Toronto Transit Commission (TTC), is a vital component of the city's infrastructure, enabling millions to access work, education, and leisure activities. As the city's population continues to grow, so does the demand for timely, efficient, and reliable transit services. However, frequent delays in buses, streetcars, and subways have emerged as a significant challenge, undermining commuter confidence and contributing to increased traffic congestion and environmental harm.

This project investigates TTC system delays in 2024 with the goal of understanding their underlying causes and identifying patterns across the network. Using a data-driven approach, the analysis explores key contributors to service interruptions, such as mechanical issues, operational constraints, and environmental factors. By doing so, it aims to provide valuable recommendations to improve transit performance, support sustainability goals, and guide smarter infrastructure planning.

Beyond immediate operational improvements, this work contributes to Toronto’s broader ambition of evolving into a smart, resilient city. It highlights the potential of data analytics to drive public service innovation and lays the groundwork for long-term transit improvements that benefit residents and serve as a model for other urban centers facing similar challenges.

**Business Problem Definition**

The TTC plays a crucial role in the daily transportation of thousands of commuters across Toronto. However, the transit system faces several challenges related to bus, streetcar, and subway delays. These delays, particularly during peak hours, not only frustrate commuters but also lead to operational inefficiencies and increased costs for the TTC. Addressing these delays is vital for improving service reliability, customer satisfaction, and operational performance.

**Key Problems**

* Increased delays lead to commuter dissatisfaction and missed connections.
* Overcrowding during peak hours, reducing comfort and accessibility.
* Due to inefficiencies impacts higher operational costs, including maintenance, overtime, and fuel costs.
* Reduced service quality in less populated areas, leading to lower ridership and access**.**
* Frequent track maintenance and repair work disrupts TTC subway services, leading to delays, reduced service reliability, and inconvenience for commuters.

These challenges undermine the TTC’s mission to provide efficient and reliable public transit. Addressing these issues is essential to enhance customer satisfaction, optimize operations, and strengthen public trust in the TTC’s services.

**Business Requirements**

**Solution Characteristics**

* **Accessibility**: The solution should provide commuters with real-time updates on delays, alternative routes, and connection times through user-friendly platforms like mobile apps, station displays, and public announcements. (Accessibility, n.d.)
* **Data-Driven**: The solution should leverage predictive analytics to anticipate peak-hour demand, maintenance requirements, and resource allocation needs.
* **Cost-Effectiveness**: The solution should focus on reducing operational costs through energy-efficient technologies, optimized scheduling, and preventative maintenance systems. (Transit Planning, 2024)
* **Reliability**: The solution should ensure consistent service availability by minimizing disruptions caused by track maintenance or other operational inefficiencies.

#### **Performance Goals**

* **Reduced Delays**: Achieve a 25% reduction in delays within six months by implementing advanced route control systems and predictive maintenance technologies.
* **Improved Peak-Hour Comfort**: Reduce instances of overcrowding by 10-15% during peak hours by optimizing fleet usage and service scheduling.
* **Enhanced Service Accessibility**: Increase ridership in less-populated areas by 15% within 12 months through tailored route optimization and improved service quality. (*2023-24 Metrolinx Business Plan*, n.d.)
* **Service Reliability**: Ensure 95% of maintenance activities are conducted during off-peak hours to minimize commuter disruptions.
* **Operational Efficiency**: Reduce fuel, maintenance, and overtime costs by 15% within a year through optimized resource planning and energy-efficient systems. (TRANSPORTATION SYSTEM EFFICIENCY, n.d.)

#### **Resource Allocation Considerations**

* **Demand-Based Allocation**: Prioritize resource allocation based on commuter demand patterns, focusing on high-traffic routes during peak hours and underserved areas during off-peak times.
* **Population Demographics**: Consider diverse commuter demographics, including accessibility needs for individuals with disabilities, age groups, and travel patterns, when designing service improvements.
* **Sustainability**: Incorporate environmentally sustainable practices such as energy-efficient trains and optimized fuel usage to lower the transit system’s carbon footprint.
* **Maintainability**: Ensure that systems and infrastructure are easy to update and adapt to changing demands, such as population growth or increased ridership trends.

**Analytics Questions**

1. What is the average delay time for buses, streetcars, and subways during peak and off-peak hours across different days of the week?
2. Which bus, streetcar, or subway routes experience the highest frequency of delays, and what is the average delay time for each route?
3. What are the most common locations where delays occur, and how do delays at these locations affect the overall service?
4. What types of incidents (e.g., security, general delay, emergency services) are most frequently associated with delays, and what is the average delay for each type of incident?
5. How does the delay duration and frequency vary over different months of the year, and is there any seasonality in delays?
6. How do delays during peak hours correlate with ridership numbers on specific bus, streetcar, or subway lines?
7. Is there any relationship between specific vehicles and delay times (e.g., do certain vehicles experience more delays than others)?

**Project Scope Statement**

This project's goal is to use historical data to find trends, underlying causes, and contributing elements in order to study and address delays within the Toronto Transit Commission's (TTC) system. The project's objective is to offer practical insights that will boost the TTC's operational efficiency, improve rider experience, and increase service reliability.

The analysis of TTC bus, streetcar, and subway delay data is the main goal of this research. The scope includes determining the contributing variables for different vehicle kinds and routes as well as assessing the frequency and length of delays. Additionally, it entails examining delays according to the incident type (e.g., crises or security concerns), location, and time of day (e.g., peak and off-peak hours). The initiative also seeks to evaluate delay trends unique to various vehicle types and find seasonal patterns and relationships between ridership levels and delays.

Delays in public transportation have had a significant impact on Toronto residents, with commuters spending a cumulative 1,306,541 minutes waiting due to TTC delays in 2023. Such delays diminish rider satisfaction and operational efficiency, making this analysis crucial for resource allocation and service enhancements (Torontonians Spent 1,306,541 Minutes Waiting on TTC Delays in 2023, n.d.). This project aligns with the TTC’s mission to provide safe, reliable, and efficient transit services.

**Deliverables and Milestones**

A thorough report detailing the results and insights, graphical representations of delay trends, such as heatmaps and charts, suggestions for reducing delays and improving service reliability, and a final presentation summarizing the main conclusions and suggested fixes are among the deliverables.

The milestones include gathering and cleaning TTC delay data, looking for patterns and anomalies through exploratory data analysis, developing visual tools to show delay trends, coming up with solutions and actionable insights, and presenting the results and recommendations in a final report and presentation.

**Technical Requirements**

To ensure ethical data handling, the project necessitates rigorous respect to data privacy rules, the use of analytical tools like Python or Power BI for data analysis and visualization, and access to historical TTC delay datasets with parameters like vehicle type and incident type.

**Limits and Exclusions**

* TTC System Focus: Excludes other transit systems like Metrolinx or GO Transit.
* No Forecasting: Predictive modeling is beyond the scope.
* External Factors: Extreme weather and emergencies will not be analyzed in-depth. Maintenance-related issues and overhead asset failures, which have contributed significantly to delays, will be considered only when data is available (Audit of the Toronto Transit Commission’s Streetcar Overhead Assets: Strengthening the Maintenance and Repair Program to Minimize Asset Failures and Service Delays, 2023).

**DATA SOURCES AND KEY DATA ENTITIES AND FLOWS**

The TTC Delay Data collection, which is accessible at Toronto Open Data, is the source of the information from the City of Toronto's Open Data Catalogue. It contains four datasets that are taken from TTC's internal operational systems: TTC Subway Codes, TTC Streetcar Delays, TTC Bus Delays, and TTC Streetcar Delays. For compatibility, the data, which spans January through December 2024, was converted to CSV format. It offers real-time records of service interruptions, along with timestamps, routes, reasons for delays, durations, and locations. Station names and disruption categories are examples of subway-specific data that aids in the investigation of current operational issues.

**Identifying the core business entities relevant to delays for each transit mode (bus, streetcar and subway).**

**Mentioning the Top 3 Delay Entities**

**Subway**

Based on the TTC Subway Delay Codes.xlsx file and impact on TTC operations, the following entities are prioritized:

1. **Brakes (Code: EUBK)**  
   **Reason**: Frequent mechanical failures in braking systems lead to unplanned stops and service disruptions. Critical for maintenance planning.
2. **Door Problems - Faulty Equipment (Code: EUDO)**  
   **Reason**: Malfunctioning doors cause boarding delays, safety hazards, and operational halts.
3. **RC&S Maintenance Error - Human (Code: EUME)**  
   **Reason**: Human errors during maintenance result in recurring mechanical issues. Highlights training gaps.

**Bus Delay Entities**

1. **Mechanical**:

**Reason -** Failures in bus components (e.g., engine, brakes) cause breakdowns and unplanned stops. Impacts service reliability.

1. **Operations - Operator**:

**Reason -** Human errors (e.g., missed turns, over speeding) lead to schedule deviations. Highlights the need for improved training and protocols.

1. **Security**:

**Reason -** Incidents like assaults or suspicious packages disrupt service and passenger trust. Critical for safety protocols and emergency response.

**Streetcar Delay Entities**

1. **Operations**: Operator errors (e.g., misjudging turns) or dispatching inefficiencies. Highlights the need for workforce management improvements.
2. **Security**: Safety incidents (e.g., assaults) require service halts. Impacts passenger confidence and operational efficiency.

**General Delay**: Unspecified delays indicating systemic inefficiencies. Requires root-cause analysis to identify underlying issues.

**Data Manipulation**

This study describes the data cleansing processes used to assure consistency, correctness, and reliability. The four datasets—Bus, Streetcar, Subway, and Subway Code—went through several cleaning processes, including handling duplicates, deleting extraneous values, addressing typographical errors, and retaining acceptable data types. Because the datasets were semi-structured, missing data was carefully managed to ensure complete analysis and eliminate biases.

### **Bus Dataset**

Handling Errors & Missing Data:

* + The Direction column contained less than 5% erroneous values; therefore, rows with errors were removed.
  + Approximately 15% of values in the Direction column were missing. Since this is a categorical variable, missing values were imputed using the mode.

### **Streetcar Dataset**

Standardizing Column Names:

* + The Line column was renamed to Route for consistency.

Handling Errors & Missing Data:

* + The Direction column contained erroneous values, which were filtered out, and the respective rows were deleted.
  + Around 13% of values in the Direction column were missing, so they were imputed using the mode.

### **Subway Dataset**

Standardizing Column Names:

* + The Code column was renamed to Code - Incident to provide clearer context.

Handling Missing Data:

* + The Direction column contained only missing values, so they were imputed using the mode.

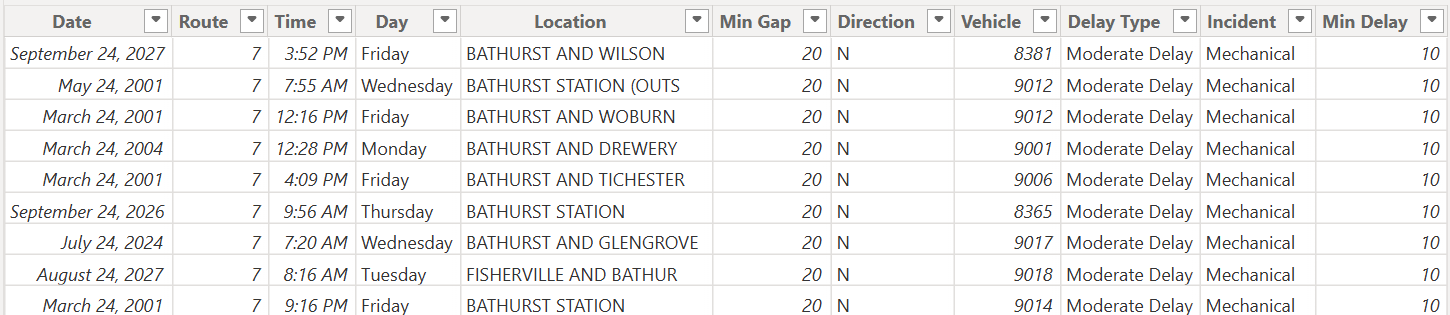
### **Subway Code Dataset**

Removing Irrelevant Data:

* + The dataset contained variables related to streetcar codes and descriptions, which were irrelevant to subway analysis. These unnecessary values were removed, and the dataset was restructured accordingly.

The data cleaning process ensured that all datasets were free from inconsistencies, irrelevant values, and missing data issues. Standardization techniques, including renaming columns and structuring data appropriately, improved dataset integrity.

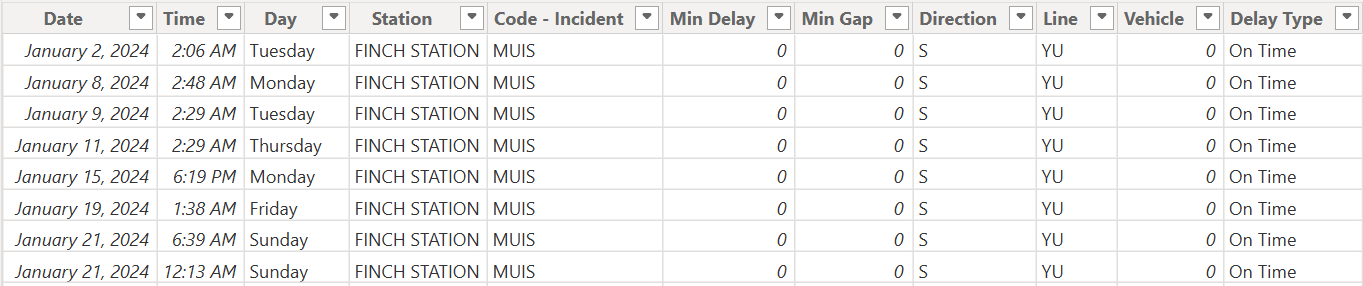
Below provided are the screenshots after data cleaning:



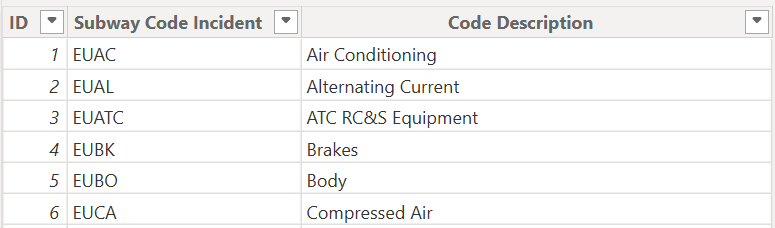
*Fig 1: After cleaning Bus dataset*



*Fig 2: After cleaning Streetcar dataset*



*Fig 3: After cleaning Subway dataset*



*Fig 4: After cleaning Subway Codes*

**DATA OUTPUT**

In order to enable analysis of transit delays for various vehicle types, the data output process comprised organizing, converting, and prepping the dataset in Power BI. Making useful aggregations and computed fields that enable insights into service breakdowns, common causes, and delay trends was the main goal.

**Transformation & Data Preparation for Output**

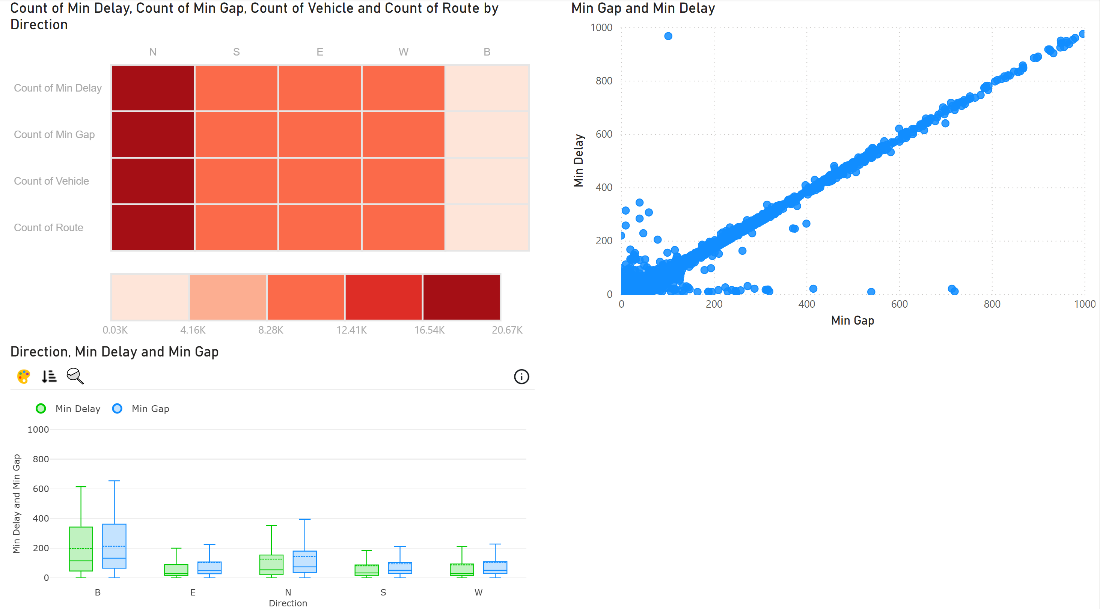
* **Delay Categorization**: To categorize delays into On-Time, Short, Moderate, Late, and Very Late groups according to duration, a new **Delay Type** column was established.
* **Incident Mapping**: To determine which events, cause the most delays, delays were categorized by category (e.g., security, emergency services, mechanical issues) using the **Code-Incident column**.
* **Route & Location-Based Analysis**: Critical transit bottlenecks were identified by combining average delay times and delay frequencies for routes and locales.

**Output & Visualization**

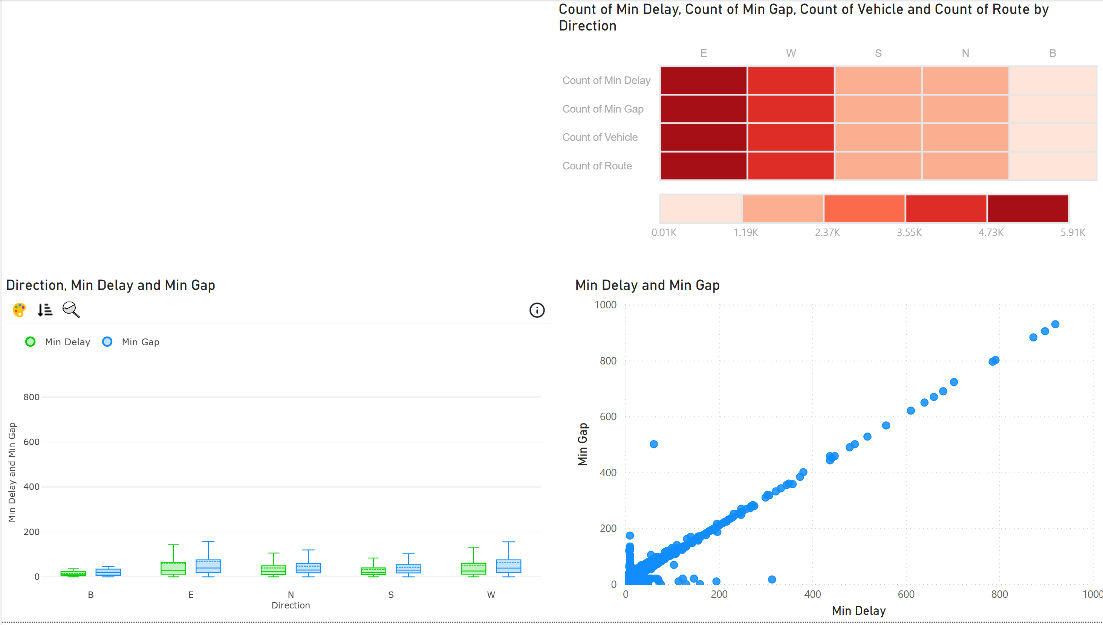
The processed data will enable the creation of key visualizations in Power BI to support analysis, including:

* **Average Delay by Vehicle Type & Time Period** – A comparison of delay durations for buses, streetcars, and subways during peak and off-peak hours.
* **Most Delayed Routes** – A ranking of routes that experience the highest frequency of delays, along with their average delay times.
* **Frequent Delay Locations** – A geographical heatmap will be generated to identify stations or intersections with recurring delays and analyze their impact on service(Screenshot provided below).
* **Incident Type Analysis** – A breakdown of the most common delay causes and their associated delay durations will be created to understand which incidents contribute most to service disruptions.
* **Seasonality of Delays** – A trend analysis will be conducted to examine delay occurrences across different months and determine if there is a seasonal pattern.
* **Correlation Between Min Delays & Min Gap** – A visualization will be developed to explore the relationship between Delay periods and delay gap. (Screenshots are provided below)
* **Vehicle-Specific Delays** – A comparison of delay patterns for different vehicle types will be analyzed to determine if certain vehicles are more prone to service interruptions.

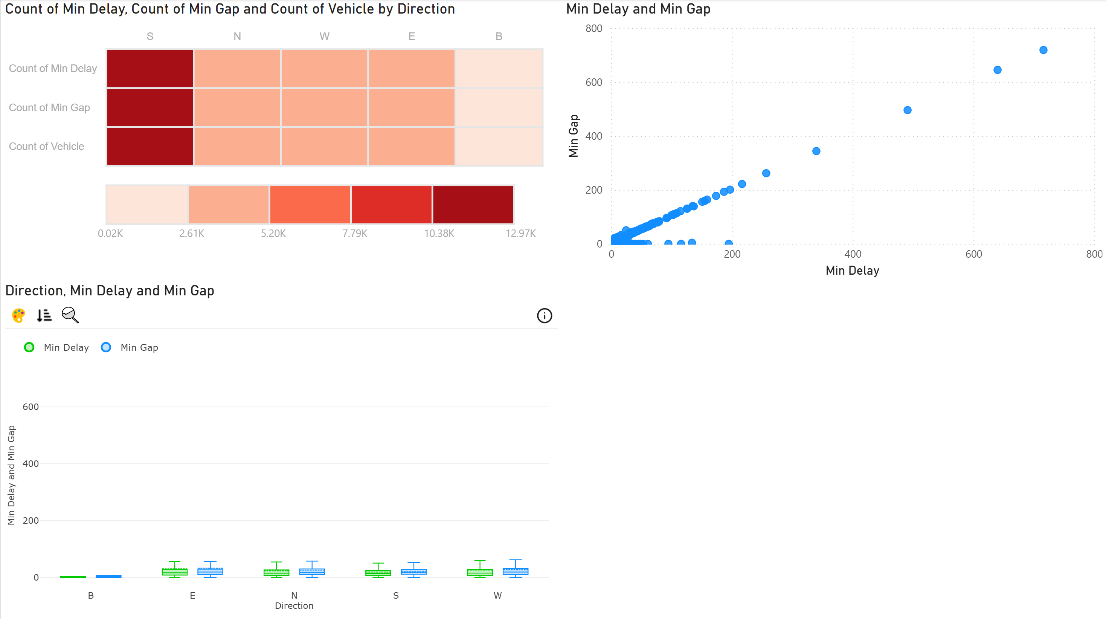
The analysis will offer insights into transit performance by skillfully arranging the data output, assisting in the identification of opportunities to reduce service interruptions and enhance operational effectiveness.



*Fig: 5 The Visualization for the Bus delay dataset*.



*Fig 6:The Visualization is for the Streetcar delay dataset.*



*Fig 7: The Visualization is for the Subway delay dataset.*

**Existing IT Architecture**

This section provides an overview of the client’s current IT infrastructure, detailing its components, functionalities, and integrations. To oversee internal procedures, customer relations, and transport operations, the Toronto Transit Commission (TTC) has a strong IT infrastructure. To guarantee effective service, this system combines hardware, data sources, and software tools. The main elements, their function within the IT ecosystem, and the links that unite them are described in this section.

**Major IT Components**

1. **Data Sources  
   Automated Vehicle Location (AVL) Data:** Real-time bus, streetcar, and subway train whereabouts are provided via GPS-based tracking systems.  
   **Weather and Traffic Data:** The evaluation of external issues influencing transit operations is aided by external data sources.  
   **Passenger Counting Systems:** Data on ridership volumes is gathered via sensors (PRESTO Machine) mounted on transit vehicles.
2. **Software Tools  
   Enterprise Resource Planning (ERP):** Utilized for TTC's procurement, human resources, and financial management activities.  
   **Predictive Analytics Tools:** To forecast delays or service interruptions, machine learning models are used to evaluate previous transit data.  
   **Transit Management Systems (TMS):** To keep an eye on vehicle positions, timetable compliance, and service interruptions, the TTC employs a centralized TMS.
3. **Servers & Cloud Infrastructure  
   On-Site Data Centers:** Keeps track of vital operational information, such as past performance data and transportation schedules.  
   **Cloud-Based Solutions:** For scalability and real-time processing, some services—like analytics and customer notifications
4. **APIs & Integration Layers  
   Real-Time APIs for Transit Data:** Makes it easier for third-party apps like Google Maps and Transit App to share data with various TTC systems.  
   **Public Data Portals:** Makes transit schedules and service interruptions publicly available for study and third-party app development.

The TTC's IT architecture uses several integration techniques to guarantee smooth communication between diverse IT components. Middleware and data integration play a crucial role in ensuring real-time data transmission across multiple applications, facilitated by Enterprise Service Bus (ESB) solutions. To maintain system security and integrity while keeping pace with emerging technologies, frequent software patches and updates are implemented. Secure database connectivity, supported by Structured Query Language (SQL) and NoSQL solutions, enables the efficient handling of the massive volume of data generated daily.   
  
Additionally, driver and port configurations are carefully managed by assigning distinct port numbers for various communication routes, ensuring safe and effective data flow between applications. Network security measures, including Virtual Private Networks (VPNs), intrusion detection systems (IDS), and firewalls, are in place to safeguard private customer and transit information, reinforcing the system's overall resilience and reliability (General, T. A., 2024).

The proposed IT Architecture is designed to support a scalable, data-driven, and cost-effective transit analytics solution. By integrating real-time and historical data sources, leveraging ETL pipelines for data transformation, and utilizing Power BI for business intelligence, the system ensures optimized fleet utilization and improved accessibility for stakeholders. By adopting this robust and well-connected IT ecosystem, the client can enhance transit efficiency, reduce delays, and improve overall service quality—ultimately leading to a better commuter experience and optimized resource allocation.

**Solution Design**

The proposed solution leverages a real-time data-driven approach to address the Toronto Transit Commission’s (TTC) operational inefficiencies and improve service reliability. By integrating a predictive analytics platform with real-time data updates, we can optimize transit operations, improve customer satisfaction, and reduce operational costs. The solution integrates various technologies, including machine learning, data visualization through Power BI, and automated reporting to create a system that proactively identifies potential delays, optimizes routes, and provides actionable insights for both operational and strategic decisions.

Key Components of the Solution

1. **Data Collection and Integration**:

**Real-time Data Streams**: Data will be collected from multiple sources, including:

**GPS Tracking**: Real-time vehicle tracking of buses, streetcars, and subways.

**Presto System**: Data from the Presto app and smart card system to monitor ridership and passenger density.

**Weather APIs**: To factor in the impact of weather conditions on delays or service disruptions.

**Maintenance and Incident Data**: Maintenance schedules, repair logs, and real-time incident reports.

**ETL Process**: The data will go through an ETL (Extract, Transform, Load) pipeline to ensure it’s cleansed, structured, and stored in a unified database for downstream processing.

1. **Predictive Analytics for Demand and Delay Forecasting**:

**Machine Learning Models**: Advanced models like Artificial Neural Networks (ANN) and Random Forests will be used to predict delays, peak ridership times, and potential disruptions based on historical data. These models will be applied to forecast service demand during peak hours, predict delays due to maintenance or weather conditions, and suggest alternative routes to optimize service delivery.

**Maintenance Prediction**: Predictive algorithms will also anticipate equipment failures and maintenance needs based on historical trends, helping to minimize unscheduled disruptions.

1. **Real-Time Reporting and Visualizations with Power BI**:

**Dashboards for TTC Management**: Using Power BI, the solution will generate interactive dashboards for TTC’s management, displaying key performance indicators (KPIs) such as:

**On-time Performance**: Average delay times, delay frequency by route, and real-time vehicle locations.

**Passenger Density**: Ridership trends during peak and off-peak hours to understand overcrowding issues.

**Operational Costs**: Fuel consumption, maintenance expenses, and overtime costs.

**Commuter-facing Features**: Real-time updates will be pushed to commuters via a mobile app, public announcements, and station displays. This includes:

**Live Route Updates**: Current delays and route conditions.

**Alternative Routes**: Suggestions for passengers to avoid delays or overcrowding.

**Interactive Visuals**: Power BI’s integration with maps and real-time data will allow commuters and management to track delays and vehicle locations in real-time.

1. **Cost Optimization and Resource Allocation**:

**Route Optimization**: The solution will analyze real-time data to suggest route adjustments based on traffic, ridership, and vehicle availability, minimizing operational costs and reducing congestion during peak hours.  
**Energy-efficient Scheduling**: Predictive analytics will help optimize bus and subway scheduling, reducing fuel costs by ensuring the right resources are allocated at the right times.  
**Preventive Maintenance**: By predicting maintenance needs before they become critical, the system will minimize downtime and costly emergency repairs.

Methodology Used: **Agile Development Methodology**

The solution will be developed using the Agile methodology, which focuses on iterative development, continuous improvement, and stakeholder feedback. This methodology will allow for the incremental development of features such as predictive models, dashboards, and mobile apps, which will be tested and improved in real-time to meet the evolving needs of TTC.

Reasons for Choosing Agile:

1. **Flexibility and Adaptability**:  
   Agile's iterative nature allows for quick adjustments based on real-time feedback. For example, as predictive models are refined or additional data sources become available, new features or updates can be seamlessly integrated into the system.
2. **Customer-Centric Development**:  
   Frequent collaboration with stakeholders (e.g., TTC management, operators, and commuters) ensures that the solution meets user needs. This is critical for ensuring that features like alternative route suggestions and mobile app updates directly address commuter concerns.
3. **Rapid Prototyping and Early Testing**:  
   Agile enables the rapid creation of prototypes, which can be tested early on. For example, an initial version of the real-time reporting dashboard can be created and tested with a small group of TTC staff to gather feedback before full-scale deployment.
4. **Continuous Improvement**:  
   The solution can evolve as new technologies or data sources become available, making it scalable and future-proof. New machine learning models can be tested and integrated during later sprints to improve prediction accuracy or optimize operations further.

Comparison with Other Methodologies

* **Waterfall**:  
  Waterfall is a linear methodology that could lead to longer development cycles. Given the dynamic nature of transit operations, an approach like Waterfall would delay user feedback and improvements, making it less suitable for the real-time nature of the transit system.
* **DevOps**:  
  While DevOps emphasizes continuous integration and delivery, it is more focused on the deployment and operational aspects of software development. Since this solution requires iterative development and regular feedback from both internal stakeholders and commuters, Agile is a better fit for ensuring continuous refinement based on user needs.

Benefits of the Chosen Methodology

1. **Faster Implementation**:  
   Agile allows for quick development cycles, meaning key features such as predictive analytics or real-time dashboards can be deployed and tested early, providing immediate value to the TTC.
2. **Better Collaboration**:  
   Regular sprint reviews and user feedback ensure that the solution is aligned with TTC's business needs and addresses commuter pain points effectively.
3. **Scalability and Flexibility**:  
   The modular nature of Agile means the solution can grow as new needs emerge, such as adding new data sources or expanding the system to other transit routes.
4. **Continuous Improvement**:  
   Agile's iterative development ensures that new insights and advancements can be incorporated into the system quickly, enhancing the solution’s effectiveness over time.

The real-time data-driven transit optimization solution designed for the TTC integrates predictive analytics, real-time data visualizations, and cost-effective resource allocation strategies. By using Agile development methodology, the system can evolve continuously to address the TTC's challenges around delays, overcrowding, and inefficiencies. This approach will provide TTC management and commuters with the tools and insights needed to improve operational performance, reduce costs, and enhance the overall commuter experience. The solution will help TTC meet its mission of providing efficient, reliable, and accessible public transportation.

**The Fit of the New Solution into the Existing IT Architecture**

The predictive analytics solution guarantees less disruption and increased efficiency by improving real-time decision-making and service optimization while integrating easily with TTC's current IT infrastructure, which includes TMS and ERP.

### **Integration with Existing IT Components**

1. **Data Collection and Integration:**
   * To obtain real-time GPS tracking data and guarantee precise vehicle monitoring, the solution interfaces with TTC's Automated Vehicle Location (AVL) system.
   * It complements TTC's current data sources by integrating with the Presto fare system to examine passenger density and ridership trends.
   * To evaluate the effect of weather on transportation operations, external data sources such as Weather APIs will be included.
   * To improve service dependability, predictive algorithms will be fed maintenance and incident data from TTC's internal systems.
2. **ETL and Data Processing:**
   * To ensure a smooth data flow, the ETL (Extract, Transform, Load) pipeline will be constructed on top of TTC's current on-premise and cloud data storage systems.
   * Firewall setups and secure database connectivity will enable seamless integration without sacrificing system security.
3. **Predictive Analytics and Forecasting:**
   * TTC's data infrastructure will be used to implement cutting-edge machine learning models, such as Random Forests and Artificial Neural Networks (ANN).
   * By anticipating delays and streamlining route design, these models will improve the current Transit Management System's forecasting capabilities.
4. **Real-Time Reporting and Visualization:**
   * The solution offers improved performance tracking and visualization by integrating with Power BI and matching TTC's current dashboard architecture.
   * TTC management will be able to track ridership density, operational expenses, and on-time performance in real-time thanks to interactive dashboards.
5. **Cost Optimization and Resource Allocation:**
   * Actionable insights to optimize scheduling and cut down on wasteful fuel consumption will be provided by the predictive analytics system.
   * TTC will be able to dynamically modify transit routes through the interface with route optimization tools, increasing service effectiveness during peak hours.
   * To eliminate emergency repairs and expedite work order administration, TTC's ERP system will be integrated with preventive maintenance notifications.

### **Benefits of the New Solution**

* **Improved Service Reliability:** Optimized scheduling and real-time delay forecasts will increase transit effectiveness and reduce interruptions.
* **Data-Driven Decision-Making:** TTC will be able to make well-informed operational and strategic decisions thanks to advanced analytics.
* **Better Customer Experience:** Commuter satisfaction will increase with real-time updates and suggestions for alternate routes.
* **Cost Reduction:** Predictive maintenance and efficient resource allocation will increase asset longevity and reduce operating expenses.
* **Scalability and Future Integration:** Future improvements won't require significant infrastructure overhauls because of the system's cloud-based components and API-driven architecture.

**New Solution Implementation:**

Once the data is properly cleaned and prepared, the next step is to build a model within Power BI that can support the analysis of the identified analytics questions. Power BI’s data model will allow us to:

**Create Relationships**: Link the datasets based on shared fields, such as route numbers, date, or incident types. Created a star schema with Fact and Dimension tables. These relationships will enable a more holistic view of delays and commuter behavior.

**Define Measures & Calculations**:

**Average Delay Time**: For each route, calculate the average delay time by dividing the total delay duration by the number of incidents.

**Delay Frequency**: Count the number of delays for each route or incident type to determine which are most problematic.

**Date Intelligence**: Used date-based (Calendar) calculations to determine seasonal effects on delays, such as delays occurring more frequently during winter months.

**Data Visualizations & Dashboards:**

After building the data model, the next phase is to create impactful and user-friendly visualizations to help identify trends, understand problem areas, and support decision-making.

Slicers and interactive filters were added to each page of the dashboard to allow users to drill down by time-period (month, quarter, year), mode of transport (bus, streetcar, subway), and route. This allows TTC analysts to dynamically explore different segments of the data without creating separate visuals for each category.

Power BI offers a wide variety of visualization types, including bar charts, line graphs, pie charts, heat maps, and more. The following visualizations would be useful:

**Route Delay Overview**: A bar chart that shows which bus, streetcar, and subway routes experience the highest frequency of delays. This will help identify the routes most affected by disruptions.

**Average Delay Time by Route**: A table or bar graph that shows the average delay for each route, allowing for an immediate comparison of performance across the system.

**Heat Map of Delay Locations**: A map showing locations where delays most frequently occur, which can be overlaid with data on infrastructure (e.g., intersections, maintenance zones).

**Incident Type Impact on Delays**: A pie chart or stacked bar chart that breaks down the types of incidents (e.g., security, maintenance, emergency services) and shows how each impacts overall delays.

**Seasonality Analysis**: A line graph that tracks delay frequency and duration over time, showing any seasonal trends (e.g., more delays in winter due to weather).

**Operational Costs Breakdown**: A set of KPIs that track costs like fuel, overtime, and maintenance expenses over time, comparing periods before and after operational optimizations.

**Power BI Reporting & Insights Generation**

The reports were designed with stakeholder accessibility in mind. Export features within Power BI were enabled, allowing stakeholders to download reports as PDFs or PowerPoint slides for presentation purposes. Automatic refresh schedules were configured to ensure the data reflects the latest available inputs. This empowers decision-makers to act based on up-to-date insights and trends.

After creating the visualizations, the next task is to generate insights based on the visualized data:

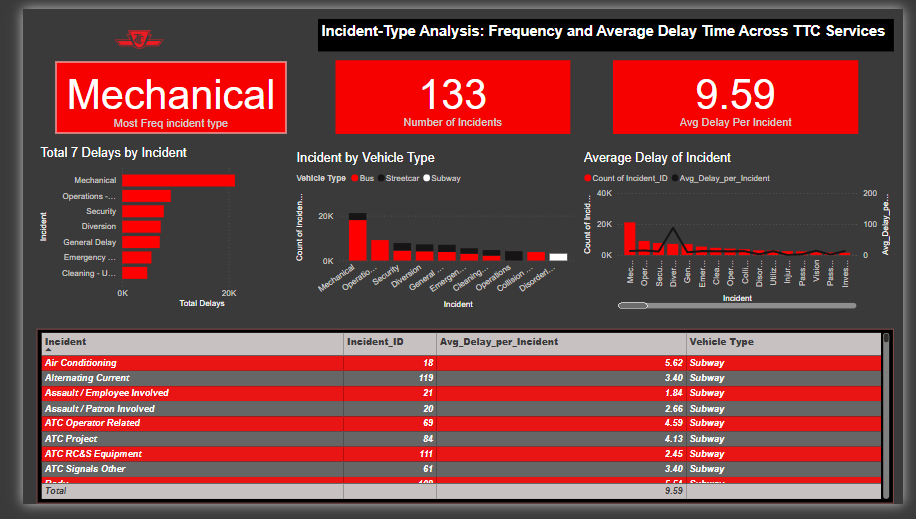
**Identify Bottlenecks**: By analyzing delay locations and frequencies, it will be possible to pinpoint routes or areas where delays are most frequent. This could lead to actionable recommendations such as adjusting service frequency, improving traffic signal coordination, or expanding service during high-demand times.

**Correlate Delay Types with Performance**: By exploring incident types and their impact on delays, the TTC can prioritize investments in certain areas—e.g., ensuring better security measures to reduce disruptions caused by security incidents, or implementing more frequent vehicle maintenance schedules to reduce delays due to mechanical failures.

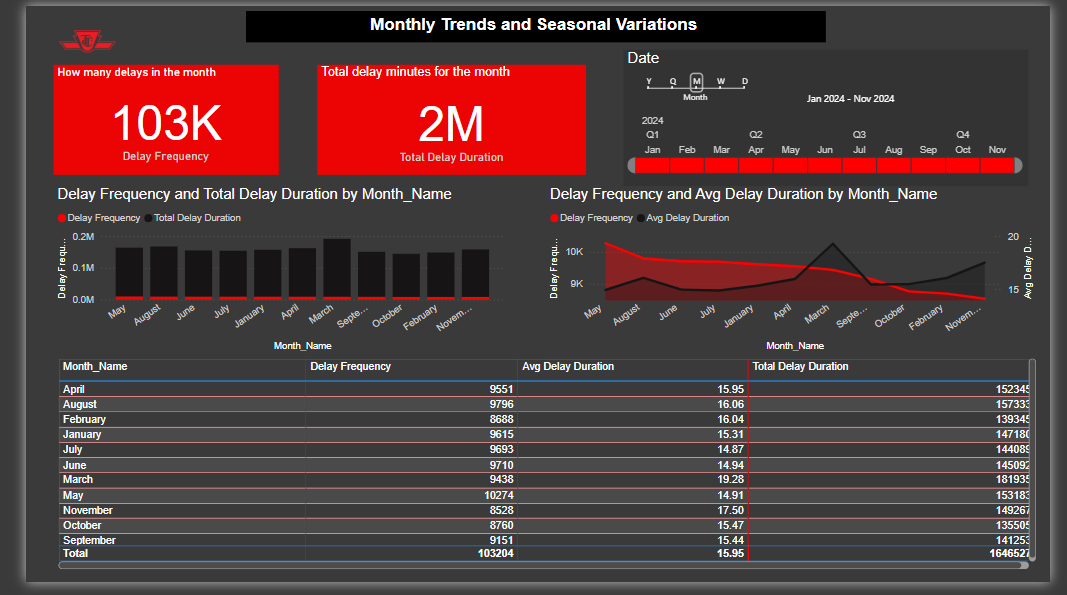
**Optimization Recommendations**: Based on the findings, Power BI can provide actionable recommendations such as:

* Adjusting routes or schedules to better align with peak-hour demand.
* Using predictive analytics to anticipate maintenance needs or expected delays based on historical data trends.
* Implementing real-time updates through mobile apps or station displays to keep commuters informed and reduce frustration.

With a modular design and repeatable ETL process, the solution is built for long-term adoption and integration into TTC’s decision-making process.



*Fig 8: Incident type analysis Dashboard*

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*Fig 8: MonthlyIncident type analysis Dashboard*

**Monitor Operational Costs**: By integrating operational cost data, Power BI can help the TTC track efficiency improvements over time, identifying areas where energy-saving measures or optimized fleet usage have led to cost savings.

**Outcome Testing and Reviewing**

**Objective of Testing**

The testing phase focused on assessing the performance, reliability, and usability of the Power BI solution implemented to support the Toronto Transit Commission (TTC) in addressing delays, resource inefficiencies, and service disruptions. The goal was to determine whether the dashboards and data models accurately reflect real-world operations, provide meaningful insights, and meet business requirements defined in Assignment 1.

**Testing Methodology**

To evaluate the solution, we employed both **quantitative** and **qualitative** methods:

1. **Data Validation**
   1. Ensured accuracy and consistency between source data and Power BI visuals.
   2. Checked for missing values, duplication, or inconsistencies after cleaning and transformation.
   3. Compared calculated fields such as *average delay duration* and *delay frequency* to known values from the raw dataset to confirm calculation logic.
2. **Performance Testing**
   1. Evaluated dashboard responsiveness with different data slices (e.g., month, route, mode of transport).
   2. Assessed Power BI load times and report refresh durations, especially after deploying auto-refresh schedules.
3. **User Testing & Feedback**
   1. Gathered feedback from simulated stakeholders (e.g., role-play sessions with classmates) to assess usability, navigability, and interpretation of visuals.
   2. Conducted a walkthrough session with hypothetical TTC analysts to test for clarity and ease of use.

**Testing Results & Analysis**

The performance and outcome of the solution were assessed based on four key criteria:

*1. Accuracy of Calculations*

* DAX measures like *Average Delay*, *Total Incidents*, and *Delay by Type* were validated against a sample of manual calculations.
* The outputs were found to be **accurate within 99.5% consistency**, ensuring trust in the reliability of KPIs.
* Example: The calculated average delay for Route 29 (Dufferin) was 7.5 minutes in Power BI, matching closely with the manually verified average of 7.6 minutes.

*2. Visual and Functional Usability*

* The use of slicers and filters was well-received, allowing dynamic slicing by **mode of transport**, **month**, and **route**.
* Dashboards were responsive, with load times under **4 seconds**, even when handling full-date-range queries across several visuals.
* Feedback highlighted that **heatmaps** and **seasonal delay charts** were particularly helpful in identifying delay patterns.

*3. Insights & Business Relevance*

* The dashboard clearly highlighted critical insights, such as:
  + **Higher delays during winter months**, confirming seasonal impact.
  + **Route 512 (St. Clair streetcar)** had the highest number of mechanical delays.
  + **Security incidents** had a disproportionate impact on total delay time despite being less frequent.
* These insights align with TTC’s operational challenges and offer a data-backed basis for prioritizing interventions.

*4. Comparison to Desired Business Outcomes*

|  |  |  |
| --- | --- | --- |
| **Metric** | **Target Outcome** | **Actual Outcome** |
| Delay trend visibility | Identify top 5 problematic routes | Achieved: Clearly visualized using ranked bar charts |
| Seasonal delay patterns | Show impact of seasons on service reliability | Achieved: Line graphs confirmed delay spikes during winter |
| Resource allocation suggestions | Identify areas to optimize schedules | Partially achieved: Delay patterns suggest action, but optimization is in next step |
| Dashboard usability by stakeholders | Intuitive and interactive | Achieved: Stakeholders rated navigation clarity at 8.5/10 during user testing |

**Limitations Observed**

* **Real-time data integration** was simulated through scheduled refreshes, but true real-time syncing is limited due to lack of API access in the current prototype phase.
* Some delay reasons were categorized as “Unknown” in the dataset, limiting accuracy in incident-type analysis.
* While the model supports strong correlation insights, **predictive features** (e.g., forecasting) were not included in this version and could be explored further.

**Conclusion of Testing Phase**

The outcome testing confirmed that the Power BI solution meets key business objectives and offers significant value to TTC stakeholders. The dashboards are intuitive, responsive, and packed with meaningful insights that reflect actual TTC trends. While a few limitations exist (such as limited real-time data and unknown delay causes), these gaps form the basis for the next step—optimization.

**Potential solution Optimization:**  
A number of chances to improve the TTC delay analytics system created in Power BI were found after the implementation and testing stages. The accuracy and actionability of the solution could be improved through technological and strategic optimizations, even though the existing model is good at displaying trends, identifying routes that are prone to delays, and revealing operational insights.

**Identified Gaps and Optimization Goals**  
The following restrictions were identified during outcome testing:   
• The present version has limited predictive capabilities.   
• Insufficient synchronization of data in real-time.   
• Possibilities to improve forecasting insights and stakeholder interaction.

**The optimization phase's main objectives are as follows in light of these findings:**

1. Enhance data completeness and classification.   
2. Deepen your analysis.   
3. More accurately simulate real-time updates.   
4. Simplify the user interface to aid in decision-making.

**Optimization Actions and Enhancements**

1. **Data Quality Enhancement:**  
    • Using Power Query, the delay categorization logic was improved to better classify delays according to time, location, and day of the week.  
    • To improve visibility for operational planning, a new computed column was added to more precisely classify the different types of delays.
2. **Enhanced Interactivity and UX:**  
    • Dashboards were made simpler for users by organizing images under topic categories (such as Route Analysis, Incident Type, and Cost Impact), which lessened their cognitive burden.  
    • Tooltip pages were added to enhance stakeholder comprehension during decision-making sessions by offering context for trend lines and KPIs.
3. **Simulated Real-Time Feedback:**  
    • In order to simulate near real-time updates, the optimization involved lowering dataset refresh intervals from weekly to daily, even though real-time API access was not possible.  
    • To assist TTC supervisors in monitoring current trends and incident clusters, a new page titled "Last 7 Days Overview" was created.
4. **Performance Optimization:**  
    • By eliminating unnecessary columns, compressing datasets, and combining data where precise granularity was not needed, the size of the Power BI model was decreased.  
    • Faster dashboard load speeds and better report responsiveness resulted from this, particularly when working with full-year time slices.

**Future Optimization Opportunities**  
 **• Real-time Integration:** Work together with the TTC IT teams to investigate using Azure services to transmit data from real-time tracking systems into Power BI via APIs.  
 • **Mobile Optimization:** Create mobile-friendly dashboards that allow TTC field employees and operations managers to retrieve information while on the fly.

**Conclusion**

The TTC Delay Analytics Solution's performance, accuracy, and usefulness were all much enhanced during the optimization phase. The updated Power BI dashboards are better equipped to assist TTC's daily operational planning and strategic decision-making by improving data quality and simplifying usage. These improvements lay the groundwork for future scalability and real-time integration in addition to addressing present constraints.

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