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Short-Term Planned LRT Service Disruptions: Analyzing Customer Perceptions and Enhancing Bus Bridging Strategies

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Short-Term Planned LRT Service Disruptions: Analyzing Customer Perceptions and Enhancing Bus Bridging Strategies

by

Muhammad Arslan Asim

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The undersigned certify that they have read and recommend to the Faculty of Graduate Studies for acceptance a thesis entitled “Short-Term LRT Planned Service Disruptions: Analyzing Customer Perceptions and Enhancing Bus Bridging Strategies.” submitted by Muhammad Arslan Asim in partial fulfilment of the requirements for the degree of Doctor of Philosophy.

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Abstract

Light Rail Transit (LRT) Planned Service Disruptions (PSDs) improve service reliability, extend infrastructure's life, and reduce the frequency and impact of unplanned service disruption caused by system failure. However, the literature on the impact of LRT PSDs on transit customers' travel mode choice behaviour is scarce relative to that on unplanned service disruptions. This thesis's objective is two-fold. The first part investigates transit customers' mode choice behaviour in response to short-term LRT PSD in the City of Calgary, AB, Canada, and the second part develops a methodology to design a bus bridging service strategy for LRT planned service disruptions. A Stated Preference (SP) survey was designed to gather respondents' mode choices under a set of hypothetical scenarios. A mixed multinomial logit model was estimated using stated preference data. Findings of this study include: 1) Stated LRT ridership dropped by about 35% during the examined LRT short-term service disruption. 2) Transit customers who use LRT payment passes (monthly, subsidized seniors, low income, and students) and are frequent weekend LRT users are more likely to stay with LRT mode in case of short-term PSD. 3) The value of time for transit users during short-term LRT PSD was found to be 11.76 $/hr and 13.0$/hr for travel time (excluding wait time) and wait time during travel, respectively. A sensitivity analysis was conducted on critical variables to predict choice probabilities of transit alternatives, and recommendations were made to improve Calgary Transit customers' experience during short-term LRT PSDs. This study also suggests a methodology for transit planners to provide an optimized bus bridging service strategy along a disrupted LRT section during a short-term PSD to provide a higher level of service to Transit users. An optimal bus bridging service plan (i.e., routing strategy and frequency) is suggested along a disrupted section of the LRT section, using existing infrastructure consisting of bus stops and roadways. Various bus bridging service strategies are considered in this study, with optimal bus bridging service plans based on agency and passengers' costs for each strategy. The MNL logit model was introduced in the passenger assignment to model realistic passengers' perceived choice behaviour to choose among the available routes. Values of time for parameters such as waiting time, walking time, and riding time, which were estimated for the city where the case study was conducted, were used. The proposed model was tested with variations in passenger demand levels and passenger distribution along a disrupted section and found to be robust against various levels of passenger demand and variations in ridership patterns. Results of the case study conducted in Calgary, AB, Canada, suggested that the proposed bus bridging service design model outperformed the conventional local route strategy and reduced passenger cost by up to 25%. The study contributes valuable insights and practical recommendations for enhancing transit services during short-term LRT disruptions.

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List of Acronyms

LRT	Light Rail Transit
LRV	Light Rail Vehicle
BRT	Bus Rapid Transit
PSDs	Planned Service Disruptions
SP	Stated Preference
RP	Revealed Preferences
MNL	Multinomial Logit
CT	Calgary Transit
CTrain	Calgary Train
PA	Public Announcements
MLP	Maximum Load Point
APC	Automatic Passenger Counters
AFC	Automatic Fare
WiFi	Wireless Fidelity
ID	Identification
GPS	Geographical Positioning System
OD	Origin Destination
AVL	Automatic Vehicle Location
APIS	Advanced Passengers Information System
GLPK	GNU Linear Programming Kit
i.i.a	Independent of Irrelevant Alternatives
i.i.d	Independent and Identical Distribution of errors

Chapter-1

Introduction

1.1 Background

In recent decades, traffic congestion has become a severe problem in major metropolitan areas, causing delays, pollution, reduced road safety, and degradation of infrastructure. Due to fiscal, land and environmental constraints, building more roads is often not a viable solution. Public transit has the potential to address increasing traffic congestion issues while meeting fiscal and sustainability constraints, such as environmental and noise pollution and the need for more land acquisition.

Public transit system in big Canadian cities consists of regular bus, express bus, Bus Rapid Transit (BRT), Light Rail Transit (LRT), and metro or subway services. BRT, LRT, and metro/subway are considered mass transit systems due to their vast passenger transferring capacity. To provide faster travel times and high reliability, these systems are usually provided separated right of way from general auto traffic. The reliability of mass transit systems is of prime importance to transit agencies in terms of operation and transit customers' perception. Poor reliability impacts the overall transit system's performance and customers' trust, which in turn affects ridership and results in revenue loss. Due to wear and tear, the mass transit system's infrastructure may break anytime, so it requires routine maintenance to keep the system operating and provide a desired level of service. To execute the maintenance work on the infrastructure, sometimes transit service must need to be interrupted or suspended for a certain period, which can vary from days to months or years. These types of transit service closures and interruptions are called "service disruptions."

Transit service disruption can occur at any time, anywhere along the transit network, for any reason. The disruption causation may range from a small broken part on a transit vehicle to an entire transit system breakdown, from a transit workers' strike to a fatal incident. Transit users suffer due to these disruptions. The problem of transit service disruption is common in large cities all over the world. It is evident from previous studies that frequent and/or prolonged transit disruptions impose high costs on transit agencies and result in reduced commuters' trust in the service and lost ridership from customers switching to alternate modes of commute (Carrel, Halvorsen, and Walker 2013).

In mass transit systems that run on a dedicated infrastructure, service disruptions are broadly of two types: planned and unplanned. Unplanned service disruption happens suddenly due to natural disasters, accidents, track failure, and vehicle breakdowns. Planned Service Disruptions (PSDs) can be introduced to perform scheduled maintenance or upgrade work. PSDs are an essential part of regular maintenance that aims to avoid potential future system failure, which could result in severe, frequent, and/or longer unplanned disruptions. Thus, PSDs help increase the service life of mass transit systems and result in more reliable and resilient service. PSDs require a transit system to be closed at one or multiple sections. Along the disrupted section(s) of the transit network, a replacement service, most commonly bus bridging (Christoforou et al. 2016; Pender et al. 2013), is provided to connect the transit route. Transit users are notified a few days in advance of PSDs so that they can adjust their travel plans accordingly.

The duration of LRT PSDs can vary from hours and days to months and years, depending on the nature of maintenance or upgrade. This study focuses only on short-term LRT PSDs that last up to three days and are scheduled on weekends. Short-term PSDs have yet to be analyzed in the literature up to the knowledge of the author. Short-term PSDs may involve small maintenance tasks, for example, signals, communication, and track & ballast replacement.

PSDs are scheduled during non-revenue service hours (e.g., nighttime) to avoid any impacts on transit service. However, there is an urgency to schedule these PSDs during regular service hours. In that case, such PSDs can be accommodated on weekends when ridership demand is significantly lower than on weekends.

Because of the relatively short notice, some transit customers may experience inertia and make no change in their trip plans, enduring the additional delays associated with the short-term PSDs. Conversely, some travellers may alter their plans significantly, choosing an alternative mode, rescheduling the trip, or cancelling it altogether. In all cases, PSDs negatively impact passengers' travel experiences and result in a decrease in transit ridership and customer satisfaction.

Good quality data is required to quantify the impact of PSDs on LRT ridership. Automatic passenger counts (APC) systems are considered the industry standard and are widely used on transit vehicles for collecting continuous ridership (boarding, alighting, and busloads) data. Other than the APC system, Automated Fare Collection (AFC) systems that may include smart payment cards and mobile ticketing systems, also being adopted at a fast pace by transit agencies, can be used to gather ridership information as a secondary purpose of these systems. All these systems are expensive and require extensive capital investments.

Transit agencies need to understand the short-term impacts of PSDs on transit customers' behavioural choices. This understanding can be used to devise new replacement services that can improve customers' travel experience. While passengers' responses to unplanned disruptions of transit networks have been extensively studied, the literature on planned disruptions, in particular those of short duration, remains relatively scarce (Christoforou et al. 2016). No prior studies examine how transit customers' experiences can be improved during short-term LRT PSDs. An improved understanding of customers' behaviour and attitude is crucial for improving the replacement services to account for passenger preferences during short-term PSDs.

1.2 Gaps in the related literature

Extensive research has been conducted to understand the impacts of unplanned transit service disruptions and strategies to reduce their impacts. However, there needs to be more literature examining short-term PSDs. Conversely, a few studies are looking at the impacts of long and medium-term LRT PSDs on transit customers' travel choice behaviour. While the above literature provides insights into the impacts of transit disruption on passengers' travel behaviour, it does not capture the customers' perception towards short-term LRT PSDs and the impact of short-term PSDs on ridership. To the best of our knowledge, no previous study has examined the impacts of short-term LRT PSDs on transit customers and their mode choice behaviour. In addition, no research has been conducted to examine how transit customers' experience can be improved during these short-term LRT planned service disruptions by optimizing the configuration of a combination of bus bridging strategies that complement the conventional all-stop shuttle bus service.

This study takes steps in this direction to fill the gap in literature by focusing only on short-term LRT planned service disruption to examine transit customers' travel mode choice behaviour in response, quantifying impacts on LRT ridership, and proposing an optimal bus bridging service strategy for improving customers level of service.

1.3 Research Objectives

A few studies are looking at the impacts of LRT PSDs on transit customers' travel choice behaviour and on devising bus bridging strategies to mitigate the impact of these disruptions on transit passengers. The objective of this study is thus twofold: 1) investigate and quantify the impacts of short-term LRT PSDs on LRT users' experience and their travel mode choice preferences during short-term LRT PSD and 2) develop a methodology to design an optimal bus bridging strategy for short-term PSDs.

The following are the main objectives of this research:

1. Examine LRT users’ travel mode choice preferences during a short-term LRT PSD.
    a. Understand LRT users’ perception of travel time during short-term LRT PSD in comparison to normal LRT service.
    b. Determine the value of travel time and wait time cost.
    c. Determine the market share of LRT and transit overall.
2. Quantify the actual impact of short-term LRT PSD on LRT ridership using APC data.
3. Propose an optimal bus bridging service strategy for short-term LRT PSDs to improve customers' level of service.

1.4 Research Contributions

This thesis provides several contributions to advance the literature on planned short-term transit disruptions. The contributions are summarized as follows:

1. This work is the first of its type conducted to examine LRT users’ mode choice behaviour under short-term PSDs. The contribution of this study includes the design of a stated preference survey method to gather LRT users’ responses.
2. Modelling the passenger’s responses using a mixed Multinomial Logit (MNL) model under short-term LRT PSDs. The findings of this study are important and valuable in understanding the customer's behaviour under short-term planned disruptions by improving service.
3. This research also developed a novel bus bridging service strategy for short-term LRT planned service disruptions to improve transit users’ level of service. A new optimization framework is formulated to determine the optimal bus bridging strategy

while taking into consideration passengers and operator costs. Actual values of passenger’s travel time and wait time were used from the previous part of this thesis to inform the formulation of the bus bridging model.

4. The primary methodological contribution is formulating the problem as a bilevel optimization to determine the optimal combination of bus bridging strategies with consideration to anticipated passengers' route choice responses. The developed model allows transit planners to mitigate the impacts of transit disruptions better.
5. The developed methodology was tested using real-world data on an existing LRT network in Calgary, AB, Canada. The model showed that proposed local-express and local-skip stop or local-express-skip stop strategies alternative to the conventional single local bus bridging route strategy could improve passengers' travel experience during short-term PSD by reducing passengers’ delay overall. The model was tested with variations in passengers' demand levels and passenger distribution along a disrupted section. The model was found to be robust and can successfully determine optimal bus bridging for disrupted sections of short-term PSD.

1.5 Organization of the Thesis

The dissertation is organized into six chapters. A brief description of each chapter is provided below:

1. **Introduction**

   Chapter 1 presents the background of the research along with study objectives and contributions.

2. **Literature Review**

   Chapter 2 covers the related research that has already been conducted in the area of mass transit disruptions. This chapter includes two parts. The first part covers the studies that examined the impacts of transit PSDs on transit customers using conventional choice modelling methods. The second part explores the work done to improve customers' experience by improving bus bridging strategies.

3. **Calgary Transit and short-term LRT PSDs**

   This chapter offers insights into Calgary Transit's current practices for handling planned service disruptions. It delves into the various options employed to furnish alternative transit services and outlines the methods used to communicate advance notifications to customers ahead of planned closures.

4. **Transit Customers Survey** (Examining Impacts of PSDs On Transit Passengers)

   Chapter 4 provides details on survey methodology, design, data collection, descriptive analysis, and choice modelling for examining transit passengers' experience and mode choice behaviour. Discussion on the results and recommendations for improving transit users' experience during short-term LRT PSD are also included in this chapter.

5. **Quantifying Ridership Impact of PSDs**

   In Chapter 5, the impact of short-term PSDs on ridership is analyzed using actual ridership data from APC.

6. **Optimal Bus Bridging Service for LRT PSDs**

   In this chapter, a methodology is proposed for designing an optimized bus bridging strategy for LRT planned service disruptions to provide a high level of service to transit users. The proposed model was tested for a scenario of short-term LRT planned service disruption in Calgary.

7. **Conclusion, Recommendations and Future Work**

   Chapter 7 summarises the conclusions drawn based on studies conducted in this research. Policy recommendations based on the study outcomes are presented, as well as suggestions for potential future work on this topic of examining the impacts of transit PSDs on transit users.

Chapter 2

Literature Review

This chapter summarizes the previous research work done on the topic of examining and measuring the impacts of mass transit systems' Planned Service Disruptions (PSD) on transit passengers' travel experience and their mode choice behaviour. This chapter is divided into two main sections, as follows:

- Review of studies conducted on examining PSDs' overall impacts on transit passengers' travel experience generally using various methods and specifically using choice modelling.
- Review of literature available in the field of bus bridging service design in case of short-term mass transit planned service disruptions. This will include route selection, frequency determination and passengers' assignment on various available routes.

2.1 Impacts of transit PSDs

While transit agencies consider the costs associated with LRT replacement service (e.g., bus bridging) under LRT PSDs, they still need to pay more attention to the impacts of these types of service disruptions on customers (Christoforou et al. 2016)). Negative impacts of service disruptions on transit customers may include extra travel time and cost and inconveniences such as additional transfers, walking, wayfinding, rescheduling, and cancelling trips (Bernal, Welch, and Sriraj 2016). Mode choices are influenced by the decision maker's current and past positive or negative experiences with different travel modes (Daniel McFadden 2016). It is evident from previous research studies that frequent and/or prolonged LRT disruptions are high costs for transit agencies (Carrel, Halvorsen, and Walker 2013). These costs can include reduced trust in the service and lost ridership from customers switching to alternate commuting modes.

2.1.1 Ridership decrease due to PSDs:

Abrams (1998) stated that “prolonged presence of variability caused by slow zones (slow speed LRT service provided for prolonged periods due to scheduled maintenance purpose) may have long-term adverse effects on passengers, and unless reconstruction projects can be accomplished without seriously inconveniencing them, ridership will suffer, potentially for prolonged periods after project completion.

Bernal et al. (2016) studied the impacts of slow zones (slow-speed subway/LRT service provided due to planned maintenance) on customers’ experiences and their travel choice behaviour. They found that transit customers’ satisfaction declines due to the presence of slow zones of longer duration and may cause a temporary or permanent ridership drop. Also, based on automated fare collection data, they concluded that loyal transit customers are more likely than other transit users to switch to other modes of commute due to prolonged delayed subway service.

Anderson (2014)) conducted a study to evaluate the impacts of a planned subway disruption on a parallel road network. The author developed a simple choice model using actual data from a strike in 2003, which lasted for 35 continuous days and was led by Los Angeles transit workers. The strike resulted in shutting down both the bus and metro services. It was found that the average delay on highways caused by the subway service closure was increased by up to 47% because transit customers switched to alternative modes of driving.

Zhou Yang (Z. Yang 2018) studied the impact of a year-long transit PSD on ridership. Revealed preference and Stated Preference (SP) survey data were used before, during and after analysis of the disruption on Washington Metro due to track maintenance work. They found that about 30% of customers chose alternative modes during disruptions, and only about 10% returned to transit after the disruption was over.

Eltved et al. (2021) investigated the effects of prolonged planned transit disruptions on passenger travel behaviour in the Greater Copenhagen area, utilizing smart card data. Through K-means analysis, they observed a 12% ridership decline among frequent users during the three-month disrupted service compared to normal operations.

2.1.2 Inconvenience

Short-term PSDs cause inconvenience to passengers who are travelling during a service disruption. They would make additional transfers, i.e. from LRT to a shuttle bus and from the shuttle bus back to LRT at the other end of the disrupted section and spend additional time riding the shuttle bus service. During these transfers, passengers need to walk longer, find their way to the shuttle bus stops and wait additionally for the shuttle bus and LRT.

Downward et al. (2019) examined transit customers' route choice behaviour through a Stated Preference (SP) survey in Auckland, New Zealand, during their network-wide transit routes modification exercise. They found that customers prefer direct routes over ones that involve transfers unless the service is reliable and transfer wait time is short.

Weis and Axhausen (2012) conducted a combination panel and SP survey in Zurich, Switzerland and found that inducing travel time changes in transit trips causes passengers inconvenience, which includes adjusting their departure time, switching modes, cancelling or rescheduling their trips, and /or changing the order of their daily activities.

2.1.3 Potential Strategies for Retaining Ridership during PSDs

To retain transit ridership during planned disruptions, the causation of transit customers' dissatisfaction needs to be investigated so strategies can be adopted to improve the level of service for the passengers.

Barron et al. (2013) studied investment models of 22 transit agencies related to mitigation strategies in response to LRT and subway disruptions. They concluded that agencies that focus on reducing passengers' delays during transit service disruptions are perceived as the more reliable and get higher customer satisfaction ratings.

Srikukenthran and Shalaby (*2017*) developed a simulation model of the mass transit network of the Greater Toronto Area, Canada, to analyze network-level impacts of transit disruptions on service. They tested the impacts of transit service disruption duration on passenger crowding levels at stations. They found that mitigation solutions, for example, directing passengers to specific routes via announcement, are essential to minimize impacts before the crowding levels become dangerously high

Providing improved bus bridging service during service disruptions was the strategy suggested by many studies. Christoforou et al. (2016)studied the impact of PSDs caused by railway line maintenance work in Paris, France. Their study presented a new methodology for evaluating bus bridging as a disruption mitigation strategy by estimating the generalized cost (travel times, comfort, and level of service) of the disruption to passengers. The results of the before-after scenario evaluation in the study suggested that an increase in the frequency of the bus bridging service and potential alternate transit routes significantly lower the customer's generalized cost in the whole transit network.

Saxena et al. (2019) compared the impacts of delayed (e.g., slow zones) and disrupted (bus bridging) transit service. They found that transit customers are less likely to choose disrupted service than delayed LRT service during incidents and find disrupted service three times more onerous than delayed service. Also, they recommended providing express shuttle bus service between large transit stations and limited stops service between small transit stations.

2.1.4 Applied methodologies

The methodologies used to capture impacted customer’s perceptions were mainly based on preference surveys and smart cards (electronic payment system) data. Also, all those studies were for specific networks and certain events, and the transit service disruption lasted for an extended period (a few weeks to months). (Lin et al. 2018)

The methods used in previous studies to capture impacted customer’s perceptions were mainly based on travel behaviour surveys (Lin et al. 2018) or observed data as reflected in automated fare collection (Bernal, et al. 2016). More recently, new methods have emerged using microsimulation tools augmented with transit customers' behaviour modules (Srikukenthiran and Shalaby 2017) and passive data collected from personal cell phones and WiFi technology (Stanley et al. 2016). These emerging tools require significant calibration and/or large datasets (Srikukenthiran and Shalaby 2017; Stanley et al. 2016).

2.2. Bus bridging strategies for transit planned service disruptions

2.2.1. Route(s) selection for bus bridging service: types of transit bus

Selection of candidate routes for bus bridging service depends on rail transit network topology and surrounding road network. Agencies can have different routing options, which may be a combination of more than one route based on the PSD situation. These routes can be shortest paths between the affected stations or may be chosen to offer better transfer facilities for transit users. Conventional bus services typically follow a fixed route between affected stations, stopping at all designated stops along the way. However, variations of fixed route services, such as skip-stop and express services, are introduced to increase travel efficiency and bus speed and to reduce round trip time and overcrowding.

Skip-stop service involves selectively skipping specific stops to minimize passenger travel time and reduce waiting times at transfer stations. Yang et al. (2019) and Salama et al. (2022)

proposed skip-stop strategies that prioritize reducing waiting times and minimizing travel times. They demonstrated significant reductions in vehicle riding time compared to traditional all-stop strategies.

A recent transit service pattern model proposed by Gkiotsalitis et al. (2021) considers the impact of the COVID-19 pandemic and determines skipped stops based on real-time passenger demand information to maintain safe capacity limits. The study showed that adapting service patterns reduced passenger loading per vehicle, but specific stops needed to be skipped, leading to unserved passengers. This model is suitable for low-demand areas where missing stops have a limited impact.

Zonal express service divides a corridor into zones and provides express routes that directly serve high-demand areas while skipping intermediate stops. This approach minimizes passenger travel and transfer times by collecting trips with similar origins, destinations, and departure times.

Flexible-route service offers door-to-door transit service, accommodating passengers' specific pickup and drop-off locations. This strategy is particularly effective in areas with sparse or fluctuating demand, as it can adapt to different time periods and varying demand levels.

A combination of bus services, as mentioned above, is also deployed to provide better service to passengers and enhance efficiency. At low demand and short trip lengths, on-demand service is optimal. While conventional all-stop service becomes preferable as demand increases for the same trip length, skip-stop and express services become desirable with longer trip lengths and the same demand. As trip lengths further increase, express service becomes increasingly attractive (Heidarigharehsoo and Saidi 2023).

Express-local service utilizes two independent routes to serve a single bus route. Local routes stop at all designated stops, while express routes only stop at selected stops. Teng et al. (2021)

and Lin et al. (2018) explored express-local strategies, considering factors such as varying departure times, dwell times, and passenger demand. These studies found that express-local modes reduced in-vehicle travel time, but increased waiting times compared to all-stop modes.

Gu et al. (2016) compared skip-stop and express-local strategies with the conventional all-stop service. By comparing these strategies for a variety of circumstances, passengers could choose between schemes for minimizing travel time. By using continuous models, they minimized the total generalized costs of each scheme to determine the lowest generalized cost options under varying combinations of demand and the average passengers' travel distance. They provided an analysis of the costs of implementing these strategies on buses, BRT, and railway systems. Based on their results, all-stop service remains the lowest-cost option in lower demand. Also, with skip-stop schemes, BRT is more cost-effective for more cases, and express-local services are more efficient in rail systems to accommodate high demand levels.

Kepaptsoglou and Karlaftis (2009) presented a bilevel framework to identify the best bus bridging routing strategy for unplanned transit service disruption considering passengers' demand and travel time. Codina et al. (2013) developed a programming model to assist with designing an efficient bus bridging service considering congestion at bus stops and in buses during rapid transit line disruption. The model minimizes operational and user travel time costs. The model was tested on a Madrid railway corridor and a Barcelona metro line. The model presented was static and assumed that passengers flow to a transfer station from a rapid transit line followed a Poisson distribution. It also assumed that passengers travelled in platoons from the rapid transit line to bus bridging service. However, continuous models were developed that transit agencies can use to minimize generalized costs through designs and policies. These models can be expressed as simple analytical forms that indicate both operational and user costs.

Heidarigharehsoo & Saeid's (2022) compared alternative transit services under varying demands, passenger trip lengths, and users' cost factors.

Jin et al. (2016) presented an optimally designed bus bridging service in response to unplanned and planned transit service disruption while considering travel demand at the time of disruption. They proposed a realistic approach for selection, combination, and resource allocation for an optimal bus bridging service to reduce travel time delays. Their proposed model was applied on two field cases and the study results suggested that providing multiple bus bridging routes can decrease the passenger travel time by 30-58% and decrease wait time by 15-63% as compared to the standard bus bridging route, keeping the fleet size same.

Dou et al. (2019) introduced a design methodology for a bus bridging service parallel to a temporarily closed mass transit line during a two-day planned maintenance in Singapore. Their approach encompasses route planning and terminal and bus stop selection to mitigate passenger inconvenience and prevent congestion on parallel streets. While the design incorporates bus-to-bus transfers, it does not account for realistic passenger waiting times.

Luo and Xu (2021) proposed an integrated rail disruption response model to optimize the allocation of buses, schedules, and routes, considering the predicted disruption duration and passenger demand variations. The authors proposed a two-stage approach. In the first stage, they developed a disruption prediction model based on historical data and external factors to estimate the disruption duration. The second stage involves designing the bus bridging services based on the predicted disruption duration and passenger demand uncertainty. Uncertainty in passenger demand arises from the fact that passengers faced with LRT service disruption have options to choose from all available alternative transit routes (such as alternate existing rail lines or existing bus routes). So, demand for bus bridging services may not be deterministic and would be variable based on passengers’ choices. The authors proposed a multimodal shortest path model to identify alternative routes, considering transfers between modes and lines. They tested their framework using smart card fare data on Singapore's mass rapid transit network.

Overall, these alternative transit services provide opportunities to enhance the efficiency, speed, and quality of transportation while addressing specific passenger needs and optimizing resources.

2.2.2. Transit Passengers’ Assignment during Service Disruption

The planning of bus bridging services is closely tied to transit assignment and the prediction of transit passengers' route choice behaviour from their origin to their destination. The assignment problem deals with estimating flow patterns based on OD flows and network and path choice characteristics (i.e., how passengers travel in the transit network). Assignment models simulate interactions between supply and demand in a transportation network to estimate the propagation of the transit passenger demand on the various transit links and nodes (Nsair 2020). In the literature, separate approaches have been proposed for the route assignment of transit passengers in frequency-based and schedule-based transit services. In frequency-based services, vehicles on specific routes are dispatched at a particular headway. Passengers catching a bus, in this case, arrive randomly at the bus stop. Therefore, passengers’ waiting time is a probability function of passenger’s arrival at a stop. Frequency-based assignment models can further be classified into congested and uncongested models. In uncongested models, the capacity of link (route) flow is assumed to be high such that passengers can ride the first vehicle arriving at a bus stop. It is also assumed that boarding and alighting times are minimal, and there is no additional travel time for passengers already on board. Hence, link costs (i.e., total travel time) are independent of flow (ridership) on the routes/links. In congested assignment models, link/route travel time is a function of ridership (i.e., passengers boarding and alighting time). Congested models aim to represent real transit systems.

Transit equilibrium assignment models (TEAM) aim to find the equilibrium between the number of transit riders and the capacity of the transit system to serve them. The TEAM model assumes that travellers are rational and will choose the most efficient and convenient mode of transportation available to them based on their individual preferences, such as travel time, cost, and convenience. The model calculates the expected number of transit riders based on these preferences and compares it with the capacity of the transit system to handle the demand. If the supply of transit services is sufficient to meet the demand, there will be a supply of transit services and overcrowding of transit vehicles. Conversely, if the supply of transit services is less than the demand, the transit system may need to be more utilized, leading to inefficiencies and waste of resources. The TEAM model aims to find the optimal level of transit supply and demand that results in an equilibrium state where the transit system is operating efficiently and serving the needs of the population (Nsair 2020).

Early studies by Dial (1967) and Fearnside and Drape (1971) explored the concept of waiting time at stops served by multiple routes and travel time as factors to determine passengers' shortest travel path. Building upon this concept, Chriqui and Robillard (1975) proposed that passengers on a simple network with multiple routes would choose the route that arrives first to minimize their total travel and waiting times.

The work of Spiess and Florian (1989) expanded upon this concept to apply it to large transit networks. It introduced the notion of strategies, which are sets of attractive lines considered by passengers at each decision point, such as boarding or transfer stops along a route. The perceived expected cost or time for transit passengers is determined by a weighted sum of factors, including walking, waiting, and in-vehicle travel time. Passengers rely on strategies, which are sets of rules enabling them to reach their destinations. The choice of strategy is based on available information, such as the arrival time of buses, waiting time, travel time, and required transfers. Several studies have utilized the Florian model to address transit assignment challenges.

Nguyen and Pallotino (1988) introduced the concept of hyperpaths, a graphical interpretation of a strategy using directed acyclic graphs and considered crowding as a discomfort factor in their cost minimization objective function. However, their model needed to adequately capture the fact that passengers may be unable to board the first bus arriving at a stop during periods of heavy demand, resulting in an underestimation of passengers' waiting time. De Cea and Fernandez (1993) expanded upon the work of Chriqui and Robillard (1975) and introduced the concept of a restricted strategy, in which attractive sets of lines include routes that share the next stop to be served. They further extended their model in 1993 to incorporate the effect of crowding at bus stops and on buses. However, their heuristic graphical approach for large networks required significant computational effort, and the resulting flows exceeded vehicle capacities.

Kurauchi et al. (2003)proposed a model in which passengers were considered risk-averse towards crowded stations and would not board a crowded bus. The residual capacity of transit buses was determined based on boarding probability.

Wu et al. (1994) considered a semi-congested network in which waiting time was directly proportional to the effective flow, and flow distribution depended on nominal frequencies. Comminetti and Correa (2001) analyzed a completely congested network with more realistic waiting times at bus stops, considering asymptotes at bus capacity. These studies have contributed to the understanding of transit assignment and the consideration of various factors, such as congestion and capacity restraints, in modelling passengers' route choices and flow distributions in transit networks.

Van der Hurk et al. (2016) introduced a model for optimizing shuttle routes and frequencies during planned disruptions within a constrained budget to minimize passenger inconvenience, including transfer and waiting times. Applied in Boston, Massachusetts, the model suggests that the addition of extra routes through a bus bridging service can effectively distribute passenger delays on the system. So, some passengers may face additional delays on their trip. The model incorporates passenger valuation of time drawn from previous studies, which may be conducted in the region and may not be specifically tailored to planned service disruptions.

Chen and An (2021) presented an integrated linear programming-based model for the efficient design of bus bridging strategies for unplanned transit service disruptions. Their model incorporates both express and short-turn routes, complemented by a timetable to accommodate variable passenger demand. Notably, the assumptions involve avoiding passenger assignments to routes requiring additional transfers for general convenience; acknowledging this may only sometimes apply. Fixed dwell time at stations was assumed, which may not be the case in real scenarios, and a penalty term in the cost function accounted for passenger dissatisfaction. A significant contribution of their work lies in enhancing the model's efficiency, enabling rapid identification of optimal routes and timetables.

Wang et al. (2023) proposed a bus shuttle/bus bridging design and transit passengers' assignment model in case of unplanned disruption caused by a security-related emergency. In the bus bridging design, they designed routes and determined bus frequency. The model assigned passengers to a route among all available routes based on the shortest travel time. They used the number of transfers and in-vehicle travel time as parameters in the passenger's travel time optimization. For transfer time, instead of using actual walking time and waiting time, they used a fixed penalty (i.e., the sum of wait time and walking time) per transfer.

2.3 Chapter Summary:

This chapter offers a comprehensive review of research on the impact of planned service disruptions (PSD) in mass transit systems, covering two main sections. Firstly, it examines studies on PSD impacts and choice modeling, and secondly, it reviews literature on bus bridging service design during short-term planned service disruptions, encompassing route selection, frequency determination, and passenger assignment. While extensive research has focused on unplanned service disruptions due to their severe impacts, studies on planned disruptions are limited, particularly for short-term disruptions. Research on planned disruptions primarily examines medium to long-term disruptions related to specific events, utilizing diverse data sources such as preference surveys, Automatic Fare Collection (AFC) systems, cell phones, and WiFi technology. Analysis commonly employs choice modeling and simulation. The literature on bus bridging service design predominantly addresses unplanned disruptions, analyzing efficient routing strategies and computational efficiencies. Notably, none of these studies incorporate local passengers' actual valuations of time. In addition, there is a lack of research specifically addressing Light Rail Transit (LRT) in the context of short-term planned service disruptions.

Chapter-3

Calgary Transit and short-term LRT PSDs

3.1 Introduction

Calgary’s Light Rail Transit (LRT) is a relatively old transit system. With age, the infrastructure wears and tears over time. The LRT service can be disrupted due to aging components of LRT infrastructure, which could happen any time during regular LRT service and cause significant impacts on a high volume of transit riders. It is very important to maintain the state of the LRT infrastructure before it starts breaking down. To avoid or reduce the frequency and impacts of these unplanned service disruptions, the upgrade of various components of LRT infrastructure is scheduled in advance during periods of low ridership; so, the impact of these planned service disruptions stays limited to the low volume of transit customers. These planned LRT service disruptions help increase the service life of the LRT system, which can provide more reliable and resilient service in the future at the cost of shorter and less impactful PSDs.

Calgary Transit, for the past few years, has been in the process of upgrading and replacing different aging components of LRT infrastructure. This initiative intends to keep the system running reliably currently and, in the future, to meet the increasing demand for ridership of public transit. Hence, one or more of the sections of the LRT lines in Calgary are regularly subject to maintenance, upgrade or life cycling of various infrastructure components. Components of LRT maintenance range from regular replacement of track ballast to replacing signals, communication, and power systems to upgrading LRT stations and platforms. The LRT maintenance can be categorized into the following three:

- Buildings: platforms and station buildings

- Right of way (ROW): tracks, ballast, switches, and turnouts
- Control: signals, power, and communication

Execution of these maintenance tasks and upgrade projects may last for a few hours to a few days, depending on the nature of the maintenance work. Sometimes, the duration of the service closure increases if the projects cannot be completed on time due to various factors, such as weather. As Calgary is still a growing city, other than the maintenance work, the LRT service also needs to be closed for infrastructure expansion and other development projects happening beside the LRT right of way.

For the sake of this thesis, we categorize PSD based on duration:

- Short-term: The planned mass transit service disruptions that take place during weekends for up to three days to execute the smaller maintenance tasks. Mostly, it includes signal work, communication, and track & ballast replacement.
- Medium term: The planned service disruptions which last for a few weeks; for example, platform rehabilitations.
- Long-term: The maintenance or replacement tasks may take a few months to complete. Examples include track replacement.

The normal LRT service needs to be disrupted or closed along the specific section of the LRT line. A replacement service is provided to transport transit customers from one end of the disrupted LRT line to the other. Calgary’s Light Rail (CTrain) users travelling through the disrupted section transfer from the CTrain onto the shuttle bus service and then transfer back to the CTrain to continue their travel. A schematic diagram of normal and disrupted LRT service is shown in *Figure 3.1*.

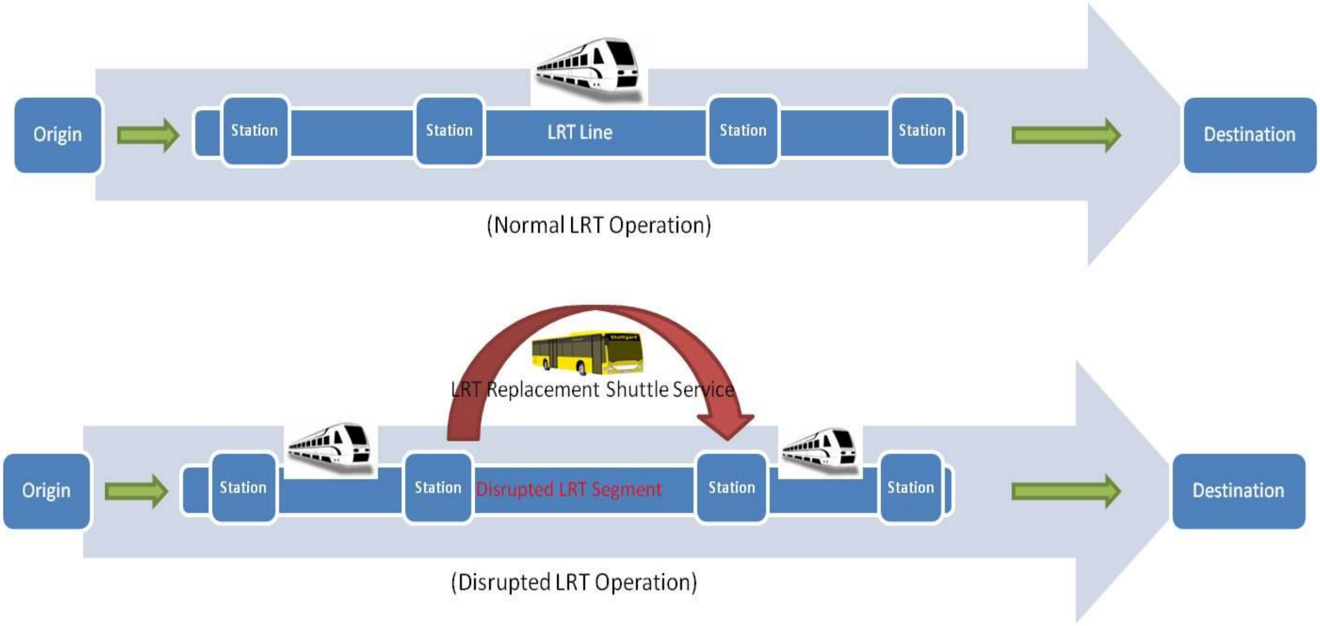

Figure 3. 1: Schematic demonstration of normal and disrupted LRT operation

Although CTrain service is stopped during the night for three to four hours (non-revenue hours) to perform some maintenance tasks like cleaning the station building, this time slot is not long enough to perform infrastructure-related repair or upgrade tasks. Therefore, these types of maintenance tasks are scheduled for weekends only.

Usually, this replacement service is bus bridging (i.e., a shuttle bus service stopping at the same stops as the LRT stations). Other than bus bridging, CT uses other replacement strategies to serve transit users, a description of which is provided in Table 3.1.

Table 3.1: Light Rail Transit (LRT) service replacement strategies used by Calgary Transit.

Serial #	Strategy	Description
1	No LRT service closure	Maintenance work is performed during the time available between the train arrivals (headways)
2	Slow zones	Maintenance work is performed within the LRT right of way, which does not directly impact the train operation. However,

		LRT runs at a slower speed through these work zones, as working crews are working in that area, and on LRT's arrival, they move away from the tracks. Slow zones are established for minor repair tasks during weekday off-peak periods.
3	Single tracking	A similar (or slightly less) level of service, as regular, is provided to customers by running trains using a single track for both directions. There are chances of the train being delayed as sometimes LRT heading in one direction needs to make a stop to let oncoming LRT pass.
4	Train-to-train transfer.	The train stops at a station (which is not the last on the line), and passengers must disembark at the platform and board the other train from the same platform.
5	Train to bus transfer.	Passengers must disembark at the platform and transfer onto LRT replacement shuttle buses to travel up to the terminal station.
6	Bus bridging	A shuttle bus service is provided to connect along the disrupted section of the LRT line. Passengers must disembark at a platform and get onto the LRT replacement shuttle bus, which takes them to the next active LRT station, and passengers must transfer to the LRT to complete their journey up to the downstream LRT station.

3.1.1 Advance notification for transit Customers

Information on these upcoming short-term LRT PSDs is provided one to three weeks in advance to transit customers by multiple means, such as displaying notices at LRT platforms, public announcements at platforms, on-trains, transit websites and app, call centers, social media such as Twitter, and radio, and via emails to subscribed transit customers. Posters are deployed at every impacted LRT station. CT's staff are assigned to the transfer stations for public information and assistance with transfers for connecting to LRT or replacement bus service. In addition, all the residential community committees and major social event organizers are notified of upcoming planned LRT service disruptions. These notifications also include information for the customers on whether the CTrain service would be slow, whether additional transfer from train to train would be required, or whether a CTrain replacement shuttle bus service is provided. CTrain customers know the situation pre-trip and may choose between using disrupted CTrain service, using alternative modes, such as transit bus route, personal car, or taxi, or even rescheduling or cancelling their trip.

3.1.2 Ridership Impacts of PSDs

Calgary Transit currently needs a framework to estimate the actual drop in LRT ridership due to LRT short-term PSDs.

Calgary's LRT system is radial, with downtown as the center. All LRT lines transport passengers from various parts of the city to/from the downtown. The usual corporate working hours of downtown make the ridership directional by the time of day. During the morning period, the majority of LRT passengers make work trips to downtown, and in the evening/afternoon period, most of the ridership is away from downtown. With peak directional trips on LRT, the station just outside of the downtown makes the point where ridership is maximum both during morning and evening/afternoon periods. These stations are termed as max load points (MPL) by the City of Calgary. The City of Calgary manually observes train loads near the four LRT stations outside the downtown boundary and uses this as an indicator of line ridership.

CT’s entire bus fleet and about half of the LRT fleet are equipped with APC systems. Buses deployed on shuttle service during short-term PSDs are equipped with APC systems, but due to the limitations of the software, it is not easy to gather data on the shuttle buses. Hence, the impacts of PSDs on actual ridership are not currently determined by Calgary Transit.

Calgary Transit will be upgrading and maintaining the LRT system in the coming years, so short-term planned LRT disruptions will continue to be scheduled frequently. The findings of this study would be important and useful in understanding the customers’ behaviour and retaining them during such short-term planned disruptions by improving service.

3.2 Chapter Summary:

Chapter 3 describes Calgary Transit's management of short-term LRT planned service disruptions (PSD), addressing the challenges posed by the city's aging infrastructure and detailing strategic interventions to ensure ongoing reliability. Maintenance tasks, spanning buildings, right of way (ROW), and control, are intricately categorized, each exerting a distinct impact on the operational efficiency of the LRT system. This research classifies planned service disruptions into short-term, medium-term, and long-term categories. Short-term PSDs are strategically scheduled for weekends and long weekends (2 to 3 days) to minimize the impact on passengers, yet they necessitate specific closures of LRT sections. Replacement services, primarily facilitated through bus bridging, are outlined alongside various strategies employed by Calgary Transit, including slow zones, single tracking, train-to-train and train-to-bus transfers. The chapter also underscores the critical role of advance notifications in disseminating information to transit customers about upcoming short-term PSDs, utilizing a multifaceted approach to ensure comprehensive communication.

Chapter-4

Transit Customers Survey

to Examine Transit Passengers’ Responses to LRT Planned Short-Term Disruptions[1]

In this chapter, a comprehensive survey was designed to collect information about transit users’ experiences during PSDs. In the first section of the survey, questions were asked about participants’ travel experience during PSDs and their perception of advance notification practice provided by local transit agencies about upcoming LRT PSDs. The second part of the survey consists of an SP questionnaire designed to understand LRT users’ travel mode choices and behavioural responses to short-term PSDs. A Multinomial Logit (MNL) model was used to estimate parameter values. The model estimates were then used to analyze the impact of various socioeconomic demographics on respondents’ mode choice preferences during the event of a short-term planned CTrain service disruption.

The questionnaire survey conducted in this study consisted of two parts: 1) a revealed preference (RP) and 2) a Stated Preference (SP). The revealed preference approach uses information collected about actual choices made by individuals in real life, to estimate statistical choice models. Accordingly, such an approach is limited to analyzing the effect of actual factors in the transport system. Obviously, collecting RP data from the field is only possible if the proposed transit service exists. In such cases, relying on stated preference data may be efficient. In general, SP experiments are considered a significant advancement in choice

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[1] Part of this chapter is based on an earlier published article by Arslan Asim, M., Weiss, A., Kattan, L., & Wirasinghe, S. C. (2021). Transit Users’ Mode Choice Behaviour During Light Rail Transit Short-Term Planned Service Disruption. Transportation Research Record, 2675(10), 711-722. https://doi.org/10.1177/03611981211012421.

modelling where respondents are directly asked about their preferences and what would they be willing to pay or accept for a specific alternative. The SP method measures customers preferences over hypothetical alternatives including potential new alternatives, by asking respondents to assess a number of alternatives described by the scenarios and choose the one that seems best to them. (S. Bigerna et al, 2017).

Although, SP method is widely used in the transportation related choice modeling, the main weakness of the SP method is unavailability of the real-world data and thus lack of predicting actual behaviour, called hypothetical bias (Laurent and Sabrina 2019). Studies comparing the RP and SP methods have found that respondents to SP surveys tend to overstate their valuation of a particular alternative, which can lead to misleading choice models. Studies that compared RP and SP methods has also suggested that magnitude of hypothetical bias tends to be higher for publicly funded good or services; and is smaller for studies which sampled RP and SP from same respondents (Kaat de Corte, 2021). In this research respondents are asked RP questions about their past trips during a planned service disruption as well as SP questions for hypothetical alternatives during planned service disruption with expectation to minimize hypothetical bias.

In this chapter, the survey development, data collection, and data modelling process are presented. Responses to the RP part of the survey are analyzed and discussed first. Secondly, the choice modelling results, interpretation, discussion and sensitivity analysis are presented.

4.1 Survey Design

In this study, a comprehensive questionnaire survey was designed to understand CTrain users' perceptions about the short-term planned CTrain disruptions and their travel mode choice behaviour during these events. Two types of surveys are mainly used: RP and SP surveys. RP surveys are based on questions to gather actual information from respondents' experience of some events. While in the SP survey, respondents are presented with hypothetical scenario(s), and their responses are gathered based on their judgement.

A questionnaire survey[2] focused on the following sections was conducted in the Fall of 2019:

- Revealed Preferences (RP) Survey: In this section of the questionnaire survey, respondents were asked to provide information based on their experience:
    - of their past trip during a short-term LRT planned service disruption and
    - of their perception of advanced information provided by Calgary Transit about the upcoming LRT PSDs.
- Stated Preferences (SP) survey: In this section, a hypothetical scenario of a personal meeting purpose trip on CTrain during a short-term planned CTrain service disruption at a specific section along the Red line was given to participants. Participants were presented with various mode alternatives to choose from for their trip.
- Socioeconomic demographics: Socioeconomic information recorded participant-specific attributes that included gender, age, occupation, employment status, driving licence possession, car ownership, access to various modes, household income, CTrain trip frequency, possession of monthly/student/senior transit pass, etc.

This study was conducted in Calgary, the third-largest municipality in Canada (after Toronto and Montreal) and the largest city in Alberta *(Alberta.ca).* Calgary Transit (CT) is the service provider in Calgary. CT's rapid transit system consists of bus rapid transit (MAX) and light rail transit (CTrain) services. Two CTrain lines – Red line and blue line – serve as the backbone of Calgary's transit system (*Figure 4.1a*) and carry over 300,000 customers daily.

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[2] The University of Calgary Conjoint Facilities Research Ethics Board has approved this study (REB_0752).

4.2 Revealed Responses of LRT Customers during PSDs

In this section, only the RP part of the survey is presented to analyze respondents’ responses. Questions in the RP part of the survey were designed to gather respondents’ choices based on their experience with travel during LRT PSDs and their perception of information provided by Calgary Transit (Transit agency in Calgary, AB, Canada) in advance of any upcoming LRT PSDs.

Questions asked to the respondents in this part were mainly related to respondents’ actual travel experience, such as mode choice between LRT and any alternative mode (such as transit bus, taxi, ride-hail service, ride from friend or family member), wait time for the shuttle bus, walking distance to/from the shuttle bus, as well as their perception towards the information provided in advance by the transit agency. Also, a few stated preference questions were asked about their potential probable choices in similar scenarios and suggestions on improving their travel experience during future LRT PSDs.

In the following section, respondents' feedback is analyzed in detail, along with descriptive statistics.

4.2.1 Customers' perception towards Planned service disruption notifications

Planned service disruptions are a big change in the day-to-day transit service and may severely impact the activities of people who rely on transit in any capacity.

In this section, the survey respondents’ feedback regarding the advanced notifications of short-term PSDs provided by transit agencies was analyzed. In the survey, respondents were asked about their experience during the most recent short-term PSDs, how they knew about the upcoming PSD, and what changes they made in their trip plan. Also, the respondents were asked about the effectiveness of various nonfiction mediums used by transit agencies and their preferred medium of getting notified about these PSDs.

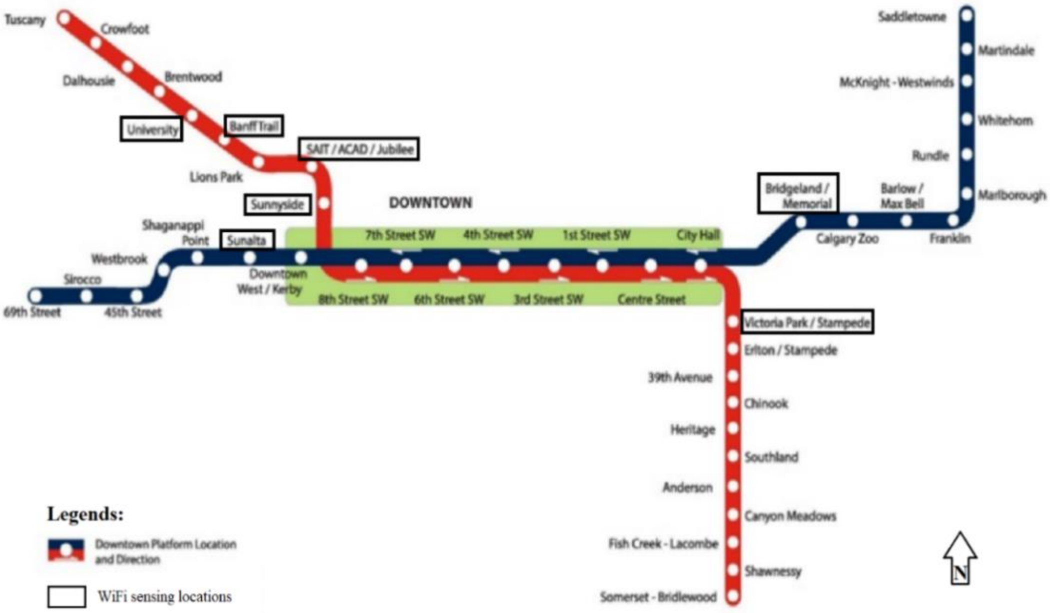


Figure 4.1a: Calgary’s LRT network

Figure 4.1b: The LRT section with hypothetical planned service disruption.

4.2.1.1 Utility of the advance notification system for short-term PSDs

As part of the RP survey of the questionnaire survey, respondents were asked about their experience of getting notified of upcoming short-term LRT PSD for their most recent trip. All possible mediums of notification systems used by Calgary Transit, as described above, were provided in the question for respondents to choose from.

Six hundred eighty-nine (689) of the participants responded to the question and made 1151 choices out of the given options, as people can get the notification by more than one medium. *Figure 4.2* displays the respondents' choices among the various available sources of advance notifications of upcoming short-term PSDs. Most of the respondents (91.6%) were aware of the upcoming short-term PSD, and only a small percentage of the respondents (8.4%) stated they were not aware of the short-term planned PSD in advance. These respondents would have come to know about the service disruption only when they arrived at the LRT station These respondents can be added to those who benefit from the at-station information displays which is 32.2% of the total number of respondents.

"Information displayed at CTrain stations," which included sandwich boards, posters and display on digital displays, seems to be the most used (53.9% of total respondents, 32.2% of the total choices made) source of information related to upcoming or ongoing planned CTrain disruption. The second most utilized source of advanced notification for upcoming PSD, as stated by the respondents, was "Station announcements" (18.7% of total respondents, 11.2% of the total choices made).

Based on the number of respondents, Transit App (18.3%), on-train announcements (18.0%), staff at the CTrain station (14.5%), Calgary Transit website (8.1%), friends/family (7.4%), social media (5.4%), Transit email alert (2.0%), radio (2.0%) and newspaper (1.3%) were the sources of information about planned CTrain disruption service used, in descending order from higher to lower percentage, after at-station displays and announcements. About 2% of the respondents used other sources of information, including Google Maps (the most among all other sources), information at work from others or a transit bus driver.

Based on the number of total choices made by the respondents, the Transit App (11.0%), on-train announcements (10.8%), staff at the CTrain station (8.7%), Calgary Transit website (4.9%), friends/family (4.4%), social media (3.2%), Transit email alert (1.2%), radio (1.2%) and newspaper (0.8%) were the sources of information about planned CTrain disruption service used, in descending order from higher to lower %age, after at-station displays and announcements. About 1.8% of the respondents used other sources of information, including Google Maps (the most among all other sources), information at work from others or a transit bus driver. About 8.4% of the total respondents were not aware of the CTrain planned service disruption in advance.

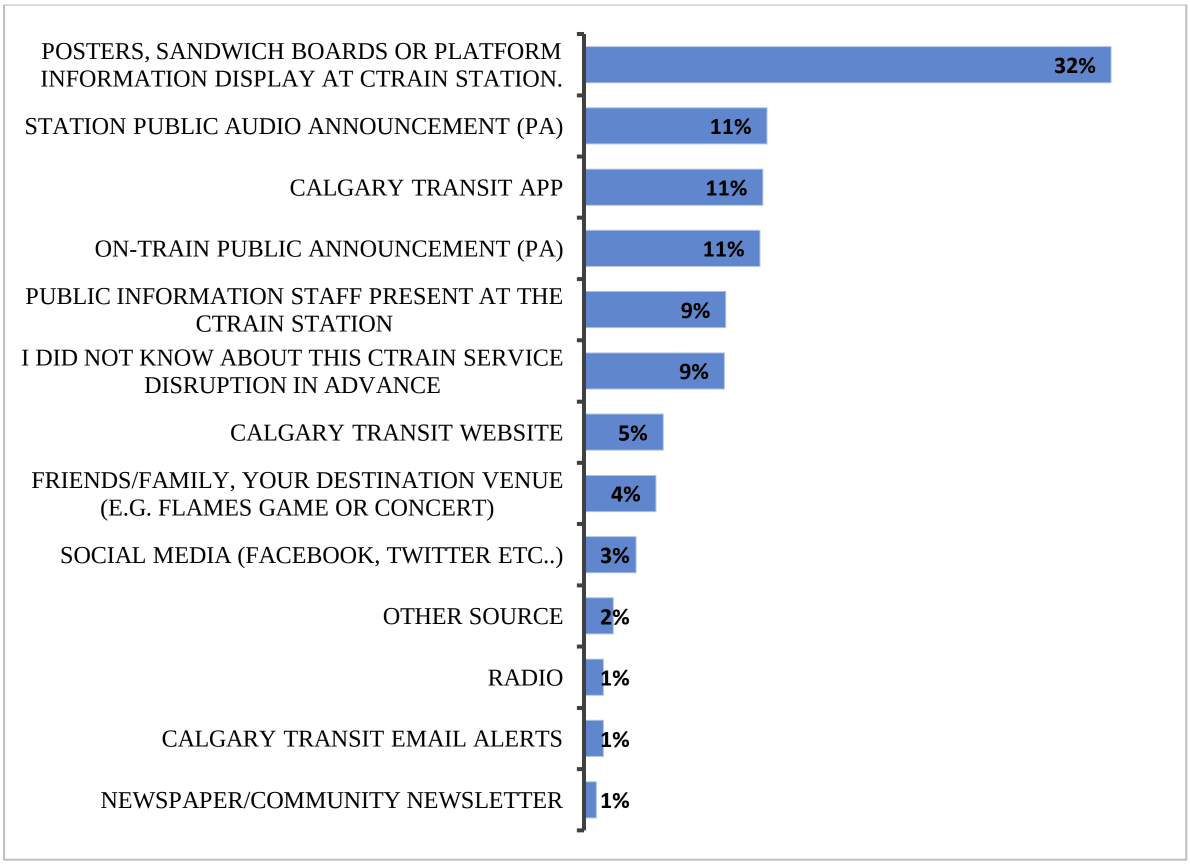


Figure 4.2: Utility of advance notification system for short-term PSDs in Calgary, AB

Results of this analysis indicate that despite the very high penetration of smartphones and access to the internet, station notifications (e.g., posters, electronic displays, and announcements) are the most effective source of providing notifications for upcoming short-term PSDs. The transit customers who use the at-station notification are most probably regular LRT users and must have been notified by the at-station sources of information. Infrequent, occasional, or weekend-only users would be the ones who would use all other means of notifications about the upcoming PSDs before starting their trips. Young people may include students and workers who are more technology-oriented and rely on the transit app transit website to check about any possible LRT service disruptions before starting their trips.

A few people have subscribed to the email alert systems, as this study showed. There can be two possible reasons for the underutilization of email alters system: 1) people do not know about this facility, 2) they do not use emails frequently, or 3) Other available means (s) are working fine for them. The small percentage of the respondents who were not aware of short-term PSD before their trip when PSD was in effect probably be occasional LRT users and not aware that short-term service disruptions can happen.

There can be various socioeconomic factors (e.g., age, gender, education) that may influence people's choice of relying on one source of upcoming PSD notifications over others. Still, these need to be explored in this study.

4.2.1.2 How early respondents get notified of upcoming PSDs.

As mentioned above, transit passengers use various sources of notification systems to get information on any upcoming PSDs. A wide range of answers was received in the survey that how early transit customers come to know about an upcoming PSD, based on the respondents' experience. *Figure 4.3* presents the number of days in advance the survey respondents came to know about the upcoming LRT PSD. More than one quarter (28.3%) of the respondents came to know about the PSD on same day of their trip, . These people might be occasional LRT users who do not consider checking for PSDs days in advance, or they are captive users who do not have alternate modes of travel available to make their trip, so they do not bother checking for service disruptions in advance.

17.4%, 11.3%, and 10.2% of the respondents reported that they came to know about the upcoming planned CTrain disruption one, two and three days, respectively, in advance of their trip. 11.6% of the respondents got a week's advance notice about upcoming CTrain service disruption, followed by 3.4% and 1.0% for two weeks and three weeks, respectively. 11% of the people came to know more than a week in advance of the upcoming short-term LRT PSD.

On average, respondents came to know more than three days in advance of an upcoming LRT PSD. About 60% of the transit customers get notification of the upcoming LRT PSD one to seven days in advance. As the service disruption day comes closer, more passengers tend to know about the disruptions. Calgary Transit disseminates notification of upcoming PSD two to three weeks in advance, as per their policy. However, the majority of the transit customers get to know about these PSDs during the week before a PSD’s effective date.

From this analysis, it can be concluded that transit customers pay attention to the schedule of upcoming PSDs about a week in advance. It can also be assumed that the frequent weekend LRT customers would look for upcoming PSD on weekends (i.e., a week in advance). Calgary Transit’s current practice (i.e., two to three weeks advance notification) is well planned so that all types of customers (e.g., frequent, frequent week only, captive, and occasional) ahead of time know in advance that some service disruption is coming. They validate that with various other sources as, the effective date of PSD comes closer.

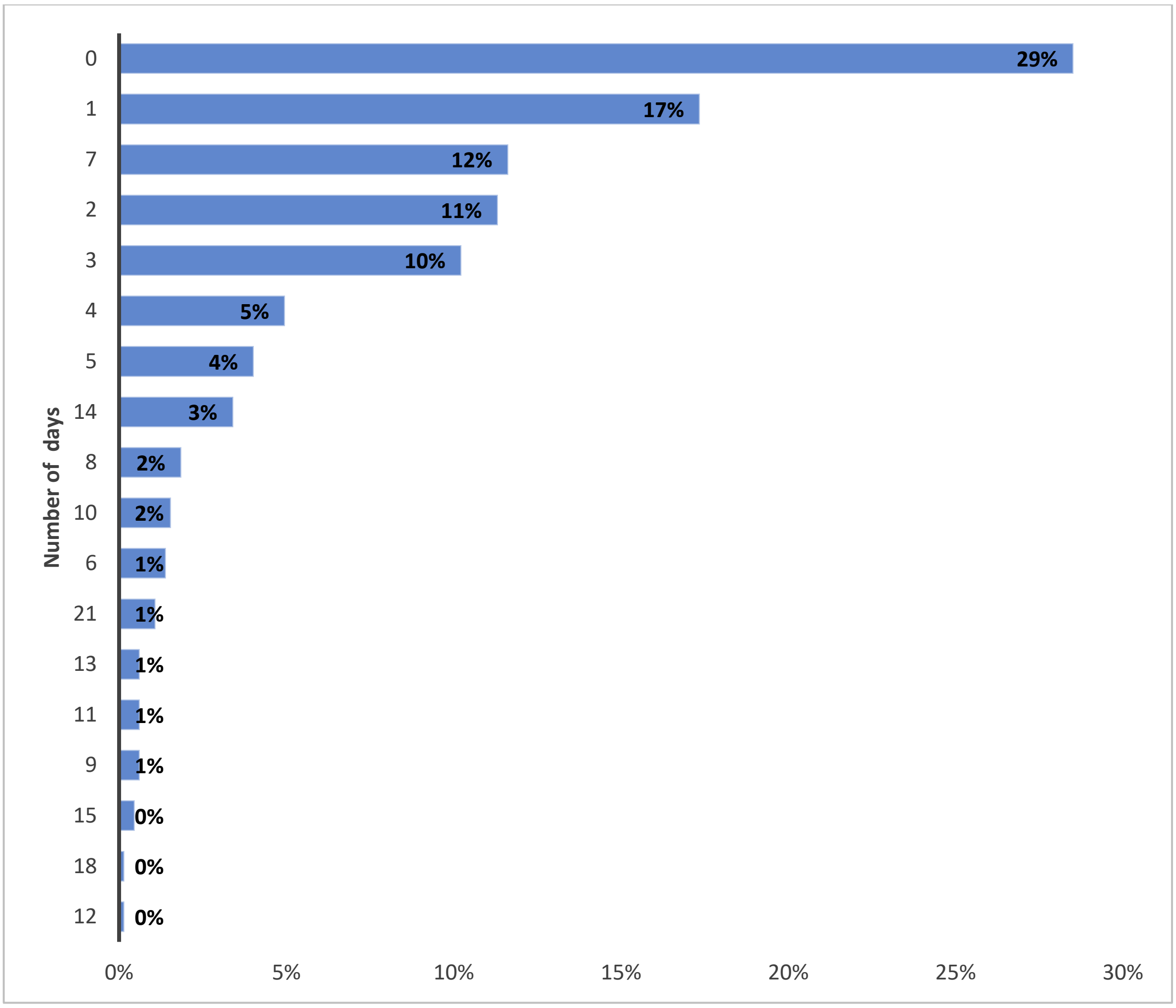


Figure 4.3: Number of days the survey respondents came to know about upcoming short-term PSDs in advance of their trip.

4.2.1.3 Satisfaction of transit customers with current PSD notification practice

Calgary Transit's current advanced notification practice for an upcoming planned CTrain service disruption is working well for most transit users. *Figure 4.4* shows the satisfaction level with the current advanced notification practice as stated by the survey respondents. 54.2% of the respondents are extremely or somewhat satisfied with the current notification process. It does not matter to 24.0% of the respondents how advanced the CTrain planned disruption notification is provided as they were neutral in their responses. 15.6% of the respondents were somewhat dissatisfied, and 5.7% were extremely dissatisfied with the current advance notification practice. There is some room for improvement in the advanced notification system for PSDs so that unhappy customers can be satisfied.

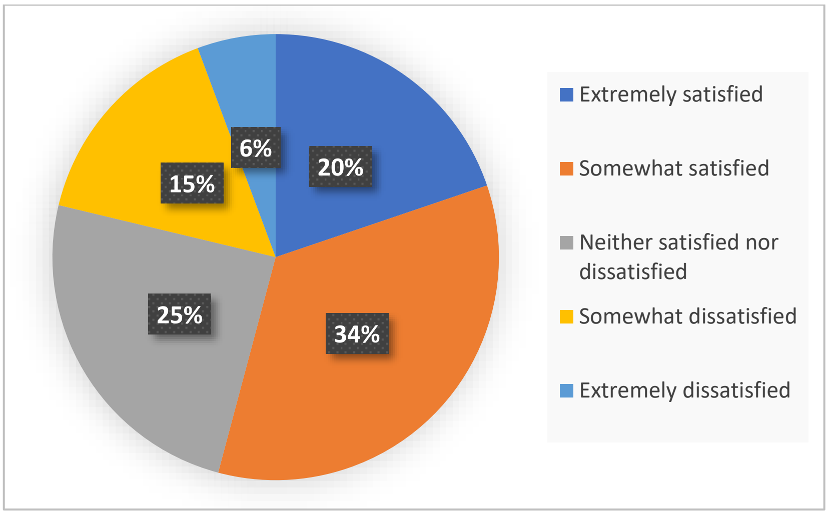


Figure 4.4: Transit customers' satisfaction level with the current advance notification system for upcoming LRT PSDs.

4.2.1.4 Preferred timing of PSD advance notification

In this survey, respondents were asked about their preferences and how early they would like to be notified about an upcoming PSD. About 19% of the respondents stated that they want to avoid getting advance notifications about upcoming short-term PSDs. These respondents would be occasional and captive transit users who have to make the LRT trip regardless, and they would have flexible schedules, so it would not matter if their trip took longer than usual. 21.5% of the respondents would like to get notified while they are travelling during LRT PSD. The rest of the 60% of respondents had different requirements to get notified of the upcoming PSD, as shown in *Figure 4.5*. Responses of these participants (i.e. 60% of the total) were further analyzed, and it found that 40% of the respondents wanted to be notified one to 4 days in advance, and 41% of the respondents wanted to be notified five to seven weeks in advance. About 5% and 8% of respondents wanted to get notified ten days and two weeks, respectively, in advance of PSD. The majority of transit customers (more than 80%) would like to get notified a week in advance of an upcoming LRT PSD.

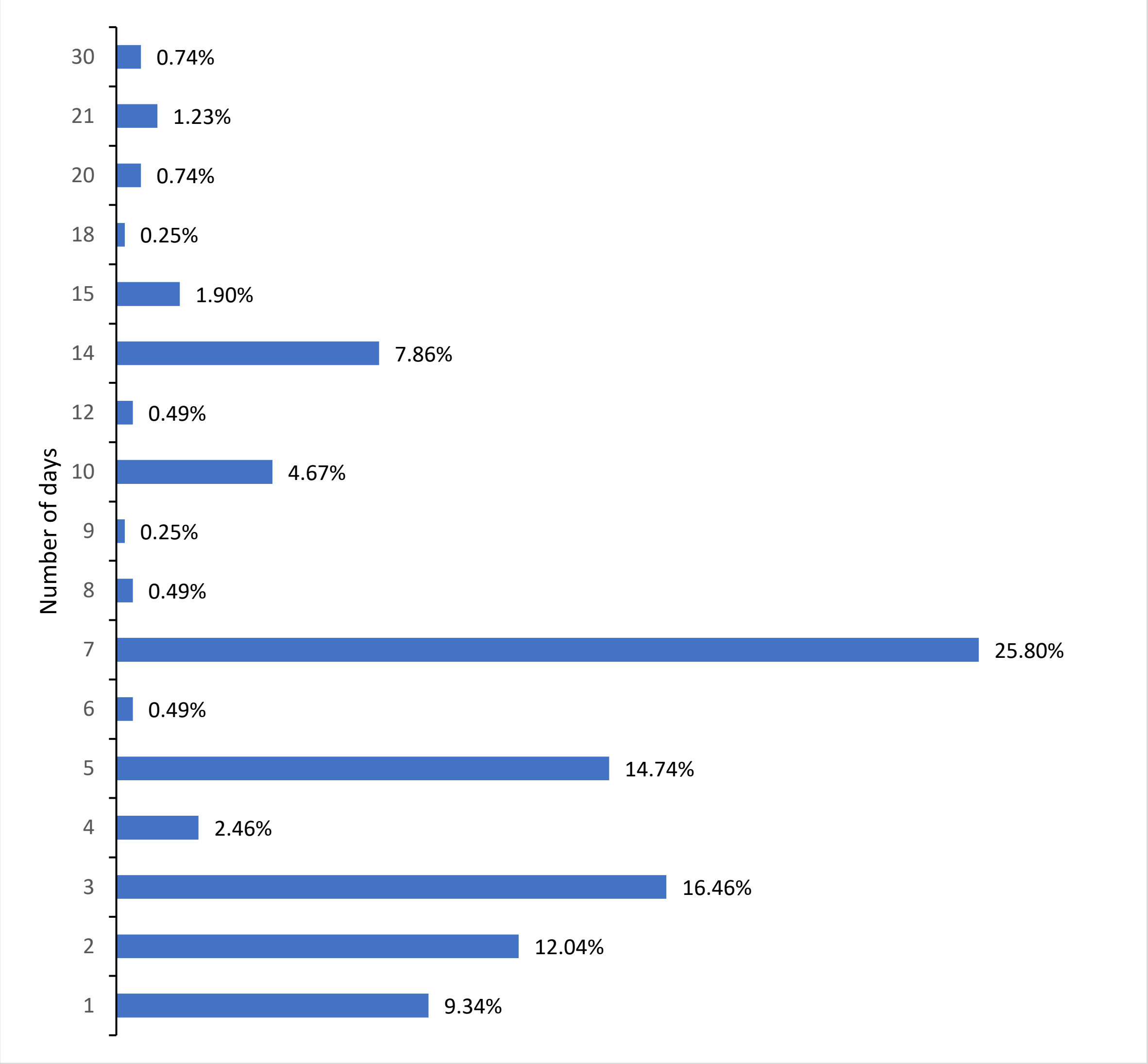


Figure 4.5: Number of days the survey respondents would like to be notified of upcoming short-term PSDs in advance of their trip.

4.2.1.5 Preferred medium for PSD advanced notification

Notifications on smartphones through the internet (34%), emails, SMS and transit apps, and at-station sources (32%) that include posters, electronic displays and platform announcements were reported to be the most preferred medium of notifications for PSDs. After these mediums, on-train announcements (11.5%), the Calgary transit website (8.2%) and social media (7.8%), such as Twitter and Facebook, were the popular preferred mediums to get notifications of upcoming PSDs, as stated by the survey respondents. *Figure 4.6* summarizes the respondents' preferences on the medium of notification they would like to get notified about upcoming PSD. This analysis provides some insights into transit customers relying on online information about their trip, including PSDs. This increasing trend may eliminate the need for other mediums of notifications, such as displaying notices at stations, public announcements onboard and at stations, and call center services.

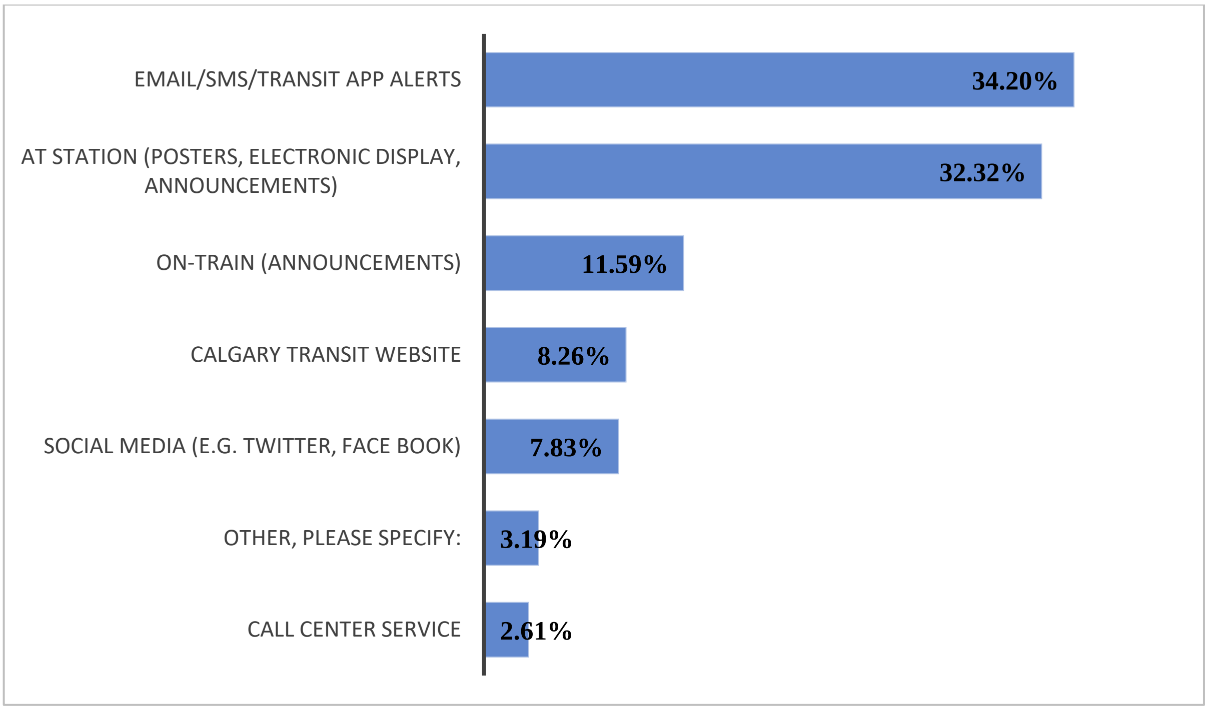


Figure 4.6: Respondent's preferred source of getting notification of upcoming PSDs.

4.2.1.6 Importance of various available mediums of PSDs advance notification

Respondents were asked to score their preference for the seven different media used for dissemination of PSD notifications in advance: Platform display, Transit app, transit website, at-station announcements, on-train announcements, call center/phone, emails and text alerts, and call center/text service. A five-point scale was used, where 5 represented the "extremely important" and 1 represented "not important at all", to gather respondent's feedback on the importance of these media of sending advance notifications. *Table 4.1* presents the percent of respondents who gave score to each medium of information.

The satisfaction scores of the notification medium, rated from 1 to 5 by respondents, were weighted according to the assigned responses in percentage. This approach was employed to calculate the mean values and then establish the respective order of the ratings. Platform display (i.e. poster and electronic) was the most important medium of PSD advance notification based on the mean score (4.7) given by the respondents. Transit app, at the station, and on-train announcements are the most important media in order, after the platform display medium rated by the respondents.

Table 4.1: Descriptive statistics of the preferred medium of LRT PSD's advance notification

Medium of Notification	**Extremely important (5)**	**Very important (4)**	**Moderately important (3)**	**Slightly important (2)**	**Not important at all (1)**	**Weighted Average**
Platform display	62.76%	24.93%	9.82%	1.76%	0.73%	4.47
Transit App.	56.89%	22.67%	12.15%	5.04%	3.26%	4.25
At station announcement	48.81%	30.36%	15.48%	4.17%	1.19%	4.21
On-train audio announcements (During the CTrain service disruption)	45.99%	27.15%	18.69%	5.64%	2.52%	4.08
Transit Website	39.73%	25.26%	21.12%	9.45%	4.43%	3.86
E-mail/Text Alerts	32.54%	26.30%	19.32%	14.26%	7.58%	3.62
Call center/Text service	26.15%	24.67%	27.04%	13.52%	8.62%	3.46

4.2.1.7 Potential improvements for customers during short-term PSDs:

A few potential improvements, to be scored based on their importance, were presented to the survey participants. A five-point scale was used, where 5 represented the “extremely important” and 1 represented “not important at all”, to gather respondent’s feedback on the importance of these media of sending advance notifications. *Table 4.2* presents the potential improvements rated by the survey participants and summary of the rating statistics for each medium of information. All the improvements were scored high by the respondents. The ratings (1 to 5) for each medium of notification were ordered based on the weighted averages. The improvement options related to the travel and schedule information en-route during the PSD that include an interactive map showing real-time availability of alternate modes (e.g., Car2Go, e-bike, e-scooter, taxi, ride-hail service) of travel and real-time shuttle bus arrival information at stations during PSD, were rated as the most important improvement (57.78%) needed for customers experience during a short-term PSD, based on mean (4.4) of the rating. The potential improvements around advanced information (onboard announcements in advance, at nearby public activity centers, and push notifications) were rated as lesser important.

Table 4.2: Descriptive statistics of the potential improvements for LRT PSD’s notification.

Potential Improvement	**Extremely important (5)**	**Very Important (4)**	**Moderately Important (3)**	**Slightly Important (2)**	**Not important at al (1)**	**Weighted Average**
1	57.78%	28.15%	11.11%	2.22%	0.74%	4.4
2	48.21%	33.33%	13.39%	4.02%	1.04%	4.24
3	39.58%	31.10%	20.39%	6.99%	1.93%	3.99
4	37.05%	33.63%	19.64%	6.40%	3.27%	3.95
5	38.10%	29.17%	22.32%	7.59%	2.83%	3.92

Legends:

1. Interactive map at CTrain stations about the real-time location of nearby transit bus routes including C-Train shuttle bus and alternative travel options availability (e.g., Car2Go, e-bike, e-scooter, taxi/Uber)
2. Regular updates at CTrain stations on the next 3 CTrain shuttle bus arrival times (similar to the C-Train during uninterrupted operation)
3. On CTrain audio announcements (a few days before a Planned service disruption)
4. CTrain service disruption information displayed at nearby shopping malls, public service centers, universities, schools, and coffee shops.
5. More media access, such as push notifications by texting/SMS and apps to the subscribed CT customers.

4.2.1.8 Summary of the findings

Following are findings based on analysis of participants' responses on mediums used to notify transit customers in advance:

- Notifications on smartphones through the internet (emails, SMS, and transit apps) and at stations (posters, electronic displays and at platform announcements) are preferred medium of notifications for PSDs
- At station notifications (posters and electronic displays, and announcements) and transit apps are perceived as the most preferred means of getting notified of upcoming short-term PSDs as stated by the participants.
- Up to one week in advanced transit customers want to get notifications about upcoming PSD.
- About 40% of transit customers are fine if they know about a PSD in effect during their trip.
- More than half of transit customers are satisfied with the current notification system of upcoming PSDs. However, and about 20% are dissatisfied with the current practice.

- Transit customers give more importance to improving alternate modes during their travel during PSD and real-time information on their availability, than the advance notification of the upcoming PSDs.

4.2.2 Customers experience with LRT planned disruptions

Questions designed in this part of the survey were to gather information about respondents' actual travel experience such as their mode choice between LRT and any alternative mode (transit bus, taxi, ride hail service, ride from friend or family member) that they actually made, wait time for shuttle bus, walking distance to/from the shuttle bus. Also, few stated preference questions were asked about their potential probable choices in similar scenarios and suggestions on improving their travel experience during future LRT PSDs.

4.2.2.1 Transfers during PSDs

Based on their personal preferences, passengers might behave differently during the planned service disruptions. The majority of the respondents (71%) of this survey reported using shuttle bus provided along the disrupted CTrain section. The remaining 29% reported that when they arrived at the disrupted LRT station, they decided to leave the CTrain station and to continue their trip using alternate modes like a different transit bus route, taxi or ride hail service or got ride from their friends or family member.

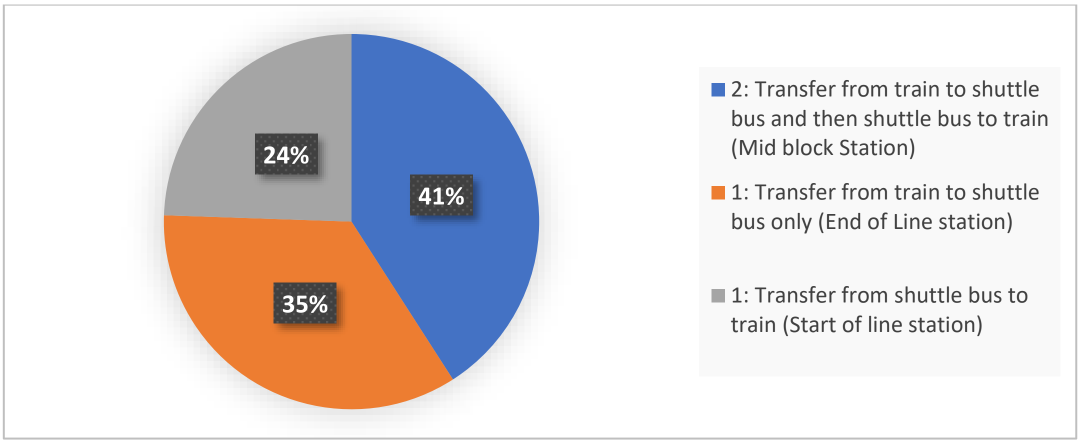


Figure 4.7: Transfers made by LRT passengers on their trip during a short-term PSD

Depending on the location of the disrupted section, transit passengers need to make additional one or two transfers during a CTrain planned disruption. If a PSD occurs somewhere in middle of their trip, then two additional transfers are made: from train to shuttle bus and then from shuttle bus to train. If a PSD is taking place at or near a terminus (i.e.., start or near the end of line) station then customers need to make only one additional transfer, which may be from train to shuttle bus or from shuttle bus to train. *Figure 4.7* shows the distribution of the number of transfers the respondents needed to make during their most recent trips during LRT PSD. As the *Figure 4.7* shows, 41% of the respondents reported that they had to make two additional transfers and rest (59%) of them needed to make one additional transfer. This finding indicates that most of the respondents' trips were made to downtown on weekends during LRT PSD.

4.2.2.2 Perception about travel time during PSDs

Generally, travel time during a PSD is increased compared to that of a normal service. Extra transfers wait and walking time to/from the shuttle service are the main contributors to the additional travel time of trips during PSDs. Additional delay may be attributed to the slower speed of the shuttle buses that replace the disrupted section of transit network. With the lack of information on measuring the actual delay, only information on additional travel time as perceived by the responses is collected. While around one quarter of the respondents (26%) perceived that it took them same time to complete their trip as it would take during normal CTrain service, the majority of the respondents (74%) reported that it took them more time than normal service. A wide spread of additional travel time as perceived by the respondents was noted, as shown in the *Figure 4.8*.

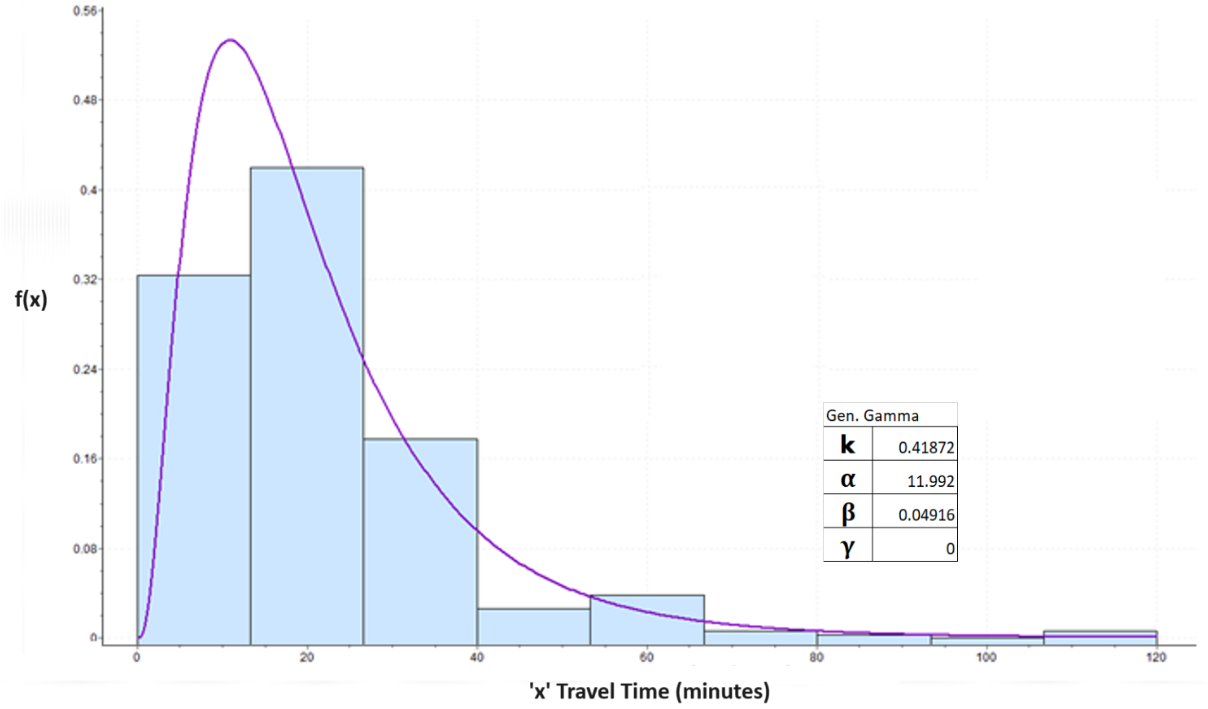


Figure 4.8: Distribution of additional travel time as perceived by the survey respondents of their LRT trip during short-term PSD.

Table 4.3 presents descriptive statistics of the additional travel time as perceived by the respondents. On average the respondents stated that it took 21 minutes on average additional to their trips on LRT during PSD. About one third of the respondents (31%) reported that it took them additional up to 10 minutes to complete their trip during PSD. It can be assumed that these would be the people who had to make one additional transfer during their trip on PSD. From rest of the participants 17% and 21% reported that they had to spent more than additional 20 minutes and 30 minutes, respectively on their LRT trip during a PSD. These would likely be the people who would have to make two transfers during their trip.

Table 4.3: Descriptive statistics of the participants perception about additional travel time during short-term PSD.

Statistics	Values
Minimum	0
Maximum	120 minutes
Mean	21.08 minutes
Std Deviation	15.75 minutes
Count	343

4.2.2.3 Perception about waiting and walking time at transfer stations

LRT stations usually have different layouts such as location and position of bus terminals, waiting areas and shuttle bus service stops. Some stations do not even have specified emergency shuttle bus service stops. Transit customers normally are not well familiar with the location of shuttle bus service stops and often face wayfinding challenges All the LRT stations are not provided with shuttle bus stops to be used in case of the disruptions. These stops could be easy to find at few LRT stations but may be far from the station building subject to transfer and require longer walk. Some stations are well designed with consideration of providing service during service disruptions, for customers convenience, and others are not.

In this study respondents were asked about their experience with finding the location of the shuttle bus stop at their transfer station. Respondents were also asked to state their perception of walking time from the transfer station to shuttle bus stop.

Figure 4.9 shows the respondents feedback about their experience with finding out the location of shuttle bus stops during short-term PSD. Only few of the respondents (13%) reported that it as difficult for them to find shuttle bus at the transfer CTrain station. Majority (87%) of the transit customers found it convenient and easy.

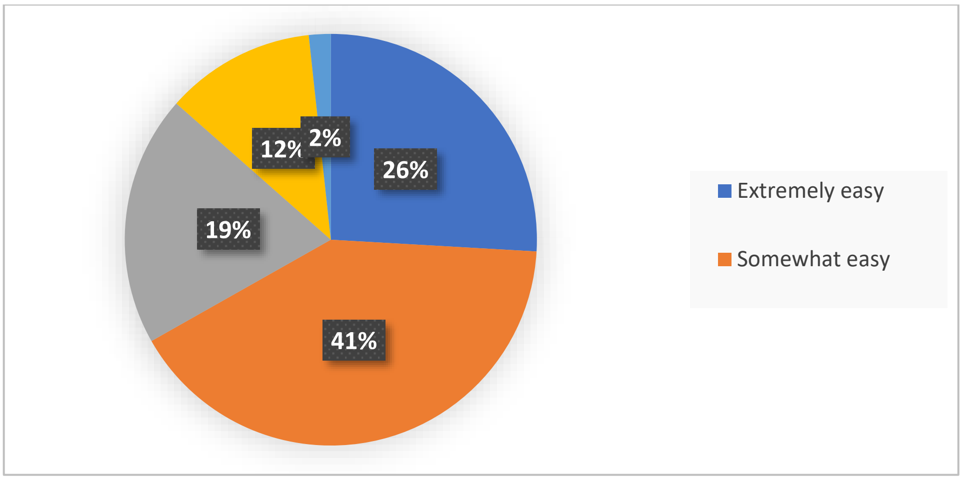


Figure 4.9: Transit customers convenience level in finding shuttle bus stop during short-term PSD

Figure 4.10 presents distribution of walking time as reported by respondents of this survey and *Table 4.4* summarizes descriptive statistics of the walking time data. Majority (72%) of the survey respondents reported that the shuttle bus was available right at the station, so they did not have to walk a long distance to access it. The rest 28% of the respondents reported that the shuttle bus was away from the CTrain station, and they had to walk longer to access the shuttle bus. The average walking time from the station to the shuttle bus stop, as stated by respondents (28%) of this survey, was just over 5 minutes. It took 1 to 2 minutes, 3 to 5 minutes, and 6 to 10 minutes to 31%, 45% and 12% of the respondents, respectively, to access the shuttle bus for the CTrain station out of 28% of the total survey respondents that thought that the shuttle bus stops far from the CTrain station.

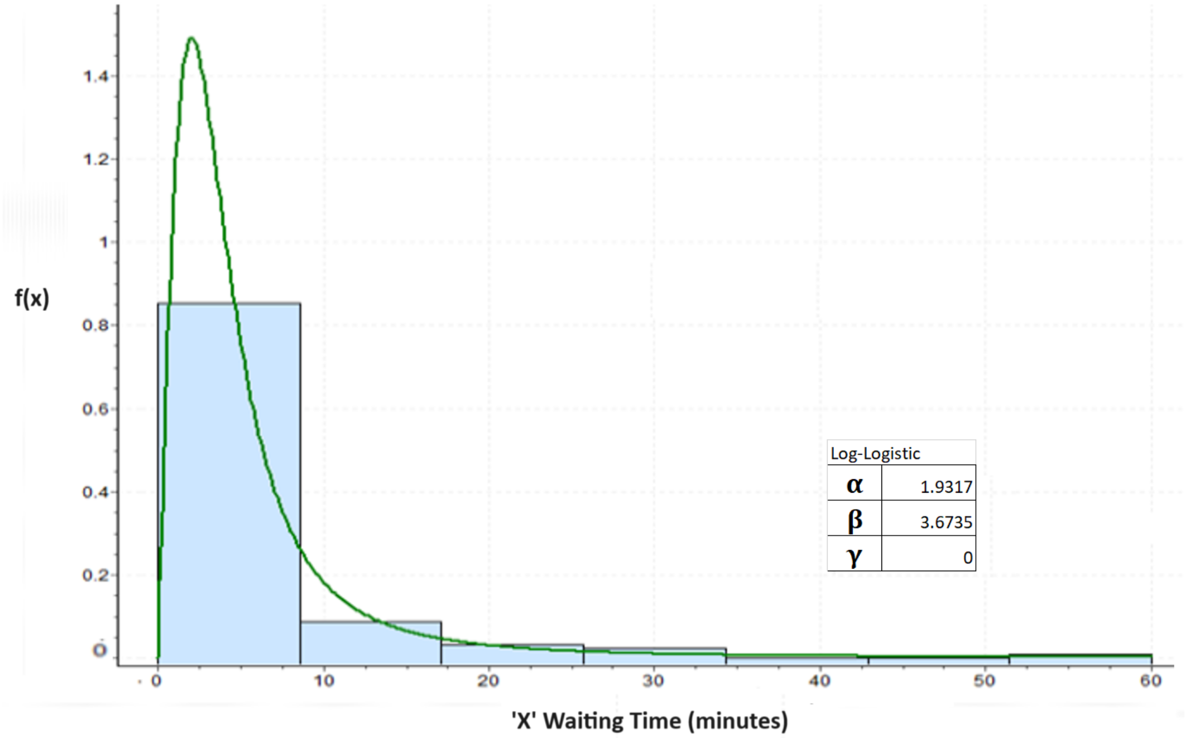


Figure 4.10: Distribution of walking time from Station to shuttle bus stop as reported by the survey respondents

Table 4.4: Descriptive statistics of the participants' perception about walking time to access the shuttle bus station on their trips during short-term PSD

Statistics	**Value** (minutes)
Minimum	0
Maximum	60
Mean	5.85
Mode	5
Std Deviation	7.46
Count	128

Analysis of wait time and walking time data indicates that the majority of the stations on the LRT network in Calgary are provided with bus stops at convenient locations near stations to facilitate transit customers during any emergencies and PSDs.

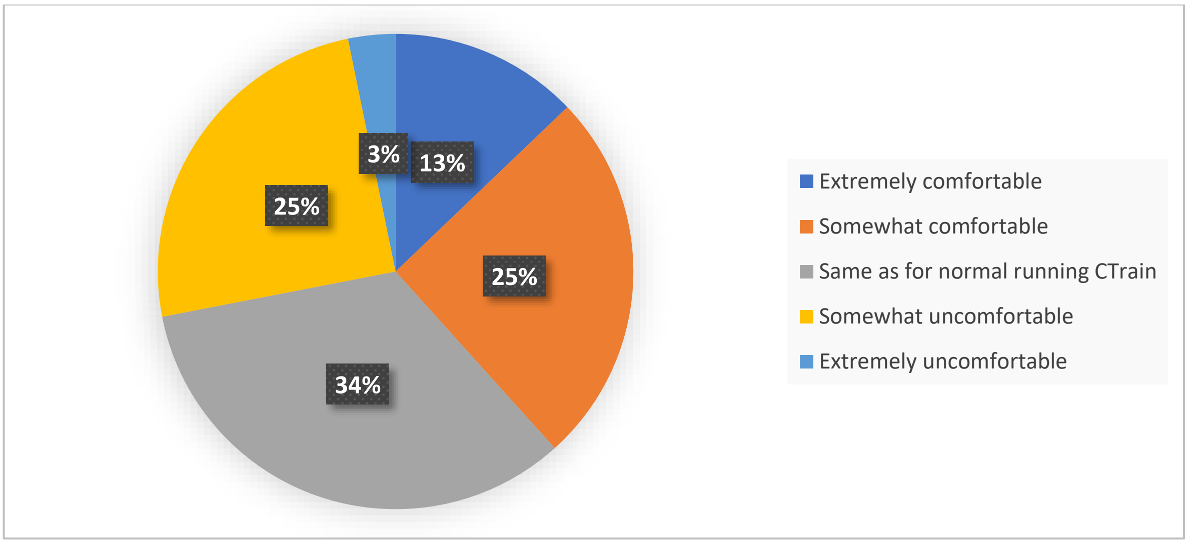


Figure 4.11: Transit customers' discomfort level while waiting for shuttle bus on trips during short-term PSD

The experience of waiting at CTrain station for shuttle bus service during short-term planned disrupted transit service is expected to differ than the normal service. Some passengers would not perceive the waiting for shuttle bus inconvenient because PSD only occurs during weekends, when most of passengers have flexible schedule and are already expecting that their this very trip will take longer than normal. Some of the passengers who have some appointments or work would perceive this waiting more inconvenient than the normal. *Figure 4.11* shows the discomfort level of respondents while waiting for shuttle bus during short-term PSD. Three fourth of the customers reported that waiting experience for the shuttle bus at the CTrain station during their trip on disrupted CTrain service was same as it was during a normal CTrain service (34%) or even better (34%). One fourth of the customers of the survey respondents reported that that had an uncomfortable waiting experience.

On weekends CTrain service frequency is 15 minutes. During the short-term LRT PSDs, the CTrain frequency is the same (15 minutes) and the service frequency of the Shuttle bus service along the disrupted CTrain section is kept the same at 15 minutes. Transit passengers arriving at the CTrain station from different direction (inbound and outbound) would experience different time for shuttle bus at the transfer station. As the shuttle bus may or may not be already present there. This additional transfer delay is separate from their weekend trip during uninterrupted service. The respondents were asked to state their perception of wait time at transfer station during short-term PSD as compared to their waiting experience while waiting for CTrain during uninterrupted transit service. The results are shown in *Figure 4.12*. About one-fourth of the respondents (26%) reported that they experience no difference in their waiting time, and the remaining 74% reported that their perceived waiting time was 1-10 minutes more than the normal transit service. This 74% is segmented as follows: a 14% reported 1-2 minutes; 30% reported 3-4 minutes and remaining 30% respondents' 5-10 minutes more perceived wait time than the normal service.

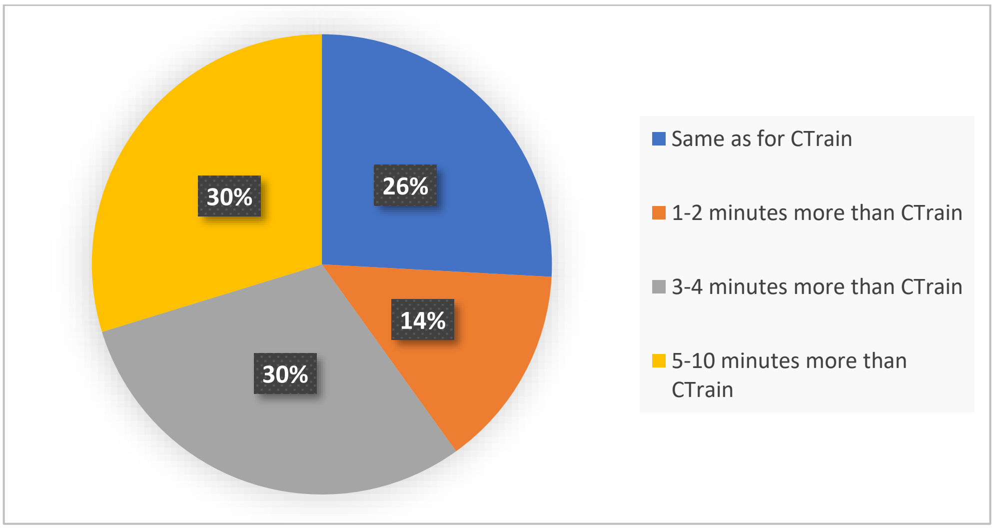


Figure 4.12: Perception of wait time at transfer station for shuttle bus during short-term PSD relative to normal CTrain service.

4.2.2.4 Additional trip cost during short-term PSD

Transit passengers may have to pay extra fare in case of PSDs. CTrain trip takes longer due to additional transfer from CTrain to shuttle bus and then back to CTrain, additional waiting time and walking time between the transfers. While commuters usually use monthly transit fare passes, occasional transit users use single ticket fare and Calgary Transit single fare Ticket is valid for 90 minutes from start of their trip on transit system. Most of weekend trips consist of shopping and personal nature trips that are relatively smaller portion of work-related trips.

Figure 4.13 shows the categories of passengers who paid regular transit or additional cost for their trip during a short-term PSD. Majority of the survey participants (80%) stated that have to pay additional cost to complete their trips during short-term PSD. These respondents are expected to be mainly regular passengers using monthly fare or those making shorter trips of duration less than 90 minutes. A smaller percentage of participants (12%) stated that they had to pay for additional single-fare tickets, which indicates that their trip took longer than 90 minutes due to short-term PSD. A very small percentage of participants (6%) had to use a taxi, ride-hail, or other paid transportation services (e.g., car2go). These passengers may consist of loyal and occasional transit customers who need to make important appointments on time where they cannot afford to be late. There is an opportunity to acknowledge the loyal transit customers and occasional customers who use the LRT service during PSD by offering free service during such CTrain short-term PSDs.

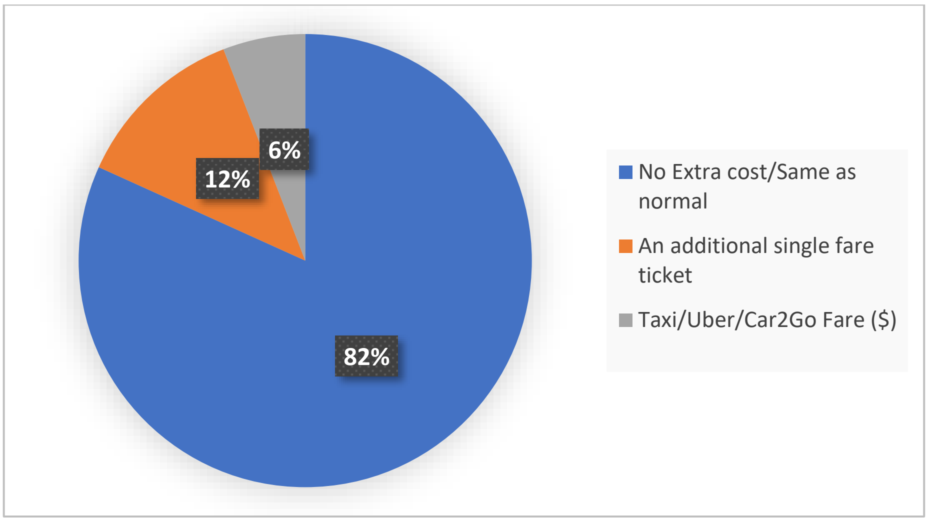


Figure 4.13: Trip cost to transit customers paid during short-term PSD

4.2.2.5 Transit Customers’ satisfaction level during PSDs

Figure 4.14 presents transit customers' satisfaction levels with the current arrangements provided by Calgary Transit during short-term PSD. More than half of the respondents (61%) were either extremely satisfied or somewhat satisfied. About one-quarter (21%) of the participants had a neutral response to this question. These passengers would be mindful of the importance of these routine LRT maintenance and, so, would be mainly concerned about reaching their destination, and not by the inconvenience (extra walking, waiting and number of transfers) and additional travel time caused by the disrupted service. Less than a quarter of the participants (17%) were either somewhat or extremely dissatisfied with the shuttle bus service provided during the short-term PSDs. This could be based on their experience of a certain day or overall based on extended experience. There can be many possible reasons for their low satisfaction level. Such as if someone was not aware that PSD was occurring during their trip or if they had been going to an important appointment and then it took longer than expected. This results in lowered satisfaction with the shuttle bus service offered during short-term PSDs.

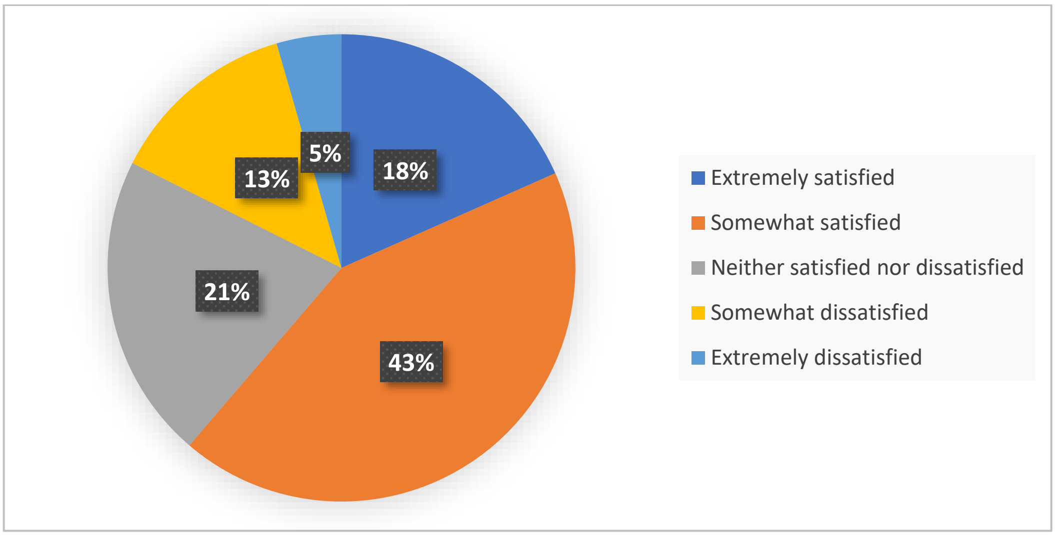


Figure 4.14: Transit customers’ satisfaction level with the current arrangements provided by Calgary Transit during short-term PSD.

4.2.2.6 Preferences for their future trips during short-term PSD

People learn from experience, and based on that learning, they make future decisions. They tend to avoid choosing if they had a bad experience with the choice in past and vice versa. When the survey participants were asked if they would use the CTrain in future as well as during short-term PSDs. Most of the participants (70%) stated that they would continue to use CTrain during the short-term PSDs, and the rest (30%) would not use it (*Figure 4.15*). This analysis indicates that arrangements made during the short-term PSDs to maintain a certain level of service are not substandard. Transit customers expect inconvenience and longer travel time in advance and acknowledge efforts put in by Calgary Transit to provide the best customer service given the conditions and available resources. For others, the longer travel time does not fit into their schedule due to the urgent nature of the trip, or the expected inconvenience can be the reason for people with health issues or physical disability.

Transit passengers' travel experience on CTrain during a PSD can be good or bad, depending on their situation. Based on their current and previous experience, they decide whether they would use the CTrain service in future in case of PSD. Transit passengers usually have access to more than one travel mode. There would be a very small percentage of people who would only have access to Transit mode and have to use transit during transit during these short-term PSDs.

In this study, participants were asked that next time, if they were aware that a CTrain short-term PSD was happening, then which mode would they use alternate to CTrain? The survey respondents’ choices are summarized in *Figure 4.15*. More than half of the participants (54%) stated that they would use the transit bus route. These passengers most probably would possess monthly transit fares, so it would be convenient for them to use the bus route instead to make good value of their monthly pass. About 17% of the participants stated that they would use a personal car next time during CTrain short-term PSD. Certainly, these people would have access to a personal car and would prefer to save on travel time. They may not possess monthly transit passes, and it would not cost them much (car insurance and ownership costs are already being paid) to use a personal car for their trip on weekends. About 12% of the participants would choose the option of using a CTrain with taxi/ride-hail service (7%) and bike/walk (5%) along the CTrain disrupted section. These people would possess monthly transit fare passes but wanted to save time by using taxis/ride-hail or bikes, which they would have to lose while waiting and travelling on shuttle bus service. Only a few transit customers (8%) would consider cancelling their trip, which probably is avoidable.

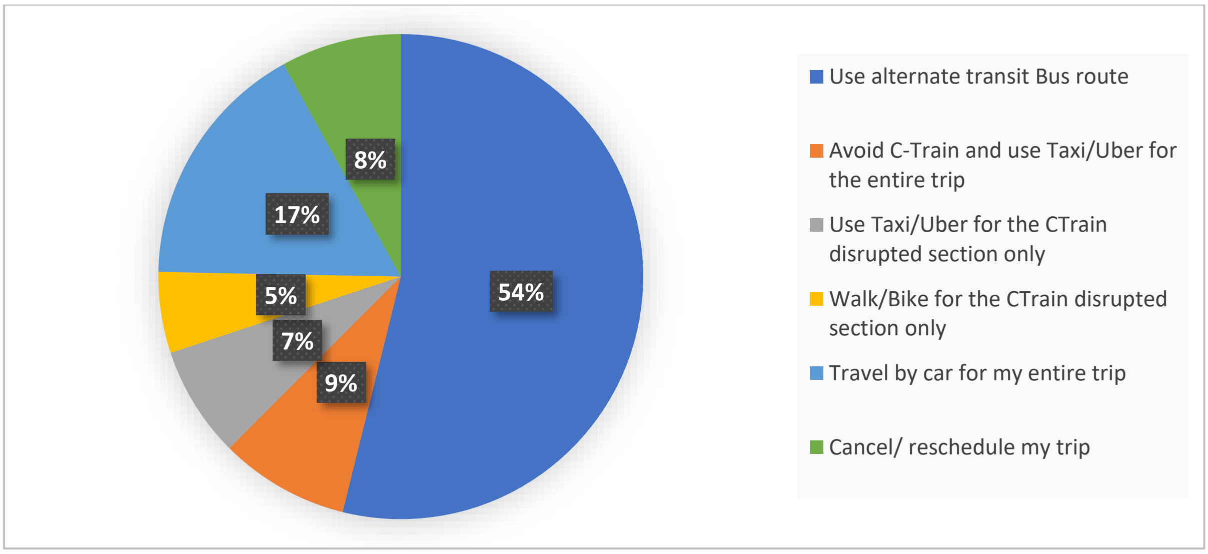


Figure 4.15: Respondents' preferred Trip cost to transit customers paid during short-term PSD

Analysis of this response suggests that customers who possess monthly transit fare passes would keep using transit (bus mode) and, saving time along the disrupted section, will consider using modes (taxi, ride-hail, bike and walk) alternate between shuttling bus service.

4.2.2.7 Suggestions for improving customers' travel experience

Survey participants were asked for suggestions that can contribute to improving their travel experience during the short-term CTrain PSDs. Most of the participants (27%) chose the option of increasing the frequency of the shuttle bus service along the disrupted section, 15% of participants suggested moving the shuttle bus stops closer to the CTrain stations, and 9%

suggested providing direct shuttles from one end to the other end of the CTrain disrupted section that does not stop on the intermediate CTrain stations to save waiting time, walking time and riding time, respectively. A few participants (11%) also suggested providing larger-size buses, so passengers do not have to wait for the next bus in case ridership is high. Some participants also suggested that bus priority measures should be provided along the route of the shuttle bus service to save some travel time.

Some participants (17%) suggested that Calgary Transit should offer free ride on CTrain during these events. These would be occasional or weekend-only transit users who use single tickets as a monthly transit fare pass, which would not be worth it for them. A few participants suggested subsidizing the ride-hail, bike, or scooter modes along the disrupted section of CTrain. These transit users are the ones who use CTrain regularly and would use monthly transit fare passes. All these suggestions, if adopted, would no doubt attract more ridership and retain the current ridership but may cost more to transit agencies; hence, they may not be feasible.

4.3 SP survey experiment design

In this stated preference survey, a hypothetical scenario was presented, which consists of a general-purpose trip on a pleasant weekend in Fall/Summer during a short-term PSD on the Calgary LRT’s Red line between two stations about 4.5 km apart. In the scenario, a shuttle bus service is provided to bridge the gap between the disrupted sections.

Participants were given a situation in which they were travelling from Canyon Meadows SE to Banff Tr NW community. They were already aware that the LRT service was disrupted, and a Shuttle bus service was provided between Victoria Stampede Station and Sunnyside Station. LRT was their preferred choice during normal LRT service. For this very trip if they choose to take shuttle bus along the disrupted section of the Red line during their trip then they will have to transfer onto the shuttle bus at Victoria Stampede station and transfer from the shuttle onto C-Train at Sunnyside station and get off at your destination (Banff Tr NW). *Figure 4.16* shows the route provided in the hypothetical trip and the disrupted section along the LRT line in Calgary.

The following modes were available to the survey respondents to choose from:

- LRT with the following connecting modes along the short-term closed section between Canyon Meadows and Banff Tr stations:
    - Many to many shuttle bus service that stops at all four intermediate LRT stations along the closed LRT section, with normal headway (10 minutes/trip).
    - One-to-one shuttle bus service that runs from one end station to the other end station along the disrupted LRT section at a larger headway (15 minutes/trip)
    - Car sharing service (car2go) to travel through the LRT disrupted section.
- Regular bus route from origin (Canyon Meadows SE) to destination (Banff Trail)
- Personal car from origin to destination
- Taxi or Uber from origin to destination
- No trip/Trip cancellation

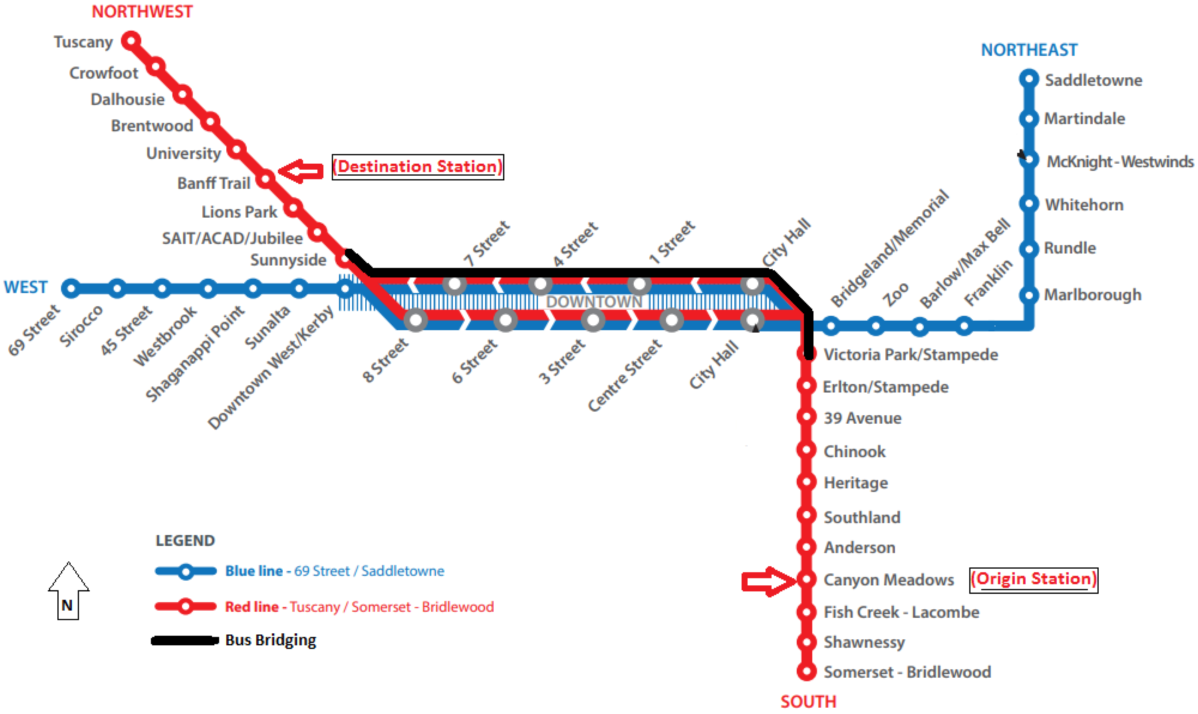


Figure 4.16: LRT route and disrupted section along the LRT line, provided as a hypothetical scenario. (Source: Calgarytransit.com)

4.3.1 Experimental design

Each alternative included in the SP design was described with various attributes. Each attribute had different possible levels, as shown in *Table 4.5*. The cost of all modes was fixed except carsharing, which adds costs if participants use it along the disrupted section of the LRT. Two cost levels exist for the carsharing mode, as the cost may vary with the time of day and demand. In-vehicle and in-LRT travel time attributes were defined with two levels each to consider travel time unreliability due to traffic congestion on roads and variability due to station dwell time at different times of the day. Wait time at transfer stations was defined by three levels for LRT alternatives and by two levels for transit bus alternatives. As the same fixed transit route is presented to all the survey participants, a single level for the number of transfers (from LRT to Shuttle bus and from Shuttle to LRT) was used.

Table 4.5: Alternatives, attributes and levels considered in the SP survey.

Alternatives		Attributes & Levels					
		Fare/ Cost ($)	**Number of Transfers**	**Access Time (minutes)**	**In-Vehicle Travel Time (minutes)**	**LRT Travel Time (minutes)**	**Wait Time at Transfer Station (minutes)**
Disrupted LRT Service	Regular Shuttle: stopping at intermediate stations (10 minutes headway)	$3.4	2	10, 15	15, 20	20, 25	0, 5, 10
	Express Shuttle: Non-stop shuttle, end to end (15 minutes headway)	$3.4	2	10, 15	10, 15	20, 25	0, 7.5, 15
	Subsidized Carsharing along the disrupted section of the LRT line	0.32 $/min, 0.42 $/min	2	10, 15	10, 15	20, 25	0
Alternate Transit Bus Route		$3.4	3	3, 5	50, 60	-	10, 15
Personnel Car (fuel + parking) (24 km)		$8	0	2	25, 30	-	0

Taxi/Uber (24 km trip distance)	$30, $40	0	1	25, 30	-	0
Trip Cancellation	-	-	-	-	-	-

The purpose of the experiment is to determine the independent influence of different variables (attributes or factors depending) on some observed outcome.

The attributes of every alternative considered in this study had different levels. Multiple choice situations were created using different levels of attributes for given alternatives. There are two methods of generating choice situations: Full factorial and Partial factorial. Full factorial considers all possible choice situations (i.e., a combination of attribute levels) to see all possible effects; thus, it is not practical for this study due to many alternatives, their attributes, and levels. In the partial factorial method of choice situation design, some of the choice situations are chosen and included in the SP questionnaire survey. There are three types of partial factorial designs used in studies: Random, Orthogonal and Efficient.

- In random design, as obvious from its name, choice situations are picked from the set of full factorial design, This is not the best design and may cause biases in the model estimate. On the other hand, Orthogonal and Efficient designs systematically aim to balance different levels of choice situations to avoid bias.
- Orthogonal design aims to minimize the correlation between the attribute levels of alternatives in the choice situations (but not necessarily between alternatives) by minimizing variances of parameter estimates and, hence, maximizes the power of the design to detect statistically significant relationships. This design has limitations and cannot avoid choice situations in which a certain alternative is clearly preferred over the others.

- Efficient design, instead of considering the correlation between attribute levels, aims to generate choice situations such that the estimated parameters have as small as possible standard errors. The standard errors are predicted by determining the Asymptotic Variance Covariance (AVC) matrix (square root of diagonal values of this matrix are standard errors); prior information on the attributes is needed to determine the AVC matrix. Prior information on the parameters is required for this design method, which can be assigned based on the researcher’s experience, past similar studies or estimated by conducting a pilot survey.

Based on the literature, an efficient experiment design is better than the orthogonal design as it attempts to generate choice situations that minimize standard errors of the parameters (i.e.., improve the reliability of the parameters estimate at a fixed same size or reduce sample size for a fixed level of reliability in the parameters estimates). (Ngene 2018)

Bayesian Efficient design was used to generate choice situations with various combinations of the parameter levels using Ngene software (Ngene 2018). *Ngene* is software for generating experimental designs that are used in stated choice experiments for the purpose of estimating choice models, particularly of the logit type. Bayesian efficient design generates a range of potential values for parameter estimation and is used when no prior information on parameter values is available. For this study, a uniform distribution with assumed lower and upper bounds and an intuitive sign was used for the parameter priors. Walker (Walker et al. 2018) found that with some confidence in the priors being used, standard efficient design may perform better than random factorial design. As a result, they recommend utilizing a Bayesian efficient approach to survey design. The input and output of the Ngene model are provided in Appendix A1.

The following three choice contexts were developed as the survey respondents may or may not possess driver's licences and/or have access to personal cars.

- Choice context-1 was presented to the participants who did not possess a valid driver's licence, so they could not use the personal driving and carsharing alternatives.
- Choice context-2 was presented to the participants who possessed a driver's licence but did not have access to a personal vehicle for this trip, so they could not use the personal vehicle alternative. However, they could still use the carshare option.
- Choice context-3 was developed for the participants who possessed a driver's licence and had access to a personal vehicle, so they had all the modal options available to them.

Twenty-four (24) choice scenarios were generated for each choice context, which was then divided into four (4) blocks of 6 choice scenarios each. The survey was designed using the Qualtrics online survey platform. Qualtrics was set up to randomly (with an equal chance for each choice scenario) pick six choice scenarios out of 24 for participants based on their choice context. For every choice scenario, the survey respondents were asked about their confidence level in making that choice. A sample of choice situations of each scenario used in this study is provided in Appendix A3.

4.3.2 Data Collection

A convenience sampling method of data collection was used. Census data and household travel survey data are not exclusive to weekday and weekend trips. However, our sample frame was not the general population of Calgary but instead only individuals who have experienced this type of short-term PSDs in the past. This suggests that although our choice-based sample is not representative of the general populace, it is much harder to ascertain the representativeness of the sample for our recruitment criteria.

The survey invitation cards (see Appendix A) that contain the weblink to the online questionnaire were distributed to LRT users at the impacted LRT stations during all short-term LRT PSDs that occurred on weekends from September 7th to October 26th, 2019. Also, the survey invitation was distributed electronically. Only the participants who used the LRT service during a short-term planned disruption in the past were recruited for this survey. Participants provided informed consent to participate in the study, which the Research Ethics Board approved at the University of Calgary. Approximate time to fill in the web-based survey was about 15-20 minutes.

4.3.3 Data description

Nine hundred twenty-six individuals (926) aged 15 years and above participated in this survey (the minimum age required for working in Alberta is 14 years). *Table 4.6* presents descriptive statistics of the data and is summarized as follows:

- The majority (67%) of the participants were between 18 and 34 years. 51% of participants were female and 44% were male.
- Majority of the survey participants were full-time employed (28.5%) and post-secondary students (28%), followed by part-time employees (16.5%).
- A wide range of participants' annual household income was recorded from under $30,000 to above $150,000. A majority (31.8%) of the participants fall under $30,000, and about 38.5% of the participants did not report their income.
- 64.2% and 20% of the participants possessed valid driving licences and had access to a personal vehicle, respectively.
- About 50% of the participants had access to the transit bus route, 11.7% had access to a taxi or Uber, and 5.2% had access to Car2Go and carpooling, each as an alternative to LRT for their trip during short-term LRT PSD.

- Monthly passes (39.2%) and student passes (35.8%) were the transit fare types used by most of the participants of this study, followed by single fare tickets (15%). Other fare payment types used by the respondents include day pass (4%), senior pass (2.3%), Calgary Transit staff (2.3%) and junior monthly pass (1.2%).
- A majority (95%) of the participants possessed smartphone.
- 631 out of the total participants (926) completed the SP part of the survey, but a total of 3522 observations were recorded. This is because few survey participants did not respond to all six choice situations.

Table 4.6: Sample Description Statistics

Variable	**Value**	**Sample Size**	**Sample Percentage**	**Population Percentage**	**Transit Passengers Composition**
Gender	Male	277	44.18%	49.88%	57.1%
	Female	317	50.56%	50.01%	42.9%
	Prefer not to answer	33	5.30%		
Age	Under 18	52	8.02%	5.63%	
	18 – 24	244	37.65%	6.35%	14.5%
	25 – 34	190	29.32%	16.91%	31.1%
	35 – 44	83	12.81%	15.64%	22.6%
	45 – 54	38	5.86%	14.10%	17.6%
	55 – 64	17	2.62%	11.89%	10.2%
	65 and over	12	1.90%	11.17%	3.9%
	Prefer not to answer	12	1.90%		

Employment Status	Employed – Full time	204	31.40%		50.6%
	Employed – Part-time	107	16.50%		12.8%
	High school student	46	7.10%	25.00%	2.8%
	Post-secondary student	183	28.20%		5.8%
	Student (Other)	43	6.60%		2.8%
	Retired	12	1.90%		4.6%
	Homemaker	12	1.90%		2.0%
	Unemployed	21	3.20%		8.4%
	Prefer not to answer	22	3.40%		
Access to mode	Transit bus route	520	49.70%	15.80%	64.3%
	Personal car	209	20.00%	71.10%	
	Bike	87	8.30%	1.60%	
	Carsharing	55	5.30%		
	Carpooling	54	5.20%	5.14%	
	Taxi/Uber	122	11.70%		
Driving licence holder	Yes	427	64.20%		
	No	238	35.80%		
Annual Household Income	Less than $30,000	203	31.80%	7.29%	
	30,000- 69,000	94	14.70%	15.68%	

	60,000 - 150,000	82	12.80%	58.52%	
	Over 150,000	14	2.20%	18.52%	
	Prefer not to answer	246	38.50%		
Transit Fare Type used	Monthly pass	269	41.50%		21.7%
	Seniors Annual pass	15	2.30%		0.5%
	Student pass	232	35.80%		8.3%
	Junior monthly pass	8	1.20%		
	Day Pass	27	4.20%		
	Single fare tickets	97	15.00%		27.3%
Frequency of Transit use	All Week	364	51.10%		
	Frequent (weekdays only)	136	19.10%		
	Frequent (weekends only)	47	6.60%		
	Infrequently (weekdays only)	37	5.20%		
	Infrequently (weekends only)	48	6.70%		
	Occasionally	81	11.40%		

Note:

1- Transit Passengers composition is based on the 2023 annual survey conducted by Calgary Transit.

2- Calgary Population data was used from 2016 Calgary census.

4.3.4 Market Share Analysis

The survey participants choose from the given alternatives based on their characteristics. Aggregate market share of choosing alternatives, i.e., the weighted percentage of each mode being chosen is used to determine the utility of an alternative. Equation (4.1) represents the sum of probabilities of choosing alternative 'i' by all the participants, and Equation (4.2) is used to calculate the aggregated choice probability of alternative '*i.*'

$$N_T(i) = \sum_{n=1}^{N_T} P_n\left({}^{i}\!/_{x_n}\,; \theta\right) \qquad \text{---------} \; (4.1)$$

$$W(i) = 1/N_T \sum_{n=1}^{N_T} P_n\left({}^{i}\!/_{x_n}\,; \theta\right) \; = \; E\,[P\left({}^{i}\!/_{x_n}\,; \theta\right)] \quad \text{---------} \; (4.2)$$

Figure 4.17 presents the market share of all modes presented to the survey participants to choose from in various choice situations. In terms of market shares, transit modes were the top three most chosen (76%). More than half of the respondents (63%) chose not to switch from the CTrain, most of which chose the express shuttle bus (30%), followed by regular shuttle bus (27%), and then followed by carsharing (6%) along the disrupted section of the CTrain line. About 13% of the respondents chose the alternative bus route. Only 7% and 6% of the respondents chose to drive and use a taxi or Uber, respectively. About 9% of respondents chose to cancel or reschedule their trip.

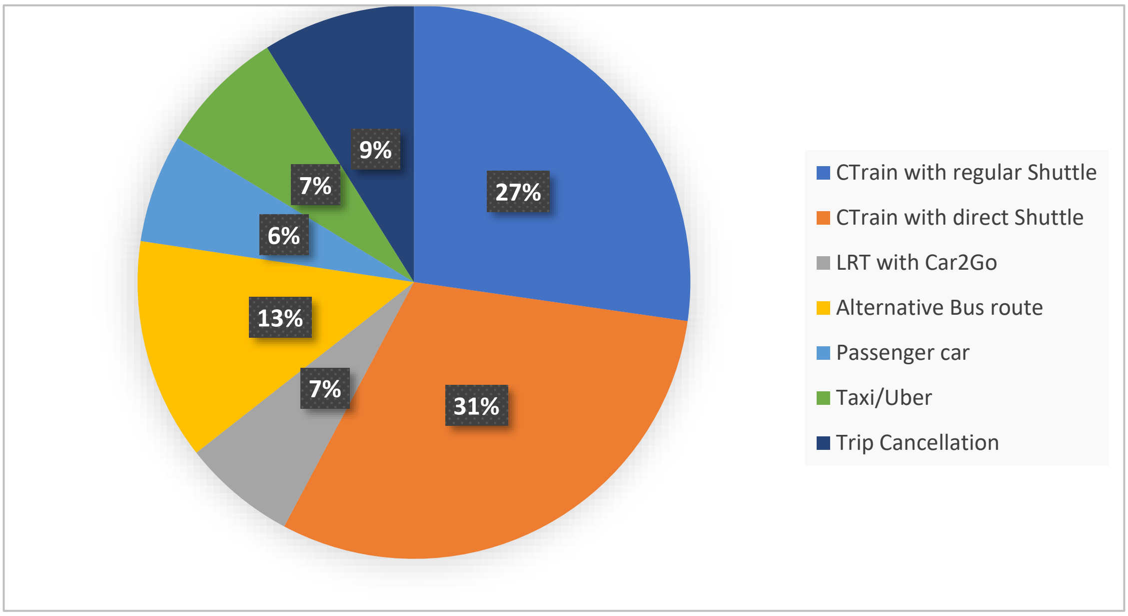


Figure 4.17: Market share of the population choosing among the alternatives.

As choice situations were assigned to participants based on their driving licence possession and access to a personal vehicle, so not all the travel modes were available to all the participants. The choice situation with Car2Go was provided only to driving licence-holding customers and

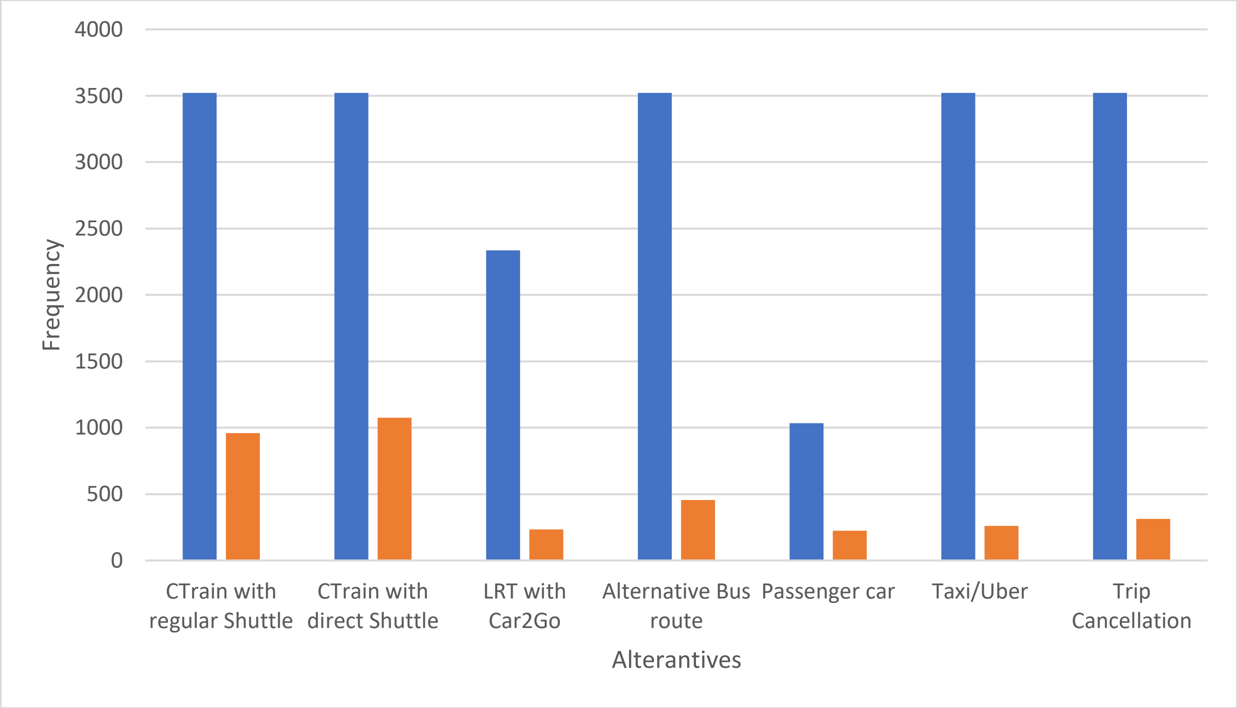


Figure 4.18: Mode choices made by the respondents as compared to the availability of travel modes in the choice situations.

Choice situation with passenger car option were given to the respondents who have access to personnel car. *Figure 18* Mode choices made by the respondents as compared to the availability of travel modes in the choice situations.

One of the limitations of the SP survey is that the respondents might make a different choice in real life than they would do in the SP survey. That is why, at the end of each choice situation, they were asked how confident they were about choice. This tells that how likely the customers will make the same choice in real life. *Figure 4.19* shows the confidence level of the respondents in the SP part of this survey. 85% of the respondents were extremely (44%) or moderately (41%) confident in choosing their preferred alternative in the survey.

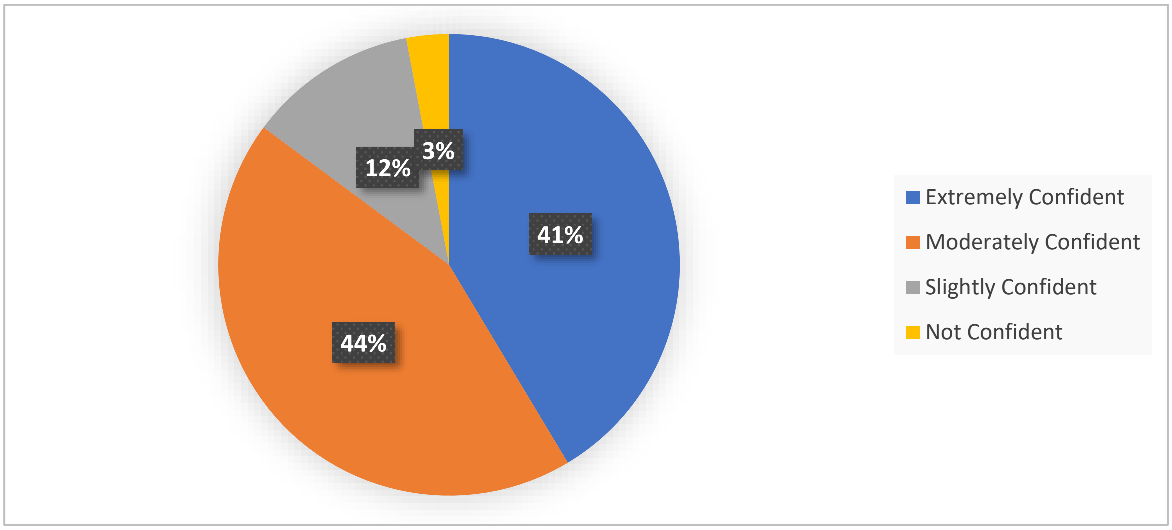


Figure 4.19: Distribution of respondents' confidence level in choosing their preferred alternatives.

The following insights can be drawn from the market share analysis:

- Respondents' choices among the available alternatives indicate that transit ridership drops by about 22% during a planned short-term service disruption. 41% of the lost ridership (22%) would cancel or reschedule their trip, 32% would use the personal vehicle, and 27% would use a Taxi or Uber.

- The results of this analysis also show that CTrain ridership would drop by about 35% during short-term planned disruption. With the introduction of a direct shuttle route, which transfers CTrain customers from one end of the disrupted line to the other, car2Go would attract more than about half (58%) of the CTrain users. So, the majority (48%) of CTrain users would prefer to take direct shuttle bus service, about 11% would try Car2Go to save wait time and willing to pay extra, and only 41% would keep using the regular shuttle along the disruption section of CTrain line. This mode choice difference among the CTrain users could be because of their perception of the value of time. The CTrain users who value time the most would prefer not to wait for the next shuttle bus and consider talking to Car2Go in case the direct shuttle bus is not available soon. The direct shuttle bus would be CTrain users' first preference as it takes the least travel time and does not cost any additional fare. CTrain users would take the regular shuttle bus only if it is already available and the next direct shuttle is coming late.

4.3.5 Choice Modelling

In discrete mode choice problems, decision-makers presented with all feasible alternatives are assumed to choose the alternative that maximizes their individual utility. Utility is an indicator of the value of an alternative to a decision-maker. The utility function consists of an individual's characteristics and attributes of feasible alternatives. Equation 4.3 shows the utility of alternative "j" to a decision maker "i". It consists of an observed/systematic portion of the utility "V_{ij}" and an unobserved/error portion of the utility "ε_{ij}". For estimation of the discrete empirical model, the systematic portion is represented with coefficients "β" and variable "X".

$$\mathbf{U_{ij} = V_{ij} + \varepsilon_{ij}} \qquad (4.3)$$

$$\text{»} \quad \mathbf{U_{ij} = \beta_j X_{ij} + \varepsilon_{ij}}$$

The random error term “ε_{ij}” is assumed to follow a Gumbel distribution and leads to the formulation of the multinomial logit (MNL) choice model, as shown in equation 4.4. The probability of choosing mode “j” out of a total number of available modes “K” is given as a function of the total systematic utility “V_{ij}” of all available modes.

$$\boldsymbol{P}_{(\mathbf{ij})} = \frac{\mathrm{e}^{v_{\mathbf{ij}}}}{\sum_{k=1}^{K} \mathrm{e}^{v_{\mathbf{i}k}}} \qquad (4.4)$$

The Multinomial Logit (MNL) model is built on the assumption of preference homogeneity, simplifying the nuanced variations in how different members of the population perceive modal attributes. In reality, individuals have diverse preferences. To account for this heterogeneity, the Random Parameter Mixed Logit (RPML) formulation is employed. In RPML, the "β" coefficients are not fixed but take the form of a distribution (normal, log-normal, uniform, etc.), capturing preference variations within the population (Bierlaire, M., 2009). The MNL model, holding the Independence of Irrelevant Alternatives (i.i.a) property, can be extended to RPML models to estimate coefficients based on different categories of decision makers, thereby relaxing the IIA property.

For this discrete choice problem Nested a Multinomial Logit (NMNL) could also be used to relax the IIA assumption of MNL model, by grouping alternative into four nests, namely: 1) LRT-based (i.e. LRT with regular shuttle bus route, LRT with express shuttle bus route, and LRT with Car2Go), 2) bus-based, 3) passengers car (i.e. taxi, private auto or car2go) and 4) other (e.g. cancelling or rescheduling the trip). However, NMNL model provides a single average value for the various parameters of the model. The analysis revealed an absence of correlation among the LRT alternatives, evidenced by the nesting coefficient (or homogeneity parameter) of the LRT nest, which was determined to be exactly one (1) in the output. The nesting coefficient, also called Logsum parameter, indicates the degree of dissimilarity between pairs of alternatives within the nest. In BIOGEME 1.8 modelling software, this dissimilarity coefficient is served as homogeneity parameter. Value one (1) of homogeneity parameter in the model estimates indicates that the alternatives in a nest are entirely uncorrelated. Hence, the RPML model was selected for parameter estimation due to its adeptness in capturing the nuanced variations in preferences observed among individuals engaged in the SP experiment.

In the RPML model we assumed a normally distributed travel cost parameter. The coefficients β in the above utility function (Equation 4.4) can be written as normal distribution with mean β_o and deviations μ as shown in Equation 4.5.

$$U_{ij} = \alpha x_{ij} + \mu_i x_{ij} + \varepsilon_{ij} \quad (4.5)$$

$$» \qquad U_{ij} = \beta(\beta_o, \mu_i) X_{ij} + \varepsilon_{ij}$$

4.3.5.1 Empirical model specifications

The random parameter mixed logit (RPML) model was estimated using BIOGEME 1.8 (Bierlaire 2009) with 631 participants' observations. All alternative specific and potential explanatory variables were tested for significance at a 95% confidence interval. A subset of feasible alternatives includes CTrain with the regular shuttle, express shuttle and Car2Go for along the disrupted section, alternative bus route, taxi, or Uber, driving and trip cancellation. All potential explanatory variables, alternative specific constants, travel time, travel cost and socioeconomic, were tested for significance. Travel time and travel cost represent mode-related attributes; assuming all other parameters are constant, the faster modes are more likely to be chosen than slower modes, and less expensive modes are more likely to be chosen than more expensive modes. Household income, gender, age, occupation, and type of fare payment were used to represent decision makers' attributes in the model. It is expected that decision-makers with high income are more likely to choose to drive or use the taxi/uber option than to use other available travel modes.

Travel time and travel cost were specified as generic variables in the model, assuming an increase of one unit of travel time or travel cost has the same impact on model utility for all modes included in this model. Socioeconomics is specified as alternative-specific variables in the model. CTrain with regular shuttle bus service was specified as the base/reference alternative for alternative specific constants (ASC). The final estimated model includes a combination of significant variables and provides important insight into the travel mode choice behaviour. , In the random parameter mixed MNL, the travel cost parameter was assumed as a normally distributed parameter,

4.3.5.2 Empirical model estimation:

Table 4.7 presents the final empirical model estimates. As anticipated, the parameters associated with travel time, wait time, and travel cost negatively influence mode choice utility. Notably, the coefficient for wait time during travel (-0.0221, t-stat: -5.08) was observed to be slightly greater than that for in-vehicle travel time (-0.02, t-stat: -6.65). Although the coefficients for wait time (out-of-vehicle travel time) and in-vehicle travel time are closely aligned, the results of the t-test indicate no statistically significant difference between these two parameters at a 95% confidence level. However, combining these two parameters into a unified travel time variable in the model yields an estimated value of -0.199 with a t-statistic of -7.42. It is widely acknowledged that wait time should be distinct from in-vehicle travel time as reported in the literature which underscore the greater value placed on wait time (out-of-vehicle) compared to in-vehicle travel time (Eccarius et al., 2020; Hossain et al., 2014). Therefore, to adhere to established literature, wait time and in-vehicle travel time were retained as separate parameters. Furthermore, the estimated cost parameter follows a normal distribution (mean: -0.102, Std. deviation: 0.0743).

Table 4.7: SP MNL estimated model

Variables		**Values**	
# of Observations		3522	
# of Respondents		631	
Null log-likelihood		-6254	
Final log-likelihood		-5418	
Likelihood ratio test		1671	
Adjusted rho-square		0.128	
Name	**Mode**	**Parameter**	**t-Statistics**
Mode Constant			
Mode Specific Constant	LRT (Regular Shuttle)	-	-
Mode Specific Constant	LRT (Express Shuttle)	-0.111	-0.62
Mode Specific Constant	LRT (Car2Go)	-1.65	-6.46
Mode Specific Constant	Bus	-0.0577	-0.3
Mode Specific Constant	Drive	3.0	4.77
Mode Specific Constant	Taxi/Uber	0.351	0.66
Mode Specific Constant	Cancel Trip	-2.11	-8.11
Travel Time & Cost			
Travel Cost (Mean in case of random)	All	-0.102	-5.94
Travel Cost (Std deviation)	All	-0.0743	-13.44
Travel Time (excluding wait time)	All	-0.02	-6.65
Wait Time at transfer station	All	-0.0221	-5.08
Gender			
Males against female	Bus	-0.333	-3.08

Males are tested against female	Drive	-0.710	-2.67
Males are tested against female	Taxi/Uber	-0.646	-2.34
Males are tested against female	Cancel Trip	-0.644	-4.79
Age			
25 - 44 years	Drive	0.789	3.13
Income			
$40 - $150K	Bus	-0.416	-3.08
$40 - $150K	Cancel trip	-2.540	-3.48
Above $150 K	LRT (Regular Shuttle)	-1.640	-2.44
Above $150K	LRT with Car2Go	-1.820	-2.48
Above $150K	Bus	-2.590	-3.31
Above $150K	Cancel Trip	-1.660	-2.09
Occupation			
Student	LRT (Regular Shuttle)	-0.608	-4.18
Student	LRT (Express Shuttle)	-0.339	-2.35
Fare Type			
Single ticket fare	Drive	-2.490	-4.56
Monthly Fare pass (Student, senior, Junior, employee, etc.)	LRT (Regular Shuttle)	0.841	6.15
	LRT (Express Shuttle)	0.717	5.53
	LRT (Car2Go)	0.657	3.3
	Drive	-1.470	-2.99
Frequency of LRT use			
Frequent on Weekends	LRT (Regular Shuttle)	0.0263	0.87
	LRT (Express Shuttle)	0.0861	2.99

	LRT (Car2Go)	0.1490	4.1
	Bus	0.0727	2.25

4.3.5.3 Choice Model Interpretation

The influence of parameters on customers' mode choice behaviour is discussed in this section.

4.3.5.2.1 Value of travel time

The estimated value of wait time and in-vehicle travel time (i.e., total trip travel time excluding wait time at transfer station/stops) was found to be $13.00/hr and $11.76/hr, respectively. This was determined by taking a ratio of in-vehicle wait time and the estimated average travel cost coefficient. This indicates that LRT users value their wait time 11% more than in-vehicle travel time during a short-term PSD. The value of time estimated in this study is lower than Calgary's average daily wages (i.e., $30.13 in 2017 as per www.openalberta.ca). This is justified by the fact that travellers will often make non-work-related trips on weekends and thus attribute a lower value of time for such non-utilitarian trips. In addition, LRT customers are assumed to be aware of upcoming PSDs and accordingly expect a longer travel time than usual.

4.3.5.2.2 Gender

People of different genders exhibit different choice behaviours. Compared to female respondents, male respondents were found to be more inclined to experience inertia with respect to LRT alternatives during a short-term LRT PSD. This finding suggests that women are more likely to avoid longer than normal travel time, thereby cancelling or rescheduling their trips during the short-term LRT PSDs. We attribute this outcome to women's multiple commitments such as household duties, childcare and taking care of their elderly, pressuring them to place more emphasis on decreasing delays.

4.3.5.2.3 Age

In this choice model, participants of different age groups were tested separately for each alternative. The only significant effect was a positive impact on the driving utility of young people (25 – 44 years) as compared to other age groups. In our opinion this is because young people (25 – 44 years) like driving and find higher utility/happiness in driving, even if it comes with a higher cost.

4.3.5.2.4 Income

Household income has a strong influence on travelers' mode choice behaviour. Economic theory and empirical evidence suggest that higher-income travellers are less likely to choose transit alternatives.

We interpret this result that both middle-income ($40,000 – $150,000) and high-income (above $150,000) LRT users, as compared to other categories, were found to be less likely to take a bus or cancel their trip. Moreover, high-income users were found to be less likely to take transit altogether during short-term LRT PSD. These individuals are more likely to have other modal options available to them. In contrast, lower-income individuals may feel priced out of using the more expensive drive, carshare or taxi modes.

4.3.5.2.5 Occupation

Compared to other occupational classes, students who chose to take LRT were found to be more likely to take the express shuttle over the regular shuttle along the disrupted section of the LRT line. This is likely explained by students being more technology savvy and being able to pass the extra wait time associated with the express shuttle on their smartphones.

4.3.5.2.6 Transit Fare Type

The LRT customers who hold monthly, student and senior transit fare passes were found more likely to continue using the LRT during a short-term LRT PSD compared to LRT users who use other type of fare payments. These individuals might be captive users or may be motivated to use transit service to maximize the value of their pass purchased, even when PSDs occur. It should be noted that much of the literature suggests that they may not choose to continue renewing their passes in the future if they experience significant inconvenience due to PSDs.

4.3.5.2.7 Transit users

An interesting finding of this study is that frequent LRT users (all week and/or weekend users) were more likely to keep using the LRT service or take alternative transit bus routes during short-term LRT PSDs and are willing to experience extra travel time and transfers for their regular weekend trips. Again, we speculate that these people are captive users or possess monthly transit fare passes and have an incentive to use transit service. Conversely, some of these individuals may be strongly loyal to transit based on their underlying beliefs or attitudes and, as such, would select transit options even under sub-optimal conditions. Further investigation of these issues is warranted.

4.3.6 Sensitivity Analysis and Recommendations

Participants' choice probabilities are evaluated with respect to transit fare, carshare cost and wait time at transfer stations for the express shuttle separately. In all cases, the dependent variable is the probability of choosing from the given alternatives. Note that we have opted to employ this method as the introduction of preference heterogeneity via mixed logit relaxes the i.i.a property of the standard logit structure. This means that conventional elasticity or marginal effect calculations no longer have a closed-form equation, and the model will exhibit non-proportional substitution patterns.

Figure 4.20 presents the relationship between the choice probability of the given alternatives and a decrease in transit fare, keeping all the other explanatory variables unchanged. The graph shows that the probability of choosing all the transit options increases and that of driving and trip cancellation/rescheduling decreases as the transit fare decreases. However, the probability of choosing a taxi remains inelastic due to the change in transit fare. If transit is made free during short-term LRT PSDs, the probability of choosing LRT would increase by about 3%, resulting in a total 4% increase in choice probability of transit-based modes (i.e., 1% increase in choice probability LRT with regular shuttle, express shuttle and carsharing, and transit bus, each). The increase in transit share is due to the corresponding drop in trip cancellation (3%) and driving (1%) alternatives when transit is made free. A large caveat with this finding comes from many transit users paying for monthly passes. This decrease in transit cost will only have an impact on them if Calgary Transit has some means of tracking their use or providing a credit or discount on subsequent pass purchases. Conversely, there is also a significant opportunity to attract infrequent transit users, who otherwise would not use transit during a PSD, to try LRT service if the service is made free on weekends. That said, some means of tracking monthly pass owners and providing them with a financial incentive to use transit is important to enable the implementation of this loyalty policy.

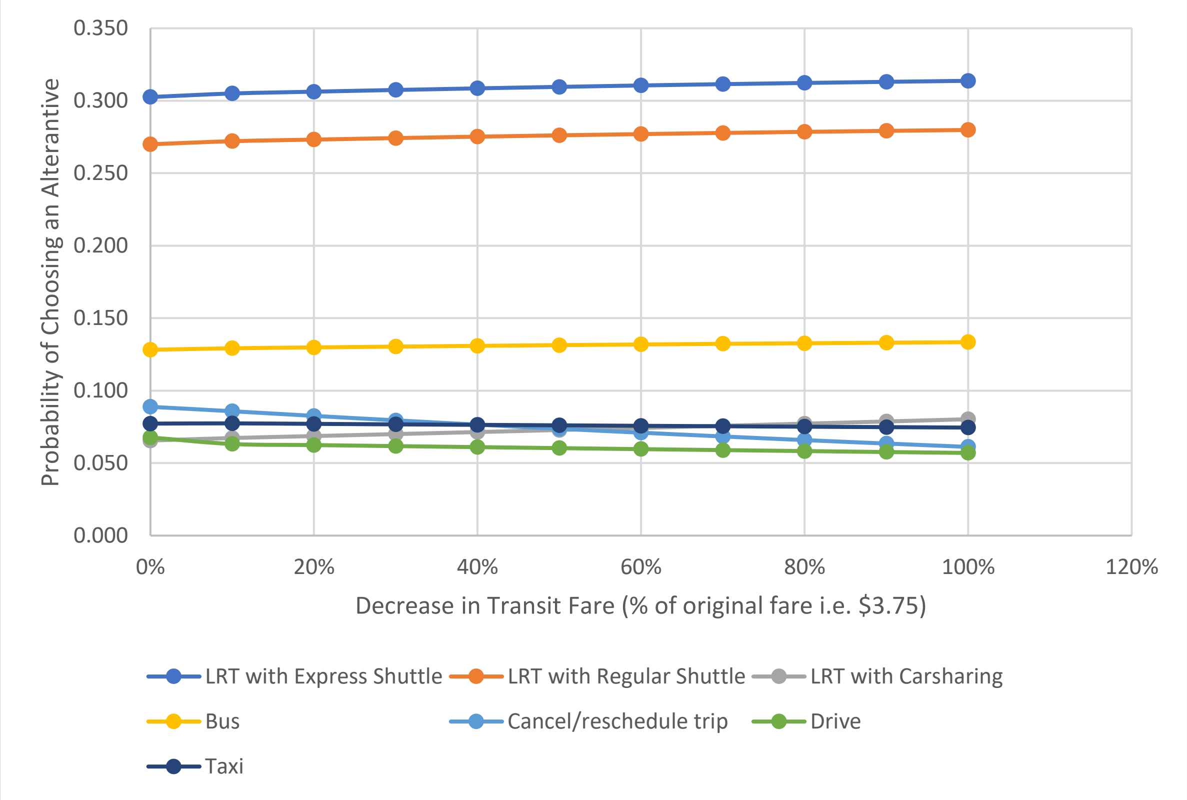


Figure 4.20: Sensitivity analysis with respect to the decrease in Transit fare

While providing a higher level of service to the transit customers, subsidizing carsharing mode along the disrupted section of the LRT only does not seem to be a very attractive option for passengers from non-transit modes. Sensitivity analysis (*Figure 4.21*) of the model with respect to a decrease in fare of carsharing showed up to 4% increase in the probability of choosing carsharing mode if the carshare mode is made free for LRT users that are affected by a short-term LRT PSD. The results show an increase in the probability of choosing LRT by 1%. The major reason for increased carshare choice probability is a result of the shift from express and regular shuttle bus mode to the carsharing mode. The choice probability of taxi was found to be insensitive with respect to changes in carshare fare. Based on this analysis, transit agencies can consider subsidizing carsharing service as well as ride-hailing service (such as Uber) to transfer passengers between the disrupted section to improve the level of transit service during planned and unplanned service disruptions. There is also a significant opportunity to use other new shared mobility options, such as shared e-scooters or e-bikes. The new e-scooter mobility options had just been introduced to Calgary when this data was being collected. Subsidizing the cost to use these micro-mobility technologies is, in many ways, analogous to subsidizing the carshare option. Furthermore, there has been significant speculation regarding the efficacy of micro-mobility as a solution to the transit first mile last mile problem(Eccarius and Lu 2020). This could mean that providing these subsidies to users may encourage other transit use accessed and/or egressed via e-scooter or e-bike moving forward, thereby increasing overall ridership.

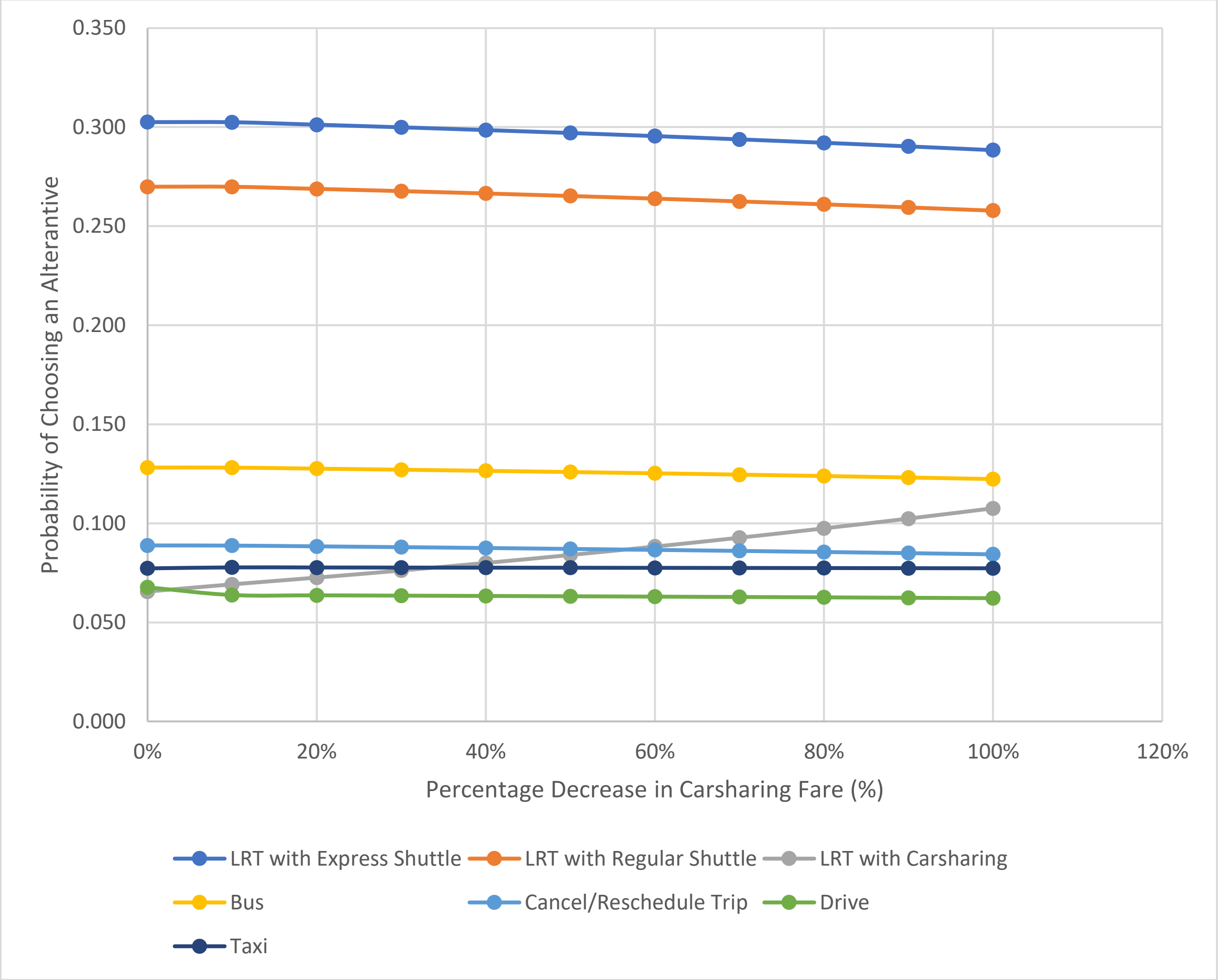


Figure 4.21: Sensitivity analysis with respect to the decrease in Carsharing fare

Wait time at the transfer station, which is related to the shuttle bus headway or frequency, is an important component of transit users' perceived utility. Among the hypothetical LRT alternatives, the express shuttle provided shorter travel time but a longer average wait time (i.e... lower bus frequency) than the regular shuttle. *Figure 4.22* represents the sensitivity of the choice model with respect to change in waiting time for the express shuttle. The probability of choosing the express shuttle increases as wait time decreases and would increase by about 4% for the examined choice context if transit customers do not have to wait for the shuttle. In other words, schedules must be coordinated such that an express shuttle bus must be waiting at the transfer station when an LRT arrives at the transfer station. This pulsing of services can be challenging to implement operationally for temporary bus bridging routes. Interestingly, the greatest substitution pattern predicted by the model was for the regular shuttle with other modes having much smaller increases in overall modal share. This potentially suggests that decreasing service headways on express vehicles is not actually a way of competitively increasing modal share. However, decreasing service headways on express vehicles can definitely improve level of bus bridging service for customers.

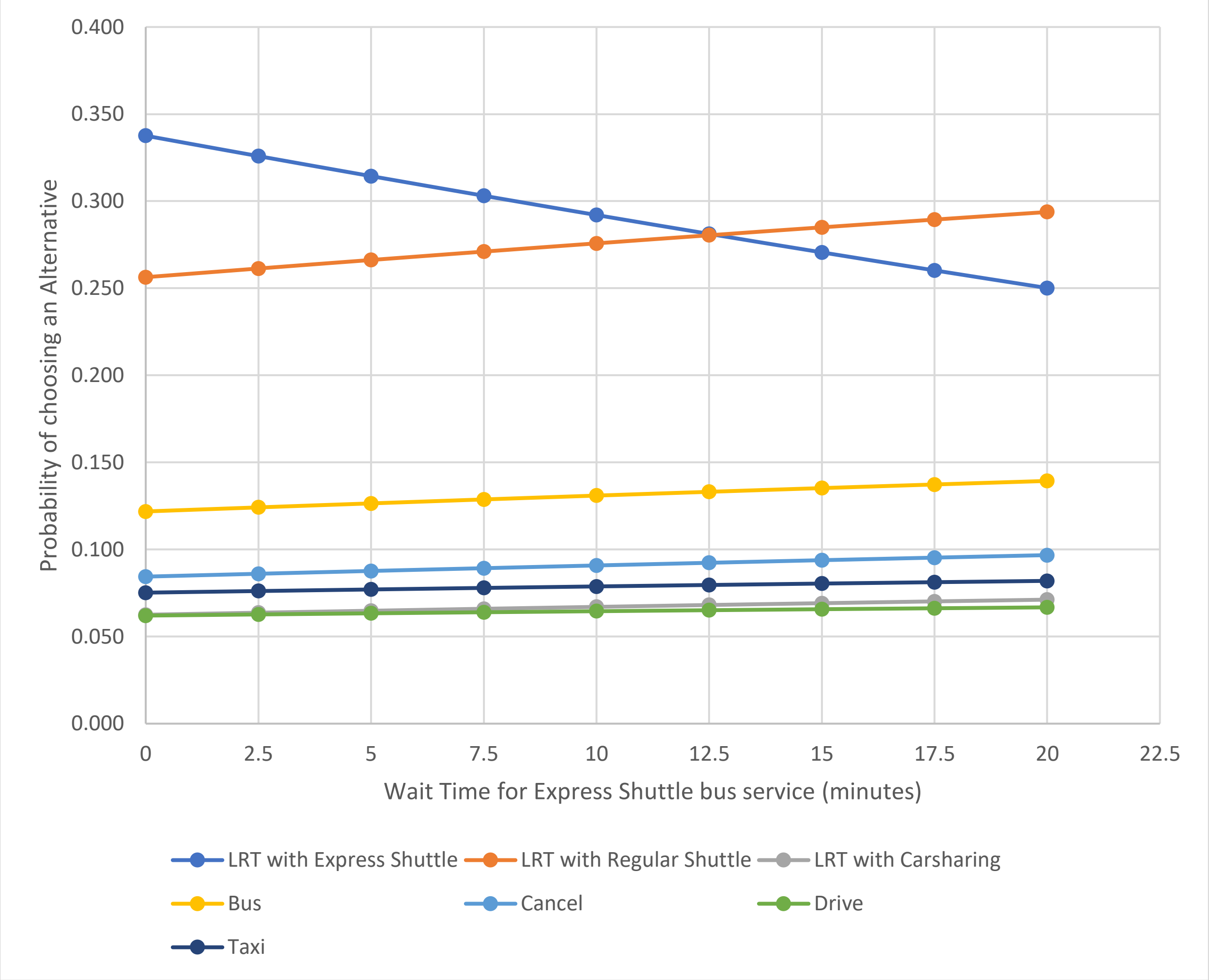


Figure 4.22: Sensitivity analysis with respect to change in wait time of express shuttle

4.4 Chapter Summary

This study examined LRT (Light Rail Transit) users' travel mode choice preferences in the event of short-term LRT (PSDs). A stated preference survey was designed and distributed to collect information on passengers' behaviour on mode choice responses under a set of hypothetical LRT PSD scenarios in the City of Calgary, AB, Canada. A mixed multinomial logit model was calibrated using the collected data to identify the factors contributing to the presented alternative mode choices. A sensitivity analysis was also conducted to examine the impact of variations in transit fare, carshare fare and wait time at the transfer stations for the express shuttle on the mode choice probabilities.

The findings of this study improve the understanding of transit passengers' behavioural choices under short-term LRT PSDs. The results of the analysis show that, in the context of the LRT PSD choice situation we investigated, LRT ridership can be reduced by up to 35%. More specifically, respondents who stated that they would avoid the LRT during the hypothetical disruption are likely to consider alternative travel mode, e.g. alternate transit bus route (17%), driving (6%), taxi/Uber (7%) or cancel/reschedule their trip (9%). The customers that use transit payment passes (monthly, seniors, students, juniors, employees, etc.) and are frequent weekend LRT users are more likely to stay with the LRT mode. If customers are provided with alternative modes (express shuttle bus and carsharing) in addition to regular shuttle bus service, they would likely use those to shorten their travel time. LRT users that belong to the high-income category are less likely to take transit during a short-term LRT PSD. The value of time was found to be 11.76 $/hr and 13.0 $/hr for travel time and wait time during travel, respectively.

The outcomes from the sensitivity analysis provide valuable information to transport planners in proposing potential measures to alleviate the impact on travellers due to service disruptions. The sensitivity analysis of important variables considered in this study showed that improving the level of shuttle bus service (bus bridging) would increase customers' choice probability for LRT. Travel time and wait time are found to be key components of bus bridging service. Bus bridging level of service can be improved significantly by providing an express shuttle service that skips intermediate stations and offers shorter travel time (in addition to the regular shuttle service). This also reduces customers' wait time at transfer stations by increasing the frequency of the bus service and by improving the bus bridging schedule such that a bus should be available at the transfer station when LRT arrives. Other policies, like making the LRT free during the PSD and/or subsidizing carsharing, ride-hailing or e-scooter service can further improve the attractiveness of LRT during short-term PSDs. These initiatives would also help promote the mobility options (carsharing, ride-hailing and e-scooters).

Chapter-5

Quantifying Ridership Impact of PSDs

As emphasized in previous chapters, LRT PSDs are important to improve service reliability, extend infrastructure's life, and reduce the frequency and impact of unplanned service disruption caused by sudden system failures. Though the planned PSDs are important, they not only impact the transit customers' travel experience by increasing their travel time and causing inconvenience of extra transfers, walk time and wait time, but also influence their travel mode choice behaviour. Due to PSDs, LRT customers reschedule or cancel their trips in the event of short-term PSDs. Recurring LRT PSDs can make some customers switch to different modes temporarily or permanently. It is evident from various previous studies that frequent and/or prolonged transit disruptions result in reduced commuters' trust in the service and lost ridership from customers switching to alternate modes of commute (Carrel, Halvorsen, and Walker 2013).

To quantify the impact of short-term PSDs on LRT ridership, good-quality data is required. Various technologies are available for collecting ridership data. Transit ridership information primarily refers to the number of passengers boarding and alighting, origin and destination demand, and transit vehicle loading. Turn gates and manual counts are still used by many transit agencies to estimate ridership at stations and on vehicles. Other automated passenger measurements include APCs, camera detection, AFC data, and axle load sensors. APC systems are considered an industry standard and are widely used on transit vehicles for collecting accurate continuous ridership data. Since these systems are expansive and require high infrastructure investments, transit agencies cannot afford to equip their entire fleet and rely on collecting limited samples to estimate ridership.

In the case of CT, two-thirds of its bus fleet and about one-third of the LRT fleet are equipped with APC) systems. In addition, a seasonal maximum load point (MLP) LRT ridership is observed manually every season. MLPs are the locations along the transit network where transit vehicles' load (number of passengers on LRT is termed in industry as "vehicle load") is usually maximum; typically, these locations are selected as just before entering a city's downtown, for instance in case of Calgary. Calgary Transit does not have a framework to estimate the actual drop in LRT ridership due to LRT short-term PSDs. Due to limited coverage of APC on bus fleet, not all buses deployed on shuttle service during short-term PSDs are equipped with APC systems. Also, the APC data from buses deployed on shuttle service is not available due to some technological constraints. Hence, the impacts of PSDs on actual ridership cannot be determined with existing resources in Calgary.

This chapter presents the quantitative analysis of APC data for estimating a direct drop in LRT ridership as the result of short-term PSDs.

5.1 Automatic Passenger Count (APC) system

APC devices collect ridership data (passengers boarding, alighting and loads) at stations/stops along a transit route. APC systems consist of devices installed at the doors of transit vehicles to count passengers as they board and alight the vehicle. These devices use infrared beams to count passengers' legs when they are interrupted. Geographical positioning systems (GPS) are also provided in these devices to track the location of buses. These systems are programmed usually to capture ridership data when vehicles' doors are opened (i.e., at station/stop). All the passengers' counting data are stored in these devices, which can be transmitted to a central APC database through WiFi or cellular medium. The accuracy of these systems is up to 99% (infodeve.ca). Few of the LRVs in Calgary Transit are equipped with the APC system.

The APC data collected creates various data fields such as time stamp, vehicle ID, location coordinates, and boarding and alighting by the data collected in the raw form. This data is then cleaned and filtered to bring it into useable form for analysis. The vehicle ID data is matched with the route schedules database to identify routes that a particular vehicle was deployed on. The location coordinates are used to identify bus stops.

The objective of this part of the study is to determine if ridership changes on LRVs during LRT PSDs using APC data.

5.2 Data Analysis

The APC data available from the LRVs in Calgary consisted of total daily boarding and alighting (stop and route level data was not available due to technical constraints). Calgary Transit was in the process of upgrading its LRV fleet. Only the new LRVs are equipped with APC systems. So, the sample size of the available APC data is about 50%.

LRT PSDs are scheduled more frequently during the spring and summer seasons. LRV APC data of all weekends was collected from May 2021 to September 2021 for analysis. Table 5.1 lists all the PSD events on both red and blue lines that occurred from May 1st, 2021, to September 30th, 2021. Ridership of the weekends with PSDs was compared with the ridership of the weekends with normal LRT service within the spring and summer period to quantify the direct impact of LRT PSDs on weekend ridership.

LRV schedule information from HASTUS (i.e., a commercial transit vehicle scheduling and dispatch computer tool) was matched with LRV APC data to obtain route information using “vehicle ID” as the common field. The boarding data of normal weekend LRT service was used as a base.

Table 5.1: Dates, sections, and alternative shuttle service sections of the LRT planned service disruptions

Sr #	Date		LRT segment with service impacted		LRT line	Shuttle service	
	Start	**End**	**From**	**to**		**to/from**	**from/to**
1	1-May-21	3-May-21	Marlborough	Bridgeland	Blue	Marlborough	Bridgeland
2	15-May-21	17-May-21	McKnight	Rundle	Blue	McKnight	Rundle
3	22-May-21	25-May-21	Stampeded/8 St/Bridgeland	Kerby/8 St/Stampeded	Red/Blue	39Ave/Bridgeland	Sunnyside/Kerby
4	29-May-21	31-May-21	39 Ave	Heritage	Red	39 Ave	Heritage
5	5-Jun-21	7-Jun-21	Saddletowne	Whitehorn	Blue	Saddletowne	Whitehorn
6	5-Jun-21	7-Jun-21	Chinook	Heritage	Red	Chinook	Heritage
7	19-Jun-21	21-Jun-21	Chinook	Heritage	Red	Chinook	Heritage
8	26-Jun-21	28-Jun-21	Chinook	Southland	Red	Chinook	Southland
9	3-Jul-21	5-Jul-21	Fish Creek	Southland	Red	Fish creek	Southland
10	24-Jul-21	24-Jul-21	City Hall	69 St	Blue	City Hall	69 Ave
11	25-Jul-21	25-Jul-21	Kerby	69 Ave	Blue	Kerby	69 Ave

12	31-Jul-21	3-Aug-21	Chinook	City Hall	Red	City Hall	Chinook
13	31-Jul-21	3-Aug-21	McKnight	Rundle	Blue	McKnight	Rundle
14	8-Aug-21	8-Aug-21	Chinook	Heritage	Red	Chinook	Heritage
15	14-Aug-21	16-Aug-21	Sunnyside	Brentwood	Red	Sunnyside	Brentwood
16	4-Sep-21	7-Sep-21	Somerset	Fish creek	Red	Somerset	Fish creek
17	25-Sep-21	27-Sep-21	McKnight	Rundle	Blue	McKnight	Rundle

5.3 Results

For determining the change in ridership, normal service ridership data was used as a base. For network-wide ridership comparison, the ridership data of the weekends was used when there was no planned PSD. Figure 5.3 shows weekend ridership on both lines during normal and disrupted service; the green plot shows normal service on both lines. The overall comparison of average daily ridership reveals that the ridership drops by 28% on both Blue and Red lines combined. Weekend ridership data for both the Blue and Red lines was plotted separately, as shown in Figure 5.1 and Figure 5.2, to analyse the ridership trends during regular and disrupted service visually. Comparing the ridership for each line separately shows that average weekend daily ridership drops by 26% on the Blue line and less than 1% only on the Red line during the planned service disruptions events, as shown in Table 5.2.

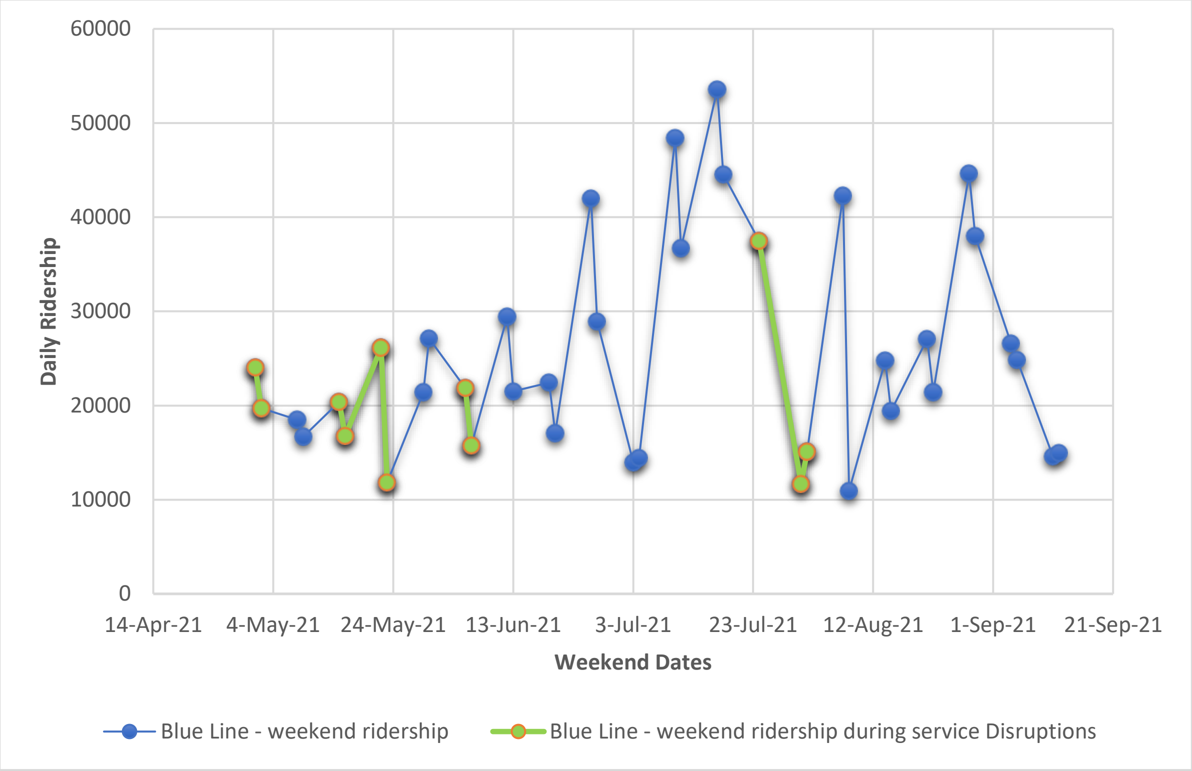


Figure -5.1: Ridership change on the blue line during PSD

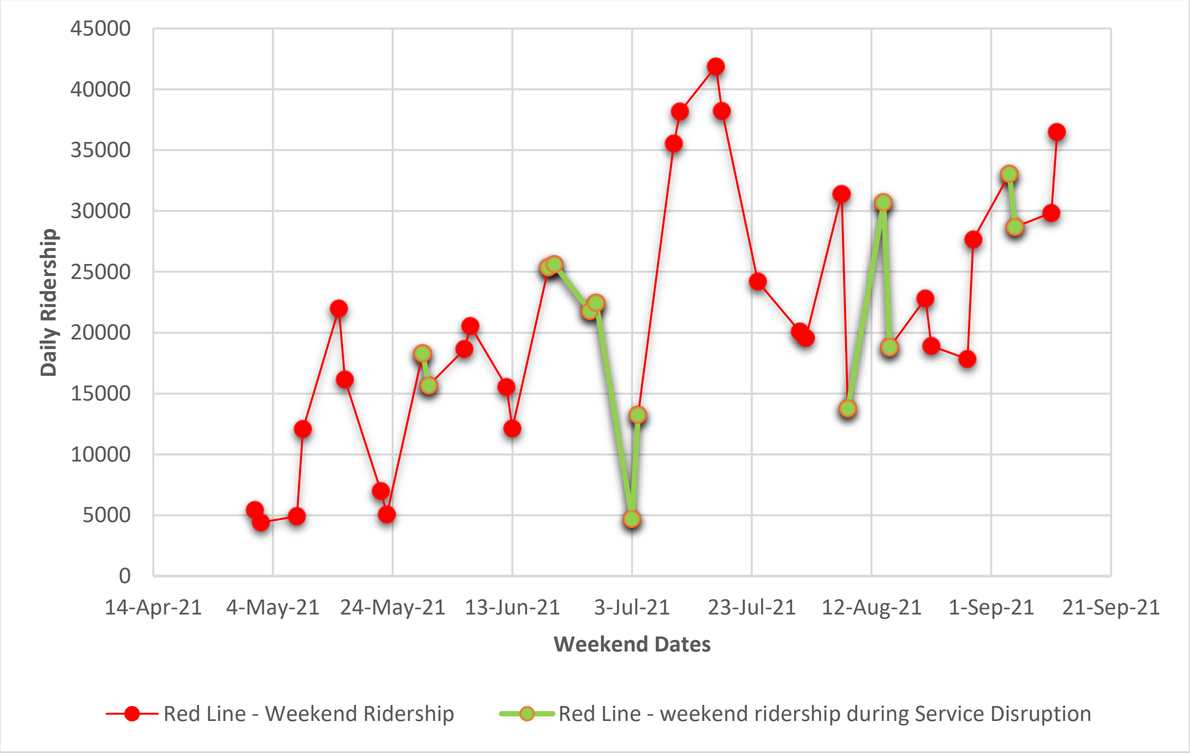


Figure 5.2: Ridership change on Red Line during PSD

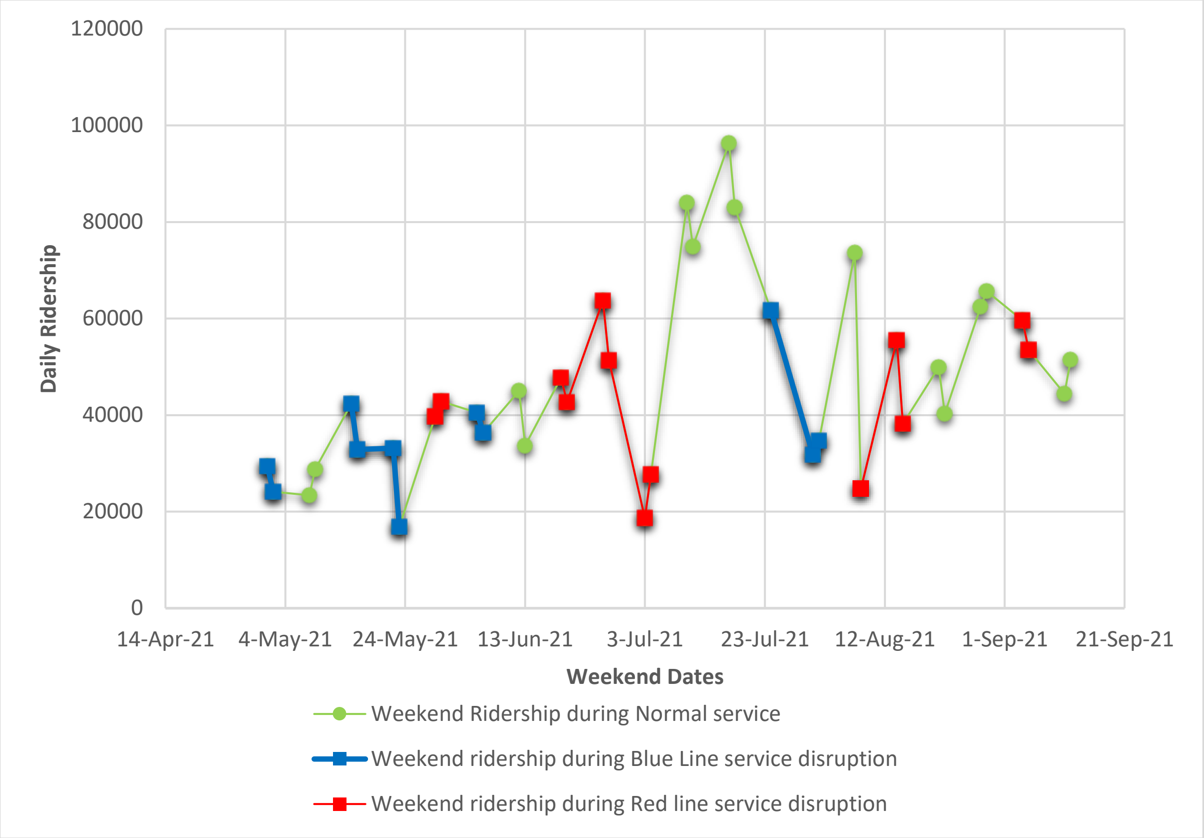


Figure 5.3: Ridership change on the LRT network during PSD

Table 5.2: Comparison of LRT ridership during normal and PSD events.

	LRT Ridership		
	Network Wide	Blue Line	Red Line
During Regular Service	57143	27367	21023
During Disrupted Service	40939	20065	20932
% Drop in Ridership during Disrupted service	28.36%	26.68%	0.43%

For ridership analysis on individual LRT lines for estimation of ridership, it was found that interdependencies exist between ridership of both LRT lines, which indicates that a significant portion of LRT trips involve transfers in between the Red and Blue Lines. Average daily weekend ridership during regular service was found to be high when there was no PSD on the other line, and a low ridership during regular service on the same line was shown when there was a PSD happening on the other line for the same weekend.

Both scenarios were considered for determining a drop in ridership, as presented in Table 5.3. Ridership of the Blue line during normal service, in the absence of PSD on the Red line, was found to be significantly high (31,495). This ridership was found to have dropped to 22,600 when there was a PSD on the Red line. Similarly, the average daily weekend ridership on the Red line during normal service was 25,500 when there were not any PSDs on the blue line, and the normal daily weekend ridership dropped to 14,800 when there were PSDs on the Blue line during the analysis period. For comparison purposes, the daily weekend ridership during normal service in the absence of PSD on another line was considered for analyzing direct ridership drop on a line as a result of PSD. Average daily weekend ridership drops by 36% and 18% on the Blue and Red lines, respectively, as a result of PSDs.

Table -5.3: Blue Line ridership during Normal versus planned service disruptions on a single line at a time.

	No PSD on the other line		**PSD on other LRT line**	
PSD Scenarios	Blue Line	Red Line	Blue Line	Red Line
During regular service and no PSD on the other line	31495	25567	22604	14828
During disrupted service	20065	20932	20065	20932
% Drop in ridership during disrupted service	36.29%	18.13%	11.23%	-41.17%

The weekend ridership graphs (Figire-5.1-5.3) show higher ridership during July (July 9th to 18th 2021), which is the Stampede season in Calgary. Calgary Stampede is claimed to be the greatest show in North America. Thousands of people come from all over Canada and various parts of the world to visit Calgary during the Stampede event. During this busy season, CTrain is the most preferred mode of transportation for tourists and citizens heading to Stampede grounds. Limited and high cost of parking also influences travellers to use CTrain during the Stampede days.

If it is assumed that the ridership stays the same during the Stampede event as if it was during the other weekends (outside the stampede season) with normal LRT service, then overall ridership would drop by 13%.

5.4. Chapter Summary

To quantify the impacts of short-term LRT PSD on LRT ridership, APC data was used to compare the ridership during a short-term LRT PSD with that of during normal undisrupted service. Analysis of APC data for the period of May to September 2021 indicates that short-term LRT PSDs do impact ridership significantly. Also, regular weekend LRT customers are informed ahead of time so they can make alternate arrangements for their travel or adjust their schedules. There can be various factors other than PSDs that would have contributed to the drop in ridership, the analysis of which is beyond the scope of this thesis.

Chapter-6

Optimal Bus Bridging Service for Short-term LRT PSDs

6.1 Introduction

This chapter focuses on mitigating the short-term light rail transit (LRT) (PSDs) to reduce its adverse impact on transit passengers. These PSDs last up to three days and are scheduled on weekends when ridership demand is significantly lower than weekday demand. Regardless of their short duration and intent to impact only weekend ridership, PSDs negatively affect passengers' travel experiences and decrease customer satisfaction due to longer waiting time and travel time, as well as additional transfers. Passengers are more sensitive to the walking distance at transfer stations than the distance from origin and destination (Seki H 2009). Passengers associate additional penalties with walking time at transfer points because of the uncertainty of wayfinding and walking through busy streets to catch connecting vehicles (Hossain, Mohammad - Hunt, John - Wirasinghe 2015). Transit agencies spend many resources to provide a good replacement bus service (bus bridging), yet the objective is often not passengers focused. Transit agencies need to understand the short-term impacts of PSDs on transit customers' behavioural choices and accordingly devise bus bridging services (replacement services to normal LRT service) that can improve customers' travel experiences.

Due to its temporary nature, the bus bridging problem differs from the standard bus route design problem. There are often limited possibilities to offer adequate infrastructure for bus bridging service, such as additional passenger pick-up stations, bus bays at LRT stations while considering the additional transfer times. In addition, unlike the regular bus route design problem, whose objective is to ensure good service quality and low operating cost in the long term, bus bridging service aims to minimize impacts over a shorter time horizon. In planning to respond to the short-term PSDs, the challenge is to design shortest-path bus routes (s) and deploy these routes according to the specific demand profile to provide efficient service with the shortest possible travel time to the impacted transit passengers.

In this thesis, the emphasis is to design a bus bridging service along a disrupted section of the rail route where no alternative rail or bus routes are available for passengers to bypass the very disrupted section. While bus bridging service design in responses to unplanned disruptions has extensively been studied, the bus bridging service design for planned disruption, especially for short duration, still needs to be explored. To the author's knowledge, no prior studies examined how transit customers' experiences can be improved during short-term LRT PSDs by providing a better bus bridging servicer.

The objective of this study is to develop an analytical model to determine an optimum bus bridging strategy (routing is pre-defined) for short-term LRT PSDs to improve passengers' satisfaction; in other words, the operating cost may or may not be minimal. The performance of the developed strategy is then examined on the Calgary LRT network using field data. Various bus bridging scenarios consisting of different combinations of routes are evaluated to assess their effectiveness.

The contributions of this section are as follows:

1. This study is unique in the type of application on short-term LRT PSD. This study proposes an optimal bus bridging service plan (i.e., routing strategy and frequency) along a disrupted section of the LRT section, using existing bus stops and roadway infrastructure. Various bus bridging service strategies are considered in this study, with optimal bus bridging service headways based on agency and passengers' costs for each strategy.
2. Passengers' response to the bridging strategy is incorporated in their likely route choice behaviour. It is modelled as a transit assignment model based on passengers' cost using discrete choice and deterministic approaches separately. Discrete choice model

parameters estimated from the SP survey study conducted in Calgary, presented in chapter 4 of this thesis, are used in the passenger assignment model.

The remainder of this chapter is organized as follows: Bus bridging problem is described in section 6.1.1. Section 6.2 discusses the research methodology, model formulation, and study applications. The case study and model results are provided in section 6.2. Finally, sensitivity analysis and insights recommendations are discussed in Sections 6.4 and 6.5.

6.1.1. Bus bridging service problem

The bus bridging service design aims to match the level of service with that of the undisrupted normal transit service. Therefore, in the bus bridging service design, the emphasis is to provide a better passenger experience and to retain the attractiveness of the transit service to users, at the cost of increasing the operating cost if required. In the context of our transit PSD problem, passengers using the LRT system during the weekends differ from those during weekdays due to trip purpose, so their perceived cost of travelling (i.e., in-vehicle travel time and waiting time) changes from those passengers travelling on weekdays. Among the weekend passengers, some who know of upcoming PSD may consider changing their trip plans (e.g., canceling their trip or using an alternate route). Yet, some passengers will have no other choice but to use the disrupted service, even if they are aware of service disruption.

Normally, LRT/metro lines serve as trunk services with feeders connecting at stations; therefore, no parallel transit service routes are usually provided along the LRT/metro lines. Also, due to a lack of feasible technology, no historical field data is normally available on passengers’ origin-destination (OD) during undisrupted LRT service and passengers' route choices among the provided bus bridging service.

In the bus bridging problem, the number, and locations of stops to be served by bus bridging service along the disrupted section of mass transit line are known. The routes’ frequencies for the bus bridging strategies need to be determined based on passengers' distribution of origin-destination (OD) demand to/from the impacted stations with intent to improve customer level of service.

6.2. Methodology

6.2.1. Overview:

A common practice is replicating the lost train service by running bus bridging services in parallel that serve all stations along the disrupted section of the network. However, this is not the best strategy as the travel patterns of commuters are not considered. Thus, the conventional bus bridging service can be complemented by providing additional routes serving the terminals only if the demand is high on these specific OD pairs. Similarly, another route can be deployed to connect between multiple high-demand stations. Various routing strategies can be created using the combination of routes provided in the bus bridging strategy, some of which may include transfers among the routes provided. However, since passengers have an inherent preference against transfers, there will be penalties for transfers, resulting in additional passengers’ costs.

As shown in *Figure 6.1*, this chapter develops a bi-level optimization model that considers various combinations of pre-selected service types (i.e., express vs. regular, skip-stop vs. express), analyses passenger cost on all feasible paths and recommends the bus bridging service strategy that offers minimum system wide passengers cost. In the upper-level model preselected bus bridging service strategies consisting of combination of routes (i.e., local, express, and skip-stop routes) are entered, based on transit planner’s experience considering initial passengers’ demand. To initiate the optimization process, for the first iteration, predefined apriori headway values for all routes considered for bus bridging strategies are input. In the lower-level model, the passenger demand is re-assigned to various routes of the bus bridging strategies considered based on passenger’s cost calculated for all feasible paths for every OD pair. The outcome of the lower model is a newly estimated passenger assignment on all routes considered in the bus bridging strategies. This new passengers assignment on routes is fed back into the upper-level model to re-optimize headways of all routes in the bus bridging strategies, and the process is iterated until convergence.

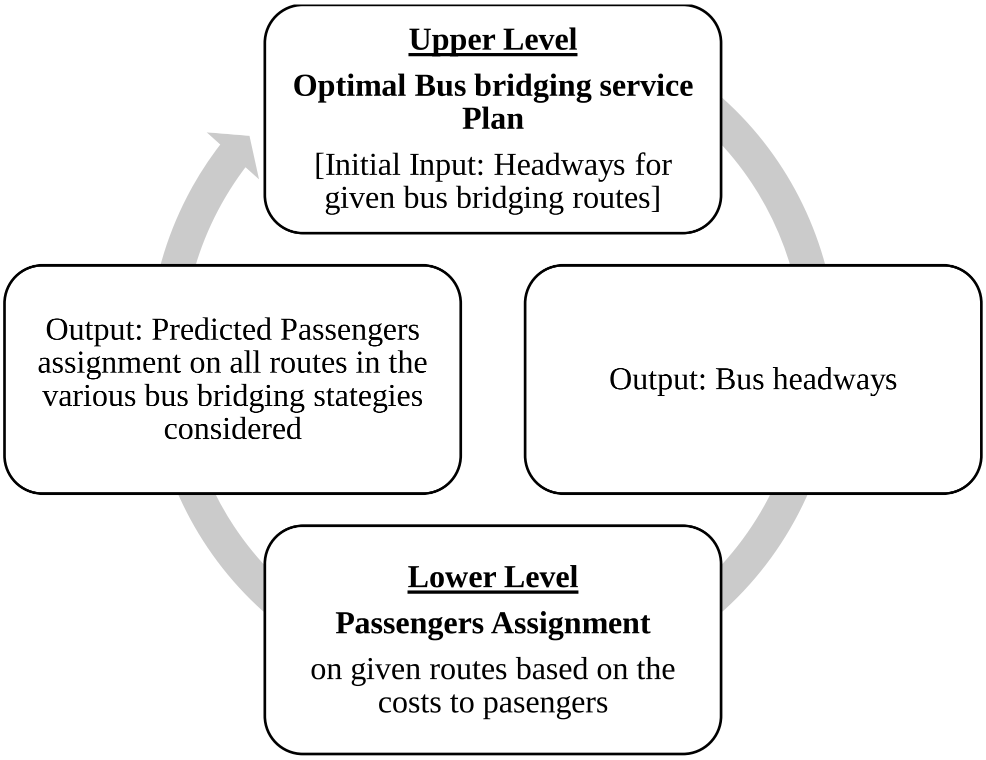


Figure 6.1 Framework of the bus bridging service planning

Various combinations of local, express, and skip-stop routes are considered in this research to serve impacted passengers along disrupted sections of LRT. The continuum approximation modelling method is used to formulate the upper-level optimization model in terms of minimizing the total PSD cost function for determining the optimal frequency of routes considered in bus bridging service strategies. The values of the parameter of the attributes used in the optimization model were estimated from the SP survey analysis, as detailed in chapter 4 of this thesis. The developed bi-level model iterates between the route choices of the passengers and the optimized frequencies of the bridging bus schemes until convergence.

Two different passenger assignment models are considered at the lower-level optimization model. First, a passenger assignment model based on the optimal passenger path choice developed by Spiess and Florian (1989) is used with addition of a simple multinomial Logit (MNL) model to assign passengers to various routes available in a bus bridging strategy. The simple multinomial Logit (MNL) model is adopted to make the passengers' choice more realistic under short-term LRT PSD. The proposed model determines an optimal path choice based on the total passengers' cost and the flow conservation constraints. The total disutility for each passenger would be different for each path choice, as it depends on attributes such as the waiting and walking time at transfer stations and riding time, including the dwell time.

The second passenger assignment model uses a deterministic approach for assigning passenger on to various routes based on the path cost without the passengers perception. Therefore, this creates an ideal passengers assignment scenario.

6.2.2. Bus bridging strategy planning

To formulate a mathematical bus bridging service optimization model during short-term PSD for each bus bridging routing strategy along a disrupted LRT line (i.e., local, express, and skip-stop), the following information for the potential passenger OD demand at the stops, vehicle capacity, and other relevant parameters is required. These parameters are input to the optimization model to find the optimal combination of bus routes, bus headways/frequencies, and fleet size for the bus bridging strategy during PSDs.

6.2.2.1. Passenger types, demand, and cost

In this section, parameters related to transit passengers, including passenger type, demand, waiting time, and walking time, are discussed. Accounting for accurate estimation of passengers' cost components is crucial. If passenger cost components are not correctly estimated, the subsequent bus bridging planning, operations, and design are suboptimal and thus do not thoroughly represent the impact of passenger costs.

a) Passenger types and waiting time:

In the bus bridging service problem, there are two types of passengers riding the bus bridging services: i) enroute passengers (i.e., passengers who are arriving on LRT to the PSD stations) and ii) boarding passengers (i.e.., passengers who are coming to the PSD stations by bus or walking). Both enroute and boarding passengers can be planning or non-planning passengers. The passengers that check the information provided by transit agencies (e.g., routes, schedules, weather, etc.) and are aware of PSDs in advance are considered planning passengers. According to Ansari Esfeh et al. (2021). Planning passengers usually arrive at origin stops just before the arrival time of transit vehicles to maximize their chances to arrive at their destination without delays.

In the context of bus bridging, planning passengers consider the additional time required for transfers and for riding a slower shuttle bus ride compared to the LRT service. Planning and non-planning enroute passengers (transferring from LRT onto Bus bridging service) experience the same waiting time at transfer station for the bus bridging service running along disrupted section of rapid transit service. The coordination of LRT and bus bridging services reduces waiting times for all passengers, regardless of their trip sequence, by eliminating waiting time (i.e., $k << 0$ when a bus is already available at the transfer station) at the transfer point.

Planning boarding passengers strategically time their arrival at station along disrupted section to minimize waiting time at the first link of the trip (i.e., less than half headway of the bus bridging service; $k < 0.5$). On the other hand, non-planning boarding passengers arrive randomly, resulting in an average waiting time equal to half the headway ($k = 0.5$) of the bus bridging service. In the proposed bus bridging service, the headway of the bridging routes would be equal to or shorter than the headway of the rapid transit service to shorten passengers' waiting time. Ansari Esfeh et al. (2022) developed waiting time as a function of the headway of coordinated and uncoordinated bus bridging and rapid transit services for both planning and non-planning passengers.

In real life, passengers' waiting time can be estimated from AVL system data using rapid transit vehicles' arrival time and departure time of the bus bridging service. This is not included in the scope of this study due to a lack of reliable AVL data.

b) Passenger walking time

Walking and waiting time are crucial at transfers to/from the bus bridging services. It was previously found that the penalty for transfer can be low if transfers are on the same platform(Hine JP 2000; Guo Z 2004). A need to walk longer or to a different level and difficulty in finding the connecting vehicles, such as lack of signage, can increase the penalty of transfer for passengers (Dziekan K 2008). While waiting at transfer is not desirable to passengers, the disutility of walking is higher to passengers than that of waiting at transfers. Shafayat et al. (Hossain, Mohammad - Hunt, John - Wirasinghe 2015) conducted a SP survey in Calgary. They found that passengers' sensitivity to walking distance at transfer points is 3.4 times that of walking at the origin and destination ends. The higher disutility of walking distance is related to the uncertainty involved at transfer stations, such as wayfinding challenges where passengers may have to walk through busy streets to catch connecting buses, which makes their experience onerous.

c) Passengers travel time:

Passenger travel time includes the time passengers spend on the bus while it is cruising or dwelling at the passing station(s). Actual passengers' travel time from between all OD pairs can be determined from APC data.

d) Passengers demand

In the proposed framework, it is assumed that passengers’ OD data will be available to transit agencies (i.e. Calgary Transit in the case of this study), inferred from APC and AFC data. As transit agencies are embracing automatic fare collection (AFC) systems, passengers’ OD data would be available directly from Automatic Fare Collection (AFC) systems (i.e. in case of tap-in and tap-out is required/enforced) or with a fusion of AFC data (if only tapping in is required) combined with other data sources such as automatic passenger counting (APC) system.

6.2.2.2. Formulating the Upper-Level Optimization Model

The objective of the optimized bus bridging service is to make sure i) every passenger is served by the first arriving bus after they alight from LRT, ii) each passenger has the least waiting time and walking time to catch a bus after they alight from LRT, iii) each passenger spends the least possible in-vehicle time and access time/transfer time. Our model assume that the bus capacity is not exceeded due to the notably lower LRT ridership demand during the weekend.

The total cost of the PSD is the sum of the resulting additional passengers’ cost and the transit agency’s operation cost. Transit passengers’ experience during a short-term LRT PSD is not the same as it is during normal LRT service. Passengers are expected to spend additional time on their trip and experience inconvenience. Inconvenience includes additional transfers from LRT to bus bridging service and then back to LRT (in case of the second transfer station is not their destination), additional waiting for the bus bridging vehicle, and LRT at transfer points.

Transit fare is not considered in the model, as during PSD, impacted transit passengers are generally not charged with additional fare. All other passengers and agency-related parameters are considered outside the scope of the bus bridging service as the replacement shuttle bus trips start and end at the LRT station. Also, the access time of passengers who reach the impacted stations by other modes of transportation such as bus, park-n-ride, walk, or bike is not included in this analysis. The total cost of bus service is the sum of all performance parameters, which in this case is related to passengers' cost and agency cost.

The continuum approximation modelling method is used to minimize the total PSD cost and to obtain the optimal frequency of a bus bridging service. Only the components of the passengers' cost which can influence the bus bridging operating cost are included in the model (i.e., passengers waiting time at transfer station). The first derivative of the total cost function with respect to the bus frequency is taken, and the resulting expression is equated to zero to confirm that the function is minimum at the optimal bus dispatch rate (Wirasinghe, 1981).

$$\text{Total cost function: } \mathrm{z(t)} = [\boldsymbol{\lambda_D}\, \mathbf{g(t)} + \frac{\boldsymbol{d}}{\boldsymbol{v_T}}\boldsymbol{\gamma_T} + \boldsymbol{k}.\frac{\mathbf{1}}{\mathrm{g(t)}}\, \boldsymbol{\gamma_w} + (\boldsymbol{l} + \boldsymbol{n}\, \boldsymbol{\tau})\boldsymbol{\gamma_r}\,]\, \boldsymbol{P(t)} \quad (6.2a)$$

Where:

- $\boldsymbol{d}$: walking distance between LRT to/from the shuttle bus stop $\boldsymbol{v_T}$: average walking speed of passengers.
- $\boldsymbol{\gamma_T}$: the passenger walking cost (\$/km)
- $\boldsymbol{\gamma_w}$: the monetary value of transit passengers waiting time during PSD (\$/passenger/unit time)
- $\boldsymbol{\lambda_D}$: the agency's dispatch cost per bus per unit time
- $\boldsymbol{h(t)}$: headway of shuttle bus service, unit time/bus
- $\boldsymbol{g(t)}$: dispatch rate of shuttle bus service (number of buses per unit time)
- $\boldsymbol{n}$: number of dwelling bus stops

- $\boldsymbol{l} = \Sigma s_i$: total travel time spent by passenger on bus bridging service. This is the sum of all inter-stop travel time along passengers' trip on bus bridging vehicles.
- $\boldsymbol{\tau}$: the average passengers' trip dwell time at bus bridging stops
- $\boldsymbol{\gamma_r}$: value of in-vehicle riding time, ($/Passenger/unit time)
- $\boldsymbol{P(t)}$: passengers' demand at time *t*
- $\boldsymbol{P_R(t)}$: passengers' demand on local route at time *t*
- $\boldsymbol{P_E(t)}$: passengers' demand on the express route at time *t*
- $\boldsymbol{P_S(t)}$: passengers' demand on route at time *t*
- $\boldsymbol{k}$: factor of bus route headway to model passengers' waiting time for transit vehicle.

The first term in the total cost function (*equation6.2a*) captures the operating cost of providing bus bridging service, also called the dispatch cost. The rest of the terms in equation 6.2a cover passengers-related costs: the second term is the passengers' transfer cost at transfer stations to/from the bus bridging service, and the third term represents waiting time at transfer stations while waiting for the bus bridging route(s). There will be additional waiting time if passengers choose a bus-bridging path that involves a bus-to-bus transfer. Thus, the fourth term captures the riding time of passengers on a bus bridging vehicle, including dwell time at stations along the route.

Equation 6.2a' shows the optimal bus dispatch rate if an infinite fleet of buses with unlimited capacity is deployed, which is a theoretical scenario.

$$\text{Optimal dispatch rate: } g_R(t) = \sqrt{\frac{k\,\gamma_\omega P(t)}{\lambda_D}} \qquad (6.2a')$$

To comply with the requirement of having a bus ready at the terminal transfer station so that passengers don't have to wait for the bus, a smaller value of $\boldsymbol{k}$ can be considered for bus bridging service design in case of short-term LRT PSDs (i.e.., instead of half of the bridging service headway. At terminal stations, the bus dispatches can be aligned with the LRT arrival; thus, k can be 0.25 of headway or even smaller (Ansari et al. 2021). Hence, passengers' waiting time is very short, or they do not have to wait for a bus at all. However, at the intermediate stations, some passengers would be arriving randomly. Their waiting time can be as short as zero or maximum equal to the headway of the bridging bus route. Therefore, average passenger waiting time can be considered at intermediate stations, and to model that half of the bus bridging service headway (i.e., k = 0.5) can be used in the bus dispatch design along a disrupted section of the LRT line.

Due to the smaller value of k, the passengers waiting term becomes smaller, and the optimal dispatch value becomes smaller. Therefore, the capacity constraint is included in the optimal dispatch equation, which suggests that buses should be dispatched full (*equation 6.2b*). Also, to provide a higher level of service, bridging buses should depart from the terminal when the LRT arrives at the terminal station, and passengers from the LRT board the bus; this dispatch is called *policy dispatch*. *Equation 6.2b'* represents a complete set of criteria for bus bridging service dispatch, and the maximum dispatch rate out of the three criteria that should be used.

$$P(t) \geq \frac{C^2 k \gamma_\omega}{\lambda_D} \qquad (6.2b)$$

$$\text{Optimal dispatch rate} = g_R(t) = Max \begin{cases} \sqrt{\frac{k\,\gamma_\omega P(t)}{\lambda_D}} \\ \frac{P(t)}{c} \\ Policy\ dispatch \end{cases} \qquad (6.2b')$$

The fleet size required for a bus bridging strategy depends on the route roundtrip time and can be determined specifically for an LRT service disruption section (i.e., *fleet size = roundtrip time/headway*).

Bus Bridging Strategies:

Assumptions:

1. Passengers waiting time is very small at the terminal station when they transfer to/from LRT to/from the bus. A smaller value of k is considered at terminal stations while k equals 0.5 is used for in between stations.
2. LRT PSDs span over only a few stations (i.e., max 5 stations) along a single leg of the LRT/BRT line.
3. No alternative LRT or bus routes exist parallel to the closer section of the LRT line in consideration.
4. Historical passengers' origin-destination (OD) data is available from a local transit agency.
5. All historical transit OD data is loaded to the bi-level model assuming no passengers will shift modes because of PSD.
6. Passengers are informed of all available bus bridging strategies and their relevant details (i.e. stops and frequencies).

Four bus bridging strategies are evaluated in this study, consisting of various combinations of different bus services. *Figure -6.2* illustrates all bus bridging strategies evaluated in this study.

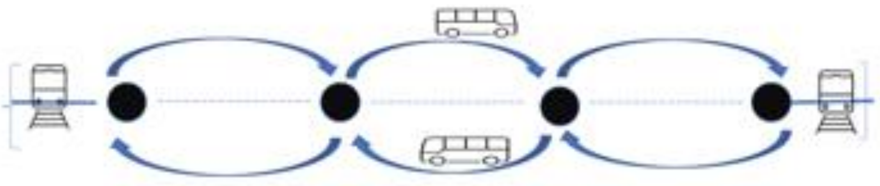
a) Local/all-stop service strategy

Typically, a bus bridging service consisting of a single route that runs parallel to the disrupted section of the transit line is provided to service all stations along a disputed section of the LRT line. The optimal dispatch rate for this strategy of bus bridging service can be determined using Equation *6.2b,'* based on passengers carrying capacity $\boldsymbol{C}$ of transit buses deployed (maximum number of buses out of the two terms will be used). Inequality 6.2b shows that if passengers' demand is equal to or more than a certain threshold, then full buses need to be dispatched. (Wirasinghe 1981).

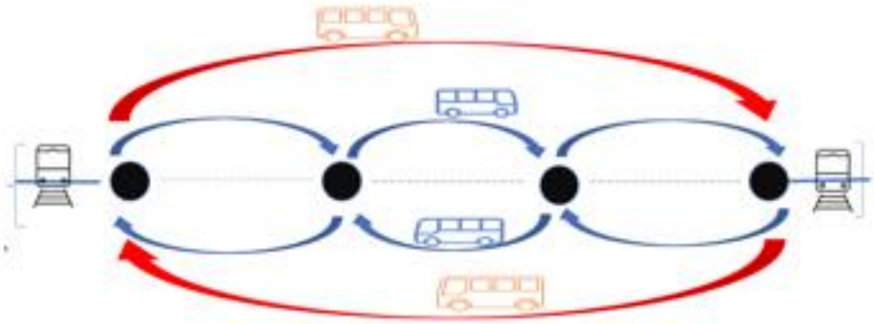
b) Local-express route strategy

Deploying local routes in bus bridging services would be convenient for passengers whose destination is one of the intermediate stations along the disrupted section. Their demand is represented as $\boldsymbol{P_R}$. However, passengers whose destination is the last station after the disrupted LRT section or beyond (i.e., passing passengers within demand $\boldsymbol{P_E}$), will experience longer in-vehicle travel time. To improve the travel experience of the passing passengers, an additional express route can be run. Although the provision of the express service may increase the operating cost of the bus bridging service, it will reduce the total passenger in-vehicle travel cost significantly and improve their travel experience.

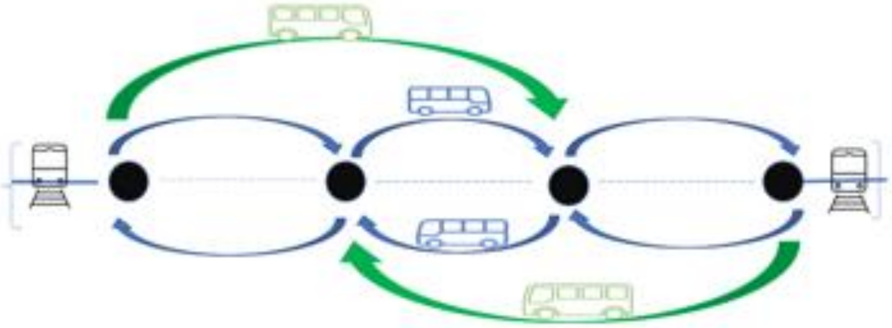
Some passengers travelling to the second last disrupted station (i.e.., station n-1, where the last station is station n) may consider taking the express route to the other end (i.e.., station n) and transferring to the local route to reach the adjacent station (i.e.., station n-1). Similarly, passengers boarding from station n-1 on the disrupted section can take the local route to station n and then transfer to the express route for faster travel to the other end (first station) of the disrupted section. The developed optimal dispatch rate equation considers the transfer of passengers between the local and express bus routes in the bridging service.



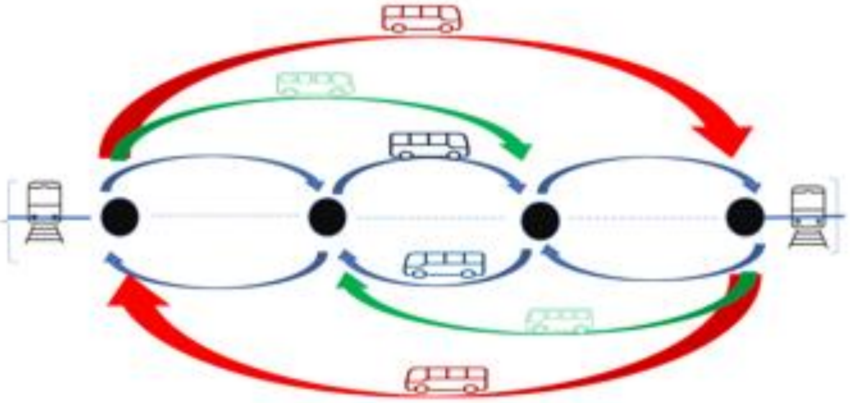
Bus bridging Strategy-1: Local route



Bus bridging Strategy-2: Local-Express routes



Bus bridging Strategy-3: Local-Skip stop routes



Bus bridging Strategy-4: Local-Express-Skip stop routes

Legends: Red: Express route; Blue: Local route; Green: Skip Stop route

Figure 6.2. Demonstration of bus bridging strategies proposed in this research.

The equations for the optimal dispatch rates of the express and regular routes are provided as (6.2c) and (6.2d), respectively. $\boldsymbol{\alpha}$ represents the fraction of passengers transferring from the express route to the local route, and $\boldsymbol{\alpha}'$ represents the fraction of passengers transferring from the local route to the express route.

$$Optimal\ express\ bus\ dispatch\ rate:$$

$$g_E(t) \ = Max \begin{cases} \sqrt{\boldsymbol{\gamma_w}\ k_E \frac{[\boldsymbol{P_E}(\boldsymbol{t}) +\ \boldsymbol{\alpha\prime}\ \boldsymbol{P_R}(\boldsymbol{t})]}{\lambda_D}} \\ \frac{[\boldsymbol{P_E}(\boldsymbol{t}) +\ \boldsymbol{\alpha\prime}\ \boldsymbol{P_R}(\boldsymbol{t})]}{c} \\ Policy\ dispatch \end{cases} \tag{6.2c}$$

$$g_R(t) \ = Max \begin{cases} \sqrt{\boldsymbol{\gamma_w}\ k_R \frac{[\boldsymbol{P_R}(\boldsymbol{t}) +\ \boldsymbol{\alpha}\ \boldsymbol{P_E}(\boldsymbol{t})]}{\lambda_D}} \\ \frac{[\boldsymbol{P_R}(\boldsymbol{t}) +\ \boldsymbol{\alpha}\ \boldsymbol{P_E}(\boldsymbol{t})]}{c} \\ Policy\ dispatch \end{cases} \tag{6.2d}$$

c) Local-skip stop bus bridging service with transfers

A separate route can be provided to connect passengers to/from the high demand stations and from/to the end station along the disrupted section of LRT. The OD data can be mined to find the high demand stations along the disrupted section of the LRT line.

There would be some transfer activities from local to skip-stop route and vice-versa in an effort to get to the other in-between stations. For example, passengers may take skip-stop route and then transfer to the local route to get to the adjacent stops as per their desired destinations. The waiting time of these transferring passengers will increase as a factor of headway of the local route, but their in-vehicle travel time would remain unchanged. In the bridging strategies examined in this thesis a maximum of two transfers are considered between the two LRT stops along the disrupted section.

Equation-6.2e and *equation-6.2f* show dispatch rate criteria for local and skip-stop routes for this strategy. **β** is the fraction of passengers transferring from the skip-stop route onto the local route; β’ is the fraction of passengers transferring from the local route onto the skip-stop route.

$$Optimal\ skip - stop\ bus\ dispatch\ rate:$$

$$g_S(t) \ = Max \begin{cases} \sqrt{\boldsymbol{\gamma_w}\ k_S \frac{[\boldsymbol{P_S(t)} +\ \boldsymbol{\beta}\ \boldsymbol{P_R(t)}]}{\lambda_D}} \\ \frac{[\ \boldsymbol{P_S(t)} +\ \boldsymbol{\beta}\ \boldsymbol{P_R(t)}]}{c} \\ Policy\ Dispatch \end{cases} \qquad (6.2e)$$

$$g_R(t) \ = Max \begin{cases} \sqrt{\boldsymbol{\gamma_w}\ k_R \frac{\boldsymbol{P_R(t)} +\ \boldsymbol{\beta\prime}\ \boldsymbol{P_S(t)}}{\lambda_D}} \\ \frac{[\boldsymbol{P_R(t)} +\ \boldsymbol{\beta' P_S(t)}]}{c} \\ Policy\ Dispatch \end{cases} \qquad (6.2f)$$

d) Local-express-skip stop route strategy

In this strategy, all three routes are implemented to provide passengers with direct and faster service to their destination stations. Passengers may also transfer between the three routes, from express and skip-stop onto local route and vice versa, with the intention to save some trip time. *Equation 6.2 g, 6.2h and 6.2I show dispatch rate criteria for local, express and skip stop routes, respectively,* for this routing strategy.

$$g_R(t) = Max \begin{cases} \sqrt{\boldsymbol{\gamma_w}\, k_R \frac{[\boldsymbol{P_R(t)} + \boldsymbol{\alpha}\, \boldsymbol{P_E(t)} + \boldsymbol{\beta}\, \boldsymbol{P_S(t)}]}{\lambda_D}} \\ \frac{[\boldsymbol{P_R(t)} + \boldsymbol{\alpha}\, \boldsymbol{P_E(t)} + \boldsymbol{\beta}\, \boldsymbol{P_S(t)}]}{c} \\ Policy\ Dispatch \end{cases} \quad \textbf{\textit{(6.2g)}}$$

$$g_E(t) = Max \begin{cases} \sqrt{\boldsymbol{\gamma_w}\, k_E \frac{[\boldsymbol{P_E(t)} + \boldsymbol{\alpha' P_R(t)}]}{\lambda_D}} \\ \frac{[\boldsymbol{P_E(t)} + \boldsymbol{\alpha' P_R(t)}]}{c} \\ Policy\ Dispatch \end{cases} \quad \textbf{\textit{(6.2h)}}$$

$$g_S(t) = Max \begin{cases} \sqrt{\boldsymbol{\gamma_w}\, k_S \frac{\boldsymbol{P_S(t)} + \boldsymbol{\beta' P_R(t)}}{\lambda_D}} \\ \frac{[\boldsymbol{P_S(t)} + \boldsymbol{\beta' P_R(t)}]}{c} \\ Policy\ Dispatch \end{cases} \quad \textbf{\textit{(6.21)}}$$

The express route will have shortest round-trip time and regular route will have the longest round-trip time, due to less dwelling and travel distance. $\boldsymbol{T_E < T_S < T_R}$ where $\boldsymbol{T_E}$ is the round-trip time of the express route, TS is the round-trip time of the skip-stop route, and TR represents the round-trip time of the local route.

6.2.3. Passengers’ assignment model

The planning of bus bridging services is closely tied to transit assignment and the prediction of transit passengers' route choice behaviour from their origin to destination. Passenger assignment on a path among available bus bridging routes can be performed in two ways: i) deterministic passengers assignment approach (i.e.., assign all demand to the minimum generalized cost strategies), or ii) discrete choice approach (i.e.., assigns a positive choice probability to all strategies based on discrete choice models).

6.2.3.1 Spiess and Florian (1989) Optimal passenger path choice behaviour

In the literature, separate approaches have been proposed for the route assignment of transit passengers in frequency-based and schedule-based transit services. In this study, we use the framework proposed by Spiess and Florian (1989) to model the bus bridging problem (passengers' path choices, network, and route features) during short-term LRT PSD. In the Florian assignment model, frequency was the condition for assigning passengers onto a route; such that probability of assigning passengers onto the routes was based on the frequency of competing routes through a stop. In that path choice behaviour, higher frequency routes would have a higher probability to be assigned regardless of their other associated costs on those routes (i.e., in-vehicle riding time, dwell time at intermediate stops and cruising time, and additional transfers at next stops).

In this research, we make the passenger's route choice behaviour more realistic during short-term LRT planned transit disruption by introducing other trip parameters. The additional parameters include the waiting time of passengers for a route (which is a function of the route frequency), walking time at transfer stops, and in-vehicle riding time (vehicle cruising time and dwell time at intermediate stops).

6.2.3.1.1 Bus bridging network modelling

A transit network G (I, A) can be represented by a set of links *A* and nodes *I*. Transit routes traverse through specific nodes (i.e., stops or stations) and links (i.e., sections between consecutive stops) in a network from one terminal to another. A path choice is a plan that a passenger adopts based on their knowledge of the transit network and available routes and features to travel from their origin stops to destination stops in a transit network. Passengers' objective is to adopt from available attractive path choices that provide faster travel time and convenience.

There are two approaches to model feasible path choices in transit networks that passengers may adopt: a) *exhaustive approach*, which considers all possible path choices, and b) *selective approach*, which only includes path choices that meet specific conditions (e.g., a path choice should not have more than one transfer) or are intuitive to passengers overall. In applications, an exhaustive approach is commonly used because of surplus computation capacity (Cascetta, n.d.). In this study, we suggest using the selective approach to identify a set of passenger path choices framed in the matrix of considered passengers' path choices $'\Delta'$ that is based on a given number of routes and customers' perceptions and is feasible and intuitive in real life. In real life, path choices for the same scenario can change based on the actual historical passengers' path choice data. AFC data with tap-in and tap-out information can be used for inferring passengers' OD travel behaviour on bridging service during short-term PSDs.

We assume passenger demand to/from all stops along the disrupted section of a rapid transit route (or along bus bridging routes) will be given in the form of an OD matrix based on the historic data. The route strategy we are proposing in this study will consist of either a single route (local), two routes (local and express or local and skip-stop), or three routes (local, express, and skip-stop). Each passenger will have route options to choose from to come up with a path choice (i.e.., take a frequent local route with longer travel time, take the skip-stop/express route with longer waiting time and additional transfer but faster travel time, or take more than one of the given routes with additional transfer). Every passenger path choice will have a different passenger cost/disutility.

In modelling passengers' path choices to choose from the bus bridging service during short-term LRT PSD, only passengers' related parameters are used in defining trip cost/disutility in this methodology. These parameters include waiting time (w_i), walking time at transfer stops (t_i), and in-vehicle travel/riding time (v_{ir}) including the dwell time (τ_{ir}). No additional fare is considered in the choice model for impacted passengers during disrupted transit service.

Using the feasible matrix of selected passenger path choices and cost of the selected trips, objective function of the assignment model can be formed as shown in equation 6.2j with x_{ijr} as decision variable (i.e.., number of passengers travelling from stop i to stop j, assigned on route r of a bus bridging strategy). Constraints are added to the passengers' assignment optimization problem so that buses do not exceed capacity, passenger flow conservation is complied with, and passengers' assignments are of positive value only. Computer programs can be used for the passengers' assignment.

$$min \sum_{(i,j,r)} \Delta_{ij} . C_{ijr} . x_{ijr} \qquad (6.2j)$$

Where:

Δ_{ij} = Matrix of selective passengers' path choices (single or combination of feasible routes)

C_{ijr} = Cost/disutility to a passenger of using route 'r' from available routes from origin 'i' to destination 'j'

x_{ijr} = Flow of passengers from origin 'i' to destination 'j' on route 'r'.

The discrete choice approach mimics more realistic passengers' route choice behaviour based on their perception, such as the express route will be faster than the regular route. However, there are provision of some passengers who can choose a less attritive path/bad path to get to their destination and end up spending more time on their trip. This approach assigns probabilities for choosing a certain path based on its characteristics.

However, a deterministic passenger assignment model can be useful for improving the system's efficiency overall. In real life, this type of system can be provided at stations, where passengers can be directed to a certain route based on their destination. Passengers would be more attracted to recommended routes if they are made aware of the estimated total travel time in comparison to the other available routes. Advanced passengers information system (APIS) can be used to direct passengers to the best route available for them. APIS consists of real-time digital displays at stations and transit vehicles and mobile apps.

6.2.3.2 Discrete choice approach

The logit model was introduced in this study to make passengers' route choice behaviour more realistic. In discrete choice problems, decision-makers presented with all feasible alternatives are assumed to choose the alternative that maximizes perceived utility or minimizes their expected disutility/cost. Utility is an indicator of the value of an alternative to a decision-maker. The utility function *(Equation 6.2k)* consists of an individual's characteristics and attributes of feasible alternatives. Utility of an alternative 'i' for an individual 'j' consists of an observed/systematic portion '$\mathbf{V}_{ij}$' of the utility and an unobserved/error '$\boldsymbol{\epsilon}_{ij}$' portion of the utility. The observed portion '$\mathbf{V}_{ij}$' of utility function for a trip by an individual 'i' is described by sum of various parameters '$\sum \boldsymbol{\beta X_{ij}}$' referred to as cost/disutility.

$$U_{ij} = \mathrm{V}_{ij} + \epsilon_{ij} \qquad (6.2k)$$

For passenger choice modelling in the case of short-term LRT PSD, walking time, waiting time at transfer, and in-vehicle riding time are used as parameters to describe trip characteristics, as given in *Equation 6.2a*. The generalized utility/cost function of a trip on route 'r' from origin 'i' to destination 'j' can be shown below by Equation 6.2l. 'r' represents a specific route provided in a strategy that could be one or a combination of various routes such as local, express, and/or skip-stop. $\boldsymbol{\beta_T}$, $\boldsymbol{\beta_W}$, and $\boldsymbol{\beta_R}$ are the estimated coefficients or weights associated with parameters walking time at transfer, waiting time at transfer, and riding time including dwell time at stops along the trip, respectively. These coefficients can be obtained through model estimation techniques like maximum likelihood based on field survey responses or can be selected by experts based on experience for a specific location during the short-term LRT PSD. The values of $\boldsymbol{T_{ijr}}$, $\boldsymbol{W_{ijr}}$, $\boldsymbol{R_{ijr}}$ can be determined using real field data. Walking time at transfers can be measured from a distance or field observation, waiting time at transfer stops can also observed in the field, or it can be a function of route headway using the appropriate value of K as described above in section 6.2.2, riding time can be obtained from APC data as described above in section 6.2.2.

$$\mathrm{V}_{ijr} = \beta_t \, T_{ijr} + \beta_w \, W_{ijr} + \beta_r \, R_{ijr}$$

$$\mathrm{U}_{ijr} = \left[\beta_t \, T_{ijr} + \beta_w \, W_{ijr} + \beta_r \, R_{ijr}\right] + \epsilon_{ijr}$$

$$\mathrm{U}_{ijr} = \left[\beta_T \left(\frac{d}{v_T}\gamma_T\right)_{ijr} + \beta_w \left(k.\frac{1}{\mathrm{g(t)}}\,\gamma_w\right)_{ijr} + \beta_r \left[(l + n\,\tau)\gamma_r\right]_{ijr}\right] + \epsilon_{ijr} \quad \text{(6.2l)}$$

The random error term $\boldsymbol{\epsilon_{ij}}$ is assumed to follow a Gumbel distribution and leads to the formulation of the multinomial logit (MNL) choice model as in *Equation 6.2m*. The choice probability of each path choice out of a set of path choices being selected can be determined as follows:

$$\mathbf{P}_{\mathbf{ijr}} = \frac{e^{U_{\mathrm{ijr}}}}{\sum_1^r e^{U_{\mathrm{ijr}}}} \qquad \text{(6.2m)}$$

$$\mathbf{P}_{\mathbf{ijr}} = \frac{e^{V_{ijr}/\theta}}{\sum_1^r e^{V_{ijr}/\theta}} \qquad \text{(6.2n)}$$

Equation-*6.2n* expresses the probability of a route '$\boldsymbol{r}$' (local, express, skip-stop) being chosen out of all available routes by passengers for a specific origin-destination pair (**i**, **j**).

Residual (error term $\boldsymbol{\epsilon_{ij}}$) in multinomial logit model usually follows a Gumbel distribution. In the Gumbel distribution, scale parameter θ represents the level of randomness/uncertainty and variability of choice probabilities, impacting the selection probabilities of alternatives by controlling the dispersion of the Gumbel distribution. A smaller value of the scale parameter results in a narrower Gumbel distribution and tends to assign a larger probability to an alternative with a larger systematic/observed utility. This highest probability for the alternative tends to be close to one (1) of the available alternatives as the scale parameter tends to zero (i.e., a more deterministic discrete choice model). On the other hand, with a higher value of the scale parameter, all available alternatives will have similar probabilities to be chosen (Cascetta, n.d.).

The application of the Logit choice model on this very problem of multiple path choices to choose from may violate both i.i.a (independent and Irrelevant Alternatives) and i.i.d (Independent and Identical Distribution of errors) assumptions. The available routes may overlap paths along certain sections and stops along the route and may make a few or all routing strategies equally attractive to passengers due to similar perceived travel time. Also, any additional routing strategy such as local-express may offer a very attractive option to passengers and passengers from other alternatives switched to this new alternative, and this causes a violation of i.i.a assumption of the logit model.

Violation of i.i.d suggests that error terms associated with alternatives are not independent, and there may be a correlation if there are unobserved factors affecting the choice and correlated with a parameter of the systematic term, i.e., availability of free WiFi on one of the routes if is not included in the systematic term. It would make that route more attractive than the other routes, and the passenger's perceived utility (travel time may become shorter) increases for that route, as passengers can spend time working on their mobile devices while riding the bus. This problem of violation of both i.i.a and i.i.d assumption of the logit model can be addressed by using the Mixed MNL Logit model, which is beyond the scope of this thesis.

Passengers in the proposed model can be assigned among available routes of a strategy using *Equation 6.2o* coded in a computer program.

$$\sum\nolimits_{(i,j,r)} \delta_{ij} \,.\, C_{ijr} \,.\, x_{ijr} \qquad (6.2o)$$

Where:

δ_{ij} = Matrix of Probabilities of each path being chosen by passengers i.e., $\delta_{ij} = \Delta \,.\, \Omega$

This is a product of the Probabilities matrix (Ω) and the matrix of selective passengers path choices (Δ). Elements of Ω are $\mathbf{P_{ijr}}$ and are determined using *Equation 6.2n.* Values of Δ are binary (0,1) based on whether a route is used in the path or not.

For each route strategy, the proposed passengers assignment model will assign each passenger to an available route based on its destination. After assigning each passenger to a route in a strategy, it will calculate the overall passenger cost of the bus bridging strategy. Out of the available bus bridging strategies, a strategy that minimizes total passenger costs in the network is recommended.

6.2.3.3 Deterministic approach

In the deterministic passengers' assignment approach, passengers are assigned to a path among various available routes in a bus bridging strategy based on their origin and destination, such that total passenger cost/disutility is minimized system wide.

Passenger cost (riding time, waiting time, and walking time at transfers) for a specific trip from origin 'i' to destination 'j' on route 'r' is described above. The total passenger cost of the system will be the sum of the product of the passenger cost of a bus bridging strategy and a number of passengers assigned to that strategy (i.e., a combination of route(s)). This passenger assignment is an optimization problem with the objective to minimize the total passenger system-wide costs (Spiess and Florian 1989). *Equation 6.2p* shows the objective function and constraints to this problem, which are provided below.

$$\min \sum\nolimits_{(i,j,r)} C_{ijr} \, . \, x_{ijr} \qquad \textit{(6.2p)}$$

$\boldsymbol{x_{ijr}}$ is the flow of passengers from origin i to destination j on route r.

Constraint-1: Total flow of passengers x_{ijr} on all available route(s) $\boldsymbol{r}$ running between a certain pair of origin i and destination j should be equal to the total passengers' demand d_{ij} on that specific origin destination pair, this constraint is shown by equation 6.2.2.3a.

$$\sum_{r \in Routes} x_{ijr} = \mathrm{d}_{ij} \qquad \forall \;\; Origin\ and\ Destiation\ stations$$

Constraint-2: Passenger assignment on any routes must be a positive integer.

$$\sum_{r \in Routes} x_{ijr} \geq 0 \qquad \forall \;\; Origin\ and\ destiation\ stations$$

Constraint-3: Sum of passengers on a bus must not exceed its capacity. $\boldsymbol{s_r}$ is the capacity of available bus deployed on route $\boldsymbol{r}$.

$$\sum_{\substack{i \in Origin\ stops; \\ j \in Destination\ Stops}} x_{ijr} \leq s_r \qquad \forall \;\; Routes$$

Constraint-4: Passengers will only be assigned to the paths defined in the Matrix of selected passengers' path choices 'Δ' as defined above (i.e.., $\forall \;\; routes\ r\ (i,j) \in \Delta$)

The model finds the values of x_{ijr} that minimize the total cost for all passengers while satisfying the flow conservation constraints. Out of the available bus bridging strategies, a strategy that minimizes total passenger costs in the network is recommended.

The model uses linear programing method to find an optimal assignment of passengers onto the routes, considering the constraints as described above. In this thesis, the *PYTHON* (high-level, general-purpose programming language) environment was used to solve the problem. *PYOMO* (Python-based, open-source optimization modelling language) was used to model the optimization model. GLPK (GNU Linear Programming kit) was used to solve the optimization problem in the Python environment.

6.3 Results of the numerical analysis

We selected an actual short-term LRT PSD that occurred on May 7th and 8th, 2022, on the south leg of the Red LRT line in Calgary, AB, Canada, as the case study to test the methodology proposed in this chapter. The LRT line between Anderson and Somerset stations was closed. LRT service was out at four stations: Canyon Meadows, Fish Creek-Lacombe, Shawnessy and Somerset-Bridlewood. Bus bridging service using articulated buses was provided at a headway of 5 minutes that provided service to all 4 LRT stations along the disrupted section of the LRT line, as typical CT policy for PSDs. Figure 6.3 shows the LRT line (in black) and bus bridging (in red) routes.

APC data from shuttle buses deployed on this event of the PSD was used to gather information on actual travel times and dwell time incurred, and passenger demand between stations along the bus bridging route (i.e.., to/from stations along the disrupted section of LRT during the short-term PSD). In this case study, we inferred OD matrices based on the experience and the boarding/alighting numbers from the APC data set. Passengers' walking distance to/from LRT and bus bridging service stops was measured from Google Maps based on the actual location of bus bridging service stops at all the impacted LRT stations.

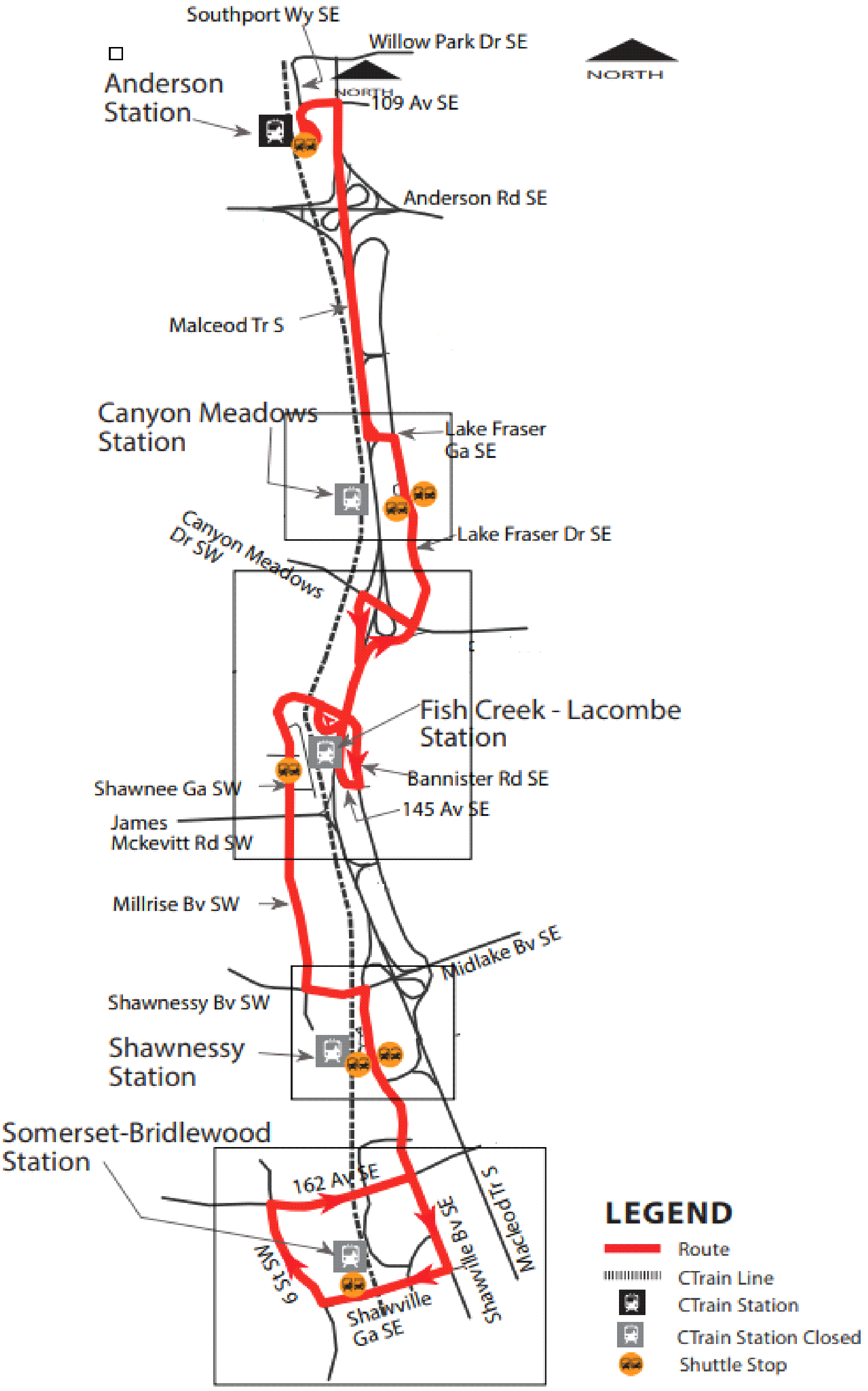


Figure 6.3: Route map of bus bridging service along the disrupted section of the LRT line in Calgary.

Our developed four bus bridging service strategies (i.e., Figure 6.2) were tested in this case study using three types of routes. The base bus bridging strategy considered in this study (i.e., local route as described above) was currently in practice by the City of Calgary, which serves all impacted stations along the LRT line. This strategy is compared with the other bus bridging service strategies, including local and express service, local and skip-stop routes strategy, and local, skip-stop and express routes strategy as described in section 6.2 earlier in this chapter. Travel time, dwell time, and OD demand were determined from the APC data on local bus-bridging vehicles from past events, compiled in *Table 6.1*. *Figure 6.5* shows four bus bridging strategies considered in this case study.

Table 6.1: Local route bus strategy information on travel time and ridership demand.

Dwell time at stations (hh:mm:ss)						
Direction	Station	Average	Minimum	Maximum	Std. Deviation	70 Percentile
South	Anderson	0:06:02	0:00:08	0:16:28	0:02:47	0:07:38
South	Canyon Meadows	0:00:37	0:00:01	0:04:57	0:00:47	0:00:47
South	Fishcreek	0:00:37	0:00:01	0:28:28	0:02:23	0:00:29
South	Shawnessy	0:00:39	0:00:04	0:02:42	0:00:42	0:00:54
South	Somerset	0:06:01	0:00:06	0:13:36	0:02:33	0:07:37

Bus Travel time between stations (hh:mm:ss)						
Direction	Section	Average	Minimum	Maximum	Std. Deviation	70 Percentile
South	Anderson to Canyon	0:05:15	0:03:04	0:45:52	0:03:16	0:05:28
South	Canyon to Lacombe	0:04:48	0:03:01	0:09:01	0:00:48	0:05:14
South	Fishcreek to Shawnessy	0:04:11	0:02:39	0:06:04	0:00:49	0:04:43
South	Shawnessy to Somerset	0:04:38	0:01:18	0:12:04	0:01:23	0:05:17

Ridership Demand (Origin-Destinaiton matrix)						
From \ to	A. Anderson	B. Canyon Meadows	C. Fishcreek	D. Shawnessey	E. Somerset	**Total**
A. Anderson	-	13	2	1	134	151
B. Canyon Meadows	4	-	16	4	7	31
C. Fishcreek	39	9	-	12	22	81
D. Shawnessey	24	1	10	-	77	112
E. Somerset	206	1	3	19	-	228
Total	272	24	31	36	239	602

Selective passengers' path choices for all OD pairs that would intuitively make sense to passengers taking bus bridging service along this LRT disrupted section were considered. *Figure 6.4* shows possible passengers' path choices in this case study for one terminal to the other terminal station as origin and destination. However, only the first (express route in red) and the second path choice (skip-stop in green) seem attractive to passengers out of all the possible path choices in the case of local, express and local and skip-stop bus routes bridging strategy, respectively. This is mainly because both path choices provide the least travel time, as passengers do not have to make additional transfers. The third strategy (local route in blue) may still be attractive to some passengers. The strategies 4 to 7 may not be attractive to passengers as they require additional transfers.

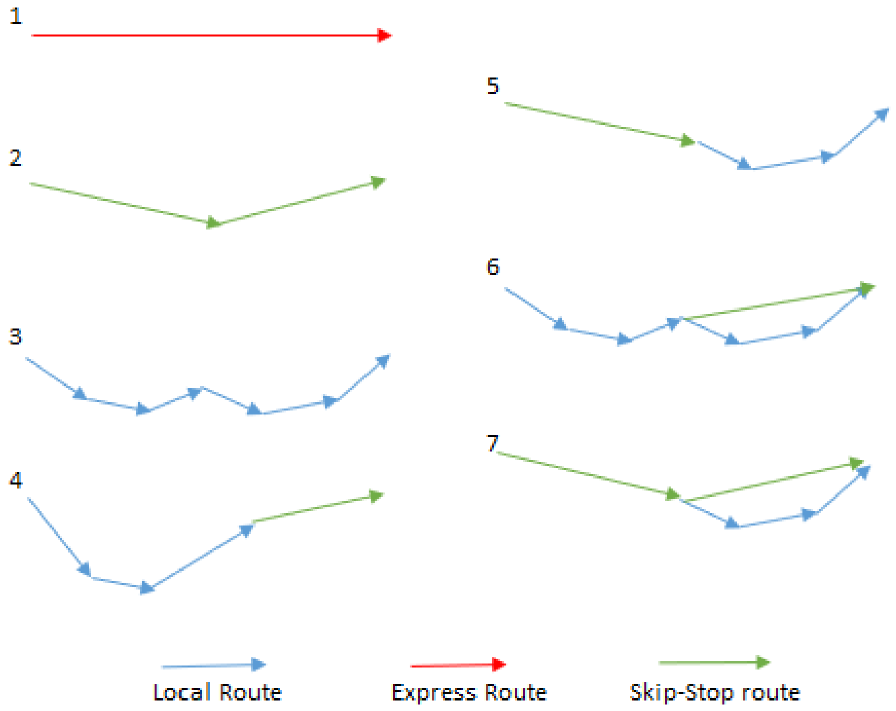


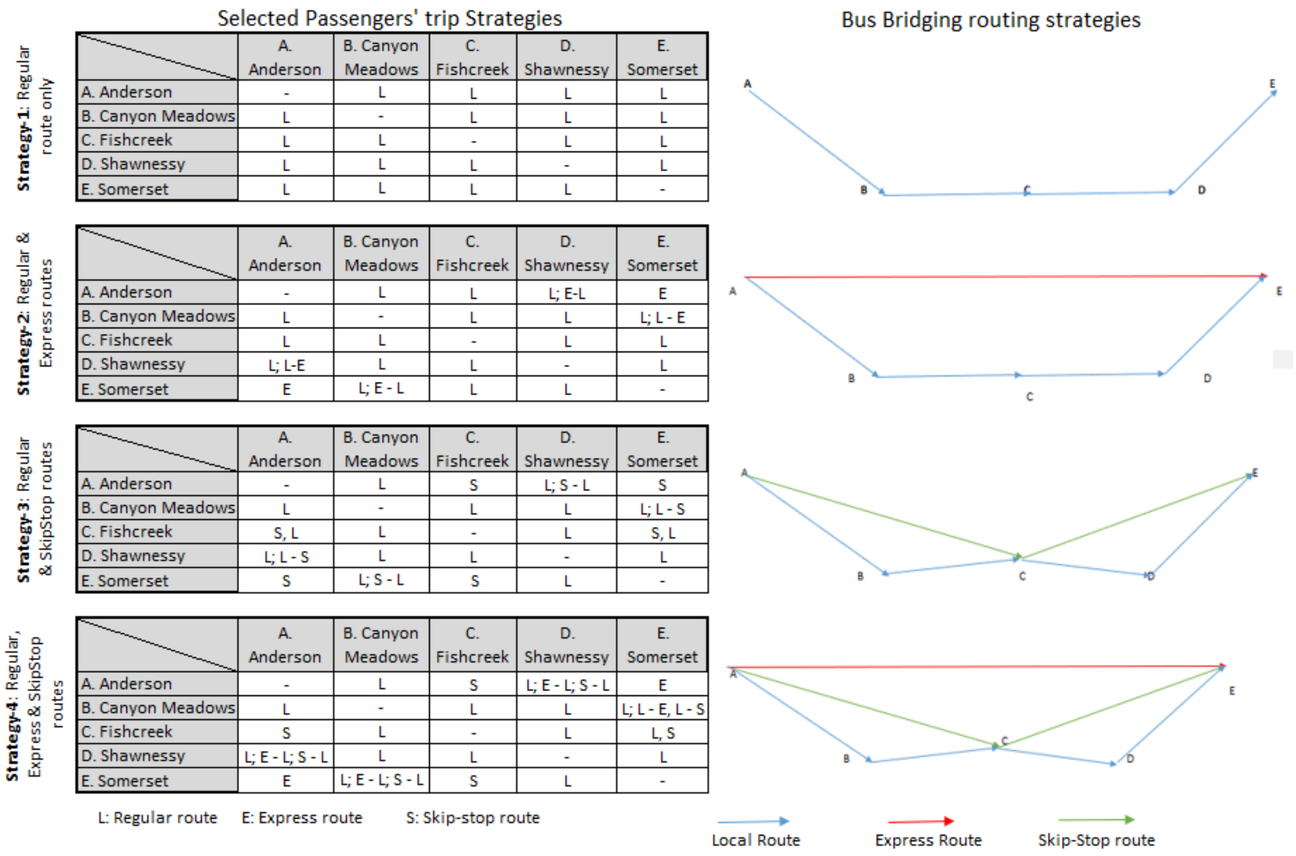
Figure 6.4: Potential passengers' path choices to travel from one terminal to other terminals using the three routes bus bridging strategy.

Selected passenger path choices for all four bus bridging strategies considered in this case study are provided for every OD pair in *Figure 6.5*. In strategy 2 with the local and express route (second table from top in *Figure.6.5*) for trips between Shawnessy and Anderson, passengers may take the local route to go to the Anderson station from Shawnessy, or they can backtrack to Somerset station and from there they can ride the express route to get to Anderson station. Passengers would choose among these strategies (local and local-express) based on the total cost (walking time, waiting time, and riding time) associated with that path choice.

Figure 6.7 presents a probability matrix of feasible passengers' path choices δ_{ij} $(\delta_{ij} = \Delta . \Omega)$ for all OD pairs. For the OD pairs with one feasible path choice i.e., local, or express, the probability of being chosen will be one (1). All elements of the probability matrices (Ω) for each OD pair of each strategy were calculated and then multiplied by the selected passengers' strategies matrix (Δ)as shown in *Figure 6.6*. The cost of each OD pair was determined using equation 6.2a and parameter values from the actual field. The number of passengers assigned to each strategy was determined, as well as the total passenger cost for each bus bridging strategy using equation 6.2o, as above.

For calculating the deterministic part of the logit model, β values were adopted from previous studies (Shafayat et al., 2017; Asim et al., 2021): Walking cost at transfer: \$20/hr, waiting cost at transfer station: \$13/hr, and riding cost \$11.76/hr.

The values of time are determined from the Logit or Probit choice models and are ratios of the coefficients of a parameter (walking, riding, or waiting etc.:) to the cost of those parameters (such as fare). In this study, we multiplied the value of time with the coefficient of fare parameter to estimate the coefficients of the logit model used in this case study.



Selected Passengers' trip Strategies

Strategy-1: Regular route only

	A. Anderson	B. Canyon Meadows	C. Fishcreek	D. Shawnessy	E. Somerset
A. Anderson	-	L	L	L	L
B. Canyon Meadows	L	-	L	L	L
C. Fishcreek	L	L	-	L	L
D. Shawnessy	L	L	L	-	L
E. Somerset	L	L	L	L	-

Strategy-2: Regular & Express routes

	A. Anderson	B. Canyon Meadows	C. Fishcreek	D. Shawnessy	E. Somerset
A. Anderson	-	L	L	L; E-L	E
B. Canyon Meadows	L	-	L	L	L; L - E
C. Fishcreek	L	L	-	L	L
D. Shawnessy	L; L-E	L	L	-	L
E. Somerset	E	L; E - L	L	L	-

Strategy-3: Regular & SkipStop routes

	A. Anderson	B. Canyon Meadows	C. Fishcreek	D. Shawnessy	E. Somerset
A. Anderson	-	L	S	L; S - L	S
B. Canyon Meadows	L	-	L	L	L; L - S
C. Fishcreek	S, L	L	-	L	S, L
D. Shawnessy	L; L - S	L	L	-	L
E. Somerset	S	L; S - L	S	L	-

Strategy-4: Regular, Express & SkipStop routes

	A. Anderson	B. Canyon Meadows	C. Fishcreek	D. Shawnessy	E. Somerset
A. Anderson	-	L	S	L; E - L; S - L	E
B. Canyon Meadows	L	-	L	L	L; L - E, L - S
C. Fishcreek	S	L	-	L	L, S
D. Shawnessy	L; E - L; S - L	L	L	-	L
E. Somerset	E	L; E - L; S - L	S	L	-

L: Regular route E: Express route S: Skip-stop route

Figure 6.5: Passenger path choices considered for the four bus bridging service strategies.

The employed passengers flow conservation constraint was different in each bus bridging strategy as for single, double, or three routes.

$$\sum \phi_{ijr} = \mathrm{d}_i \qquad (6.3a)$$

- For one route strategy: $d = \sum(x_L)$
- For two-route strategy: $d = \sum(x_L + x_E)$ or $d = \sum(x_L + x_s)$
- For three-route strategy: $d = \sum(x_L + x_E + x_s)$

Where:

- x_R , x_E, and x_s are the flow of passengers on the local, express, and skip-stop routes

- d is the demand for passengers travelling from the first station to the last station along disrupted section of LRT line.

The total trip cost for every path choice was determined for every OD pair using the equation 6.2b as described above in section 6.2.2.2. Values used for various parameters used in the equation are provided below.

Total cost function: $z(t) = \boldsymbol{\lambda_D}\, \mathbf{g(t)} + \frac{\boldsymbol{d}}{\boldsymbol{v_T}}\boldsymbol{\gamma_T} + \boldsymbol{k}.\frac{1}{g(t)}\, \boldsymbol{P(t)}\, \boldsymbol{\gamma_w} + (\boldsymbol{l} + \boldsymbol{n}\, \boldsymbol{\tau})\boldsymbol{\gamma_r}$

(*6.3b)*

- $\boldsymbol{d}$: walking distance between LRT to/from the shuttle bus stop (station specific, usually 200m for Calgary, AB).
- $\boldsymbol{v_T}$: average walking speed of passengers (1m/sec = 3.6 km/hr)
- $\boldsymbol{\gamma_T}$: Passenger walking cost \$27.73/hr for Calgary was used (Reference Shafayat et al. 2015).
- $\boldsymbol{\gamma_w}$: Monetary value of transit passengers waiting time during PSD. We used \$13/passenger/hour during LRT planned service disruptions in Calgary (Asim et al, 2021)
- $\boldsymbol{\lambda_D}$: the agency's dispatch cost per bus per unit time (\$150 per bus/hour).
- $\boldsymbol{h(t)}$: headway of shuttle bus service, time/bus, as provided in Table 6.3
- $\boldsymbol{n}$: number of dwelling bus stops varies for different path choice.
- $\boldsymbol{\tau}$: the average passengers' trip dwell time at bus bridging stops, as provided in Table 6.1.
- $\boldsymbol{\gamma_r}$: value of in-vehicle riding time, (\$/Passenger/unit time), \$11.76 during LRT planned service disruptions in Calgary (Asim et al., 2021)
- $\boldsymbol{P(t)}$: passengers' demand at time *t. Hourly demand is provided in Tale-6.2*

- *K*: factor of passengers waiting time for transit vehicle. Values from 0.15 to .5 were used for various path choices considered in this study.

Local

From \ to	Anderson	Canyon Meadows	Fishcreek	Shawnessey	Somerset
Anderson	-	1	1	1	1
Canyon Meadows	1	-	1	1	1
Fishcreek	1	1	-	1	1
Shawnessey	1	1	1	-	1
Somerset	1	1	1	1	-

Express

From \ to	Anderson	Canyon Meadows	Fishcreek	Shawnessey	Somerset
Anderson	-	-	-	-	1
Canyon Meadows	-	-	-	-	-
Fishcreek	-	-	-	-	-
Shawnessey	-	-	-	-	-
Somerset	1	-	-	-	-

Local Express

From \ to	Anderson	Canyon Meadows	Fishcreek	Shawnessey	Somerset
Anderson	-	-	-	1	-
Canyon Meadows	-	-	-	-	1
Fishcreek	-	-	-	-	-
Shawnessey	1	-	-	-	-
Somerset	-	1	-	-	-

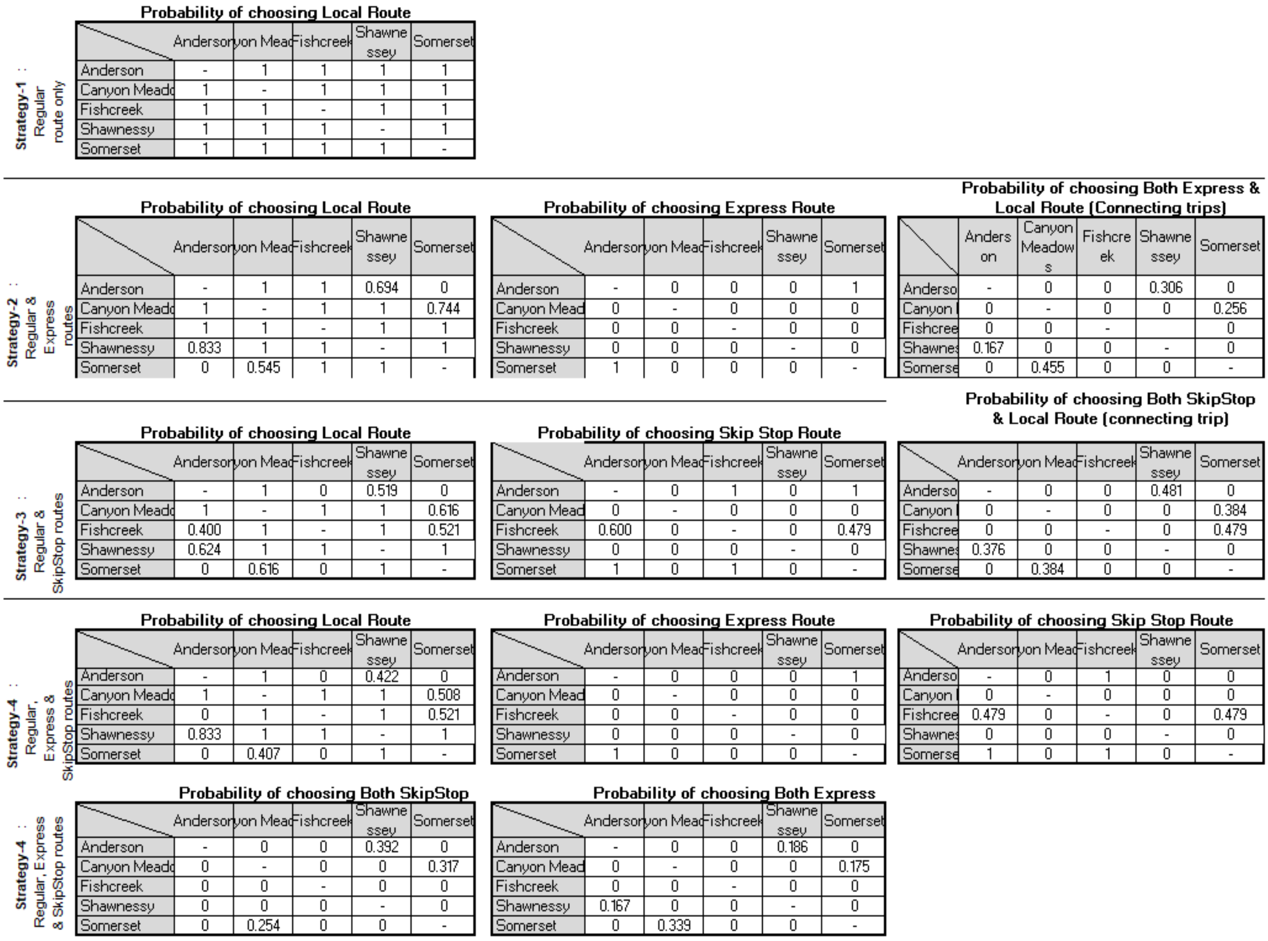
SkipStop

From \ to	Anderson	Canyon Meadows	Fishcreek	Shawnessey	Somerset
Anderson	-	-	1	-	-
Canyon Meadows	-	-	-	-	-
Fishcreek	1	-	-	-	1
Shawnessey	-	-	-	-	-
Somerset	-	-	1	-	-

Local-SkiStop

From \ to	Anderson	Canyon Meadows	Fishcreek	Shawnessey	Somerset
Anderson	-	-	-	1	-
Canyon Meadows	-	-	-	-	-
Fishcreek	-	-	-	-	-
Shawnessey	-	-	-	-	-
Somerset	-	1	-	-	-

Figure 6.6: Path incidence matrix ‘Δ’ for the provided bus bridging strategies, a cell entry of one indicates that the bus stops and 0 if it skips the stop.



Strategy-1 : Regular route only

Probability of choosing Local Route

	Anderson	yon Mea	Fishcreek	Shawnessey	Somerset
Anderson	-	1	1	1	1
Canyon Meado	1	-	1	1	1
Fishcreek	1	1	-	1	1
Shawnessy	1	1	1	-	1
Somerset	1	1	1	1	-

Strategy-2 : Regular & Express routes

Probability of choosing Local Route

	Anderson	yon Mea	Fishcreek	Shawnessey	Somerset
Anderson	-	1	1	0.694	0
Canyon Meado	1	-	1	1	0.744
Fishcreek	1	1	-	1	1
Shawnessy	0.833	1	1	-	1
Somerset	0	0.545	1	1	-

Probability of choosing Express Route

	Anderson	yon Mea	Fishcreek	Shawnessey	Somerset
Anderson	-	0	0	0	1
Canyon Mead	0	-	0	0	0
Fishcreek	0	0	-	0	0
Shawnessy	0	0	0	-	0
Somerset	1	0	0	0	-

Probability of choosing Both Express & Local Route (Connecting trips)

	Anderson	Canyon Meadows	Fishcreek	Shawnessey	Somerset
Anderso	-	0	0	0.306	0
Canyon	0	-	0	0	0.256
Fishcree	0	0	-		0
Shawnes	0.167	0	0	-	0
Somerse	0	0.455	0	0	-

Strategy-3 : Regular & SkipStop routes

Probability of choosing Local Route

	Anderson	yon Mea	Fishcreek	Shawnessey	Somerset
Anderson	-	1	0	0.519	0
Canyon Meado	1	-	1	1	0.616
Fishcreek	0.400	1	-	1	0.521
Shawnessy	0.624	1	1	-	1
Somerset	0	0.616	0	1	-

Probability of choosing Skip Stop Route

	Anderson	yon Mea	Fishcreek	Shawnessey	Somerset
Anderson	-	0	1	0	1
Canyon Mead	0	-	0	0	0
Fishcreek	0.600	0	-	0	0.479
Shawnessy	0	0	0	-	0
Somerset	1	0	1	0	-

Probability of choosing Both SkipStop & Local Route (connecting trip)

	Anderson	yon Mea	Fishcreek	Shawnessey	Somerset
Anderso	-	0	0	0.481	0
Canyon	0	-	0	0	0.384
Fishcree	0	0	-	0	0.479
Shawnes	0.376	0	0	-	0
Somerse	0	0.384	0	0	-

Strategy-4 : Regular, Express & SkipStop routes

Probability of choosing Local Route

	Anderson	yon Mea	Fishcreek	Shawnessey	Somerset
Anderson	-	1	0	0.422	0
Canyon Meado	1	-	1	1	0.508
Fishcreek	0	1	-	1	0.521
Shawnessy	0.833	1	1	-	1
Somerset	0	0.407	0	1	-

Probability of choosing Express Route

	Anderson	yon Mea	Fishcreek	Shawnessey	Somerset
Anderson	-	0	0	0	1
Canyon Mead	0	-	0	0	0
Fishcreek	0	0	-	0	0
Shawnessy	0	0	0	-	0
Somerset	1	0	0	0	-

Probability of choosing Skip Stop Route

	Anderson	yon Mea	Fishcreek	Shawnessey	Somerset
Anderso	-	0	1	0	0
Canyon	0	-	0	0	0
Fishcree	0.479	0	-	0	0.479
Shawnes	0	0	0	-	0
Somerse	1	0	1	0	-

Strategy-4 : Regular, Express & SkipStop routes

Probability of choosing Both SkipStop

	Anderson	yon Mea	Fishcreek	Shawnessey	Somerset
Anderson	-	0	0	0.392	0
Canyon Meado	0	-	0	0	0.317
Fishcreek	0	0	-	0	0
Shawnessy	0	0	0	-	0
Somerset	0	0.254	0	0	-

Probability of choosing Both Express

	Anderson	yon Mea	Fishcreek	Shawnessey	Somerset
Anderson	-	0	0	0.186	0
Canyon Mead	0	-	0	0	0.175
Fishcreek	0	0	-	0	0
Shawnessy	0.167	0	0	-	0
Somerset	0	0.339	0	0	-

Figure 6.7: Resulting probabilities 'δ_{ij}' of passenger paths to be chosen for each origin-destination pair (i, j) for all four bus bridging strategies.

The input parameters are assumed as follows. Standard-size buses (i.e., buses with capacity of 60 pass/bus) were used on local route, and articulated-size buses (i.e., buses with capacity of 110 pass/bus) on express and skip stop routes. Roundtrip times of all the routes provided were calculated from historical bus station arrival and departure time information from APC data: Local route = 55 min; Express = 32 min; Skip stop = 42 min. Hourly total passenger demand (600 passengers/hr) was obtained from the busiest hours of operation (10 AM-10 PM) from the APC data for the PSD weekend event (May 7/8, 2022). The OD matrix inferred from this model's ridership data is shown in *Table 6.2*. The dispatch rate for the three routes (local, skip-stop, and express) considered in the four bus bridging strategies was calculated using their criteria, as provided above in *section 6.2.2.* Maximum values of dispatch out of the criteria of all routes were selected to provide better a level of service to passengers, i.e., dispatch policy. Buses on all routes were dispatched at 10 minutes headway for all strategies so that they could be aligned with the LRT schedule (10 min headway). Headways and required fleet size for all the routes in each bus bridging strategy are provided in *Table 6.*3 as output of iterative optimization process. Strategies of local-express and local-skip stop required fewer buses than the existing strategy-1 (Local) to serve the same passenger demand. However, strategy-4 (local-express-skip stop) requires one more bus than Strategy-1 (local).

Table 6.2.: Passengers hourly volumes for all OD pairs along the disrupted section of LRT.

From \ to	A. Anderson	B. Canyon Meadows	C. Fish creek	D. Shawnessey	E. Somerset	Total
A. Anderson	-	13	2	1	134	151
B. Canyon Meadows	4	-	16	4	7	31
C. Fish creek	39	9	-	12	22	81
D. Shawnessey	24	1	10	-	77	112
E. Somerset	206	1	3	19	-	228
Total	272	24	31	36	239	602

Table 6.3: Suggested bus headways and fleet size by the model for all routes in the routing strategies.

Iterations	Route Type	Local (Strategy-1)		Local-Express (Strategy-2)		Local-Skip (Strategy-3)		Local-Express-Skip (Strategy-4)	
		Headway (min.)	Fleet size (# of buses)	Headway (min.)	Fleet size (# of buses)	Headway (min.)	Fleet size (# of buses)	Headway (min.)	Fleet size (# of buses)
0	Local	10	6	10	6	10	6	10	6
	Express	-	-	30	1	-	-	30	1
	Skip	-	-	-	-	30	1	30	1
	Total Fleet size		6		7		7		8
1	Local	11	5	23	2	27	2	27	2
	Express	-	-	20	2	-	-	20	2
	Skip	-	-	-	-	17	2	45	1
	Total Fleet size		5		4		4		5
2	Local	11	5	22	3	26	2	23	2
	Express	-	-	19	2	-	-	19	2
	Skip	-	-	-	-	16	3	25	2
	Total Fleet size		5		4		5		6
3	Local	11	5	22	3	26	2	23	2
	Express	-	-	19	2	-	-	19	2
	Skip	-	-	-	-	16	3	25	2
	Total Fleet size		5		5		5		6
Policy Headways	Local	5	12	10	6	10	6	10	6
	Express	-		10	3	-	-	10	3
	Skip	-	-	-	-	10	4	10	4
	Total Fleet size		12		9		10		13

Note: The policy headways are used in the evaluation from this table of all the considered bus bridging strategies, so the bus routes dispatches are aligned with the LRT headways. The 5 minutes headways for Strategy-1 shows the currently in practise by the Calgary Transit during short-term LRT PSDs.

6.3.1 Analysis of the Results

The developed bus bridging methodology was used to evaluate the short-term LRT PSD event that occurred on May 7th and 8th, 2022, examining the two different passenger's transit assignment approaches at the lower level (i.e the discrete choice and deterministic). *Table 6.4* shows the results of the discrete choice approach that assigns passengers to path choices based on the logit model (i.e. perceived utility). The results indicate that strategy-2 (local-express) and strategy-3 (local-skip stop) have the least associated total cost and are thus the recommended strategies for this scenario, with total passenger cost savings of 24% and 22%, respectively. Strategy-2 offers maximum passenger cost savings (24%) and operating cost savings (24%), with a combined savings of 25%. In this approach, the model recommends strategy-2 to be deployed along the section of Red Line LRT from Anderson to Somerset station in the case of planned short-term service disruption.

Table 6.4: Comparison of effectiveness of various bus bridging strategies using the discrete choice approach.

	Benchmark Strategy-1 (Local)	Strategy-2 (Local-Express)	Strategy-3 (Local-Skip Stop)	Strategy-4 (Local – Express-Skip Stop)
System-wide Total passenger cost	$3,153	$2,382	$2,464	$3,322
Comparison with Startegy-1	-	-24%	-22%	5%
Fleet size required (#) (Policy headway)	12	9	10	13
Bus bridging service Operating cost ($/hr.)	$3,000	$2,250	$2,500	$3,250
Operating cost comparison with Strategy-1	-	25%	17%	-8%
Total Cost (Passengers + Operating)	$6,153	$4,632	$4,964	$6,572
Total Cost (Passenger + Operating) Comparison with Strategy-1	-	-25%	-19%	7%

Table 6.5 illustrates the results of the deterministic approach that assigns passengers on the routes to get to their destination such that the total passengers' cost is minimized. The results suggest that Strategy-2 (Local-Express) and strategy-4 (local-express-skip Stop) both yield the minimum passenger cost as compared to Strategy-1 (local), 29% and 30%, respectively. However, the operating cost of Strategy-4 is higher than that of Strategy-2. Therefore, Stragey-2 offers the maximum total cost savings (i.e., 25%) and is also recommended to be deployed for this section of Red Line LRT. For the reader's convenience, *Table 6.6* summarizes the total passengers' costs in both approaches.

Table 6.5: Comparison of effectiveness of various bus bridging strategies using the deterministic transit assignment approach.

	Benchmark Strategy-1 (Local)	Strategy-2 (Local-Express)	Strategy-3 (Local-Skip Stop)	Strategy-4 (Local – Express-Skip Stop)
System-wide Total passenger cost	$3,153	$2,229	$2,415	$2,221
Comparison with Startegy-1	-	-29%	-23%	-30%
Fleet size required (#) (Policy headway)	12	9	10	13
Bus bridging service Operating cost ($/hr.)	$3,000	$2,250	$2,500	$3,250
Operating cost comparison with Strategy-1	-	-25%	-17%	8%
Total Cost (Passengers + Operating)	$6,153	$4,632	$4,964	$5,471
Total Cost (Passenger + Operating) Comparison with Strategy-1	-	-25%	-19%	-11%

Table 6.6: Comparison of results of both bus bridging Strategies approached proposed in the case study.

Bus Bridging Costs	**Strategy-1**	**Strategy-2**	**Strategy-3**	**Strategy-4**
Passengers cost (Discrete Choice Approach)	\$3,153	\$2,382	\$2,464	\$3,322
Passengers cost (Deterministic Approach)	\$3,153	\$2,229	\$2,415	\$2,221
Comparison (Total Passenger Cost)	-	-6%	-2%	-33%
Bus bridging service Operating cost (Policy dispatch)	\$3,000	\$2,250	\$2,500	\$3,250
Passengers + Operating cost (Discrete Choice Approach)	\$6,153	\$4,632	\$4,964	\$6,572
Passengers + Operating cost (Deterministic Approach)	\$6,153	\$4,479	\$4,915	\$5,471
Comparison Total Cost (Operating + Passengers)		-3%	-1%	-17%

6.4. Sensitivity Analysis

In the case study, a sensitivity analysis is performed to evaluate the performance of the developed bus bridging model under varying passenger demand patterns and considering the uncertainty of passengers' choices.

6.4.1 Effect of passengers' demand pattern using the discrete choice approach

In this analysis, total ridership was kept unchanged along the bus bridging corridor, but the passenger demand pattern was changed randomly for all OD pairs. The random OD demand was generated using random number generator with a condition to keep the total ridership same along the bus bridging corridor. Various patterns were generated and the chosen the ones that provided different scenarios such as evenly distributed demand along the corridors, heavy demand on certain stations (for example one terminal station to the other terminal, at middle station). The purpose of this exercise was to examine the sensitivity of the developed algorithm to changes in demand patterns. Route headways were assumed to remain unchanged.

In the *Figure 6.8* passenger demand patterns are shown on the horizontal axis, where “0” indicates the base demand pattern and “1” to “6” indicates other demand patterns with different OD passengers demand along the corridor. The vertical axis shows the total passengers cost on a certain routing strategy which is sum of walking time, waiting time, transfer time and riding time, of the strategy. The figure describes that the total passenger cost of strategy-2 (local-express) and strategy-3 (local-skip stop) have always been lower than that of strategy-1 (local) and strategy-4 (local-express-skip stop). Passengers’ costs in strategy-2 and 3 are very close. The local-skip stop strategy performs best and provides up to 22% better service to passengers (lower total passengers cost) than the current local only strategy with 18% average passengers total cost savings. The local-express strategy provides up to 20.8% better passenger service than the current local only strategy with 15.5% average passengers total cost savings. The results of this analysis show that the methodology proposed in this study is responsive to changes in the ridership pattern along the bus bridging corridor. The results also suggest that the bus bridging strategy, which impacts the passengers the least without increasing the operating cost of the bus bridging service to the transit agency, is recommended.

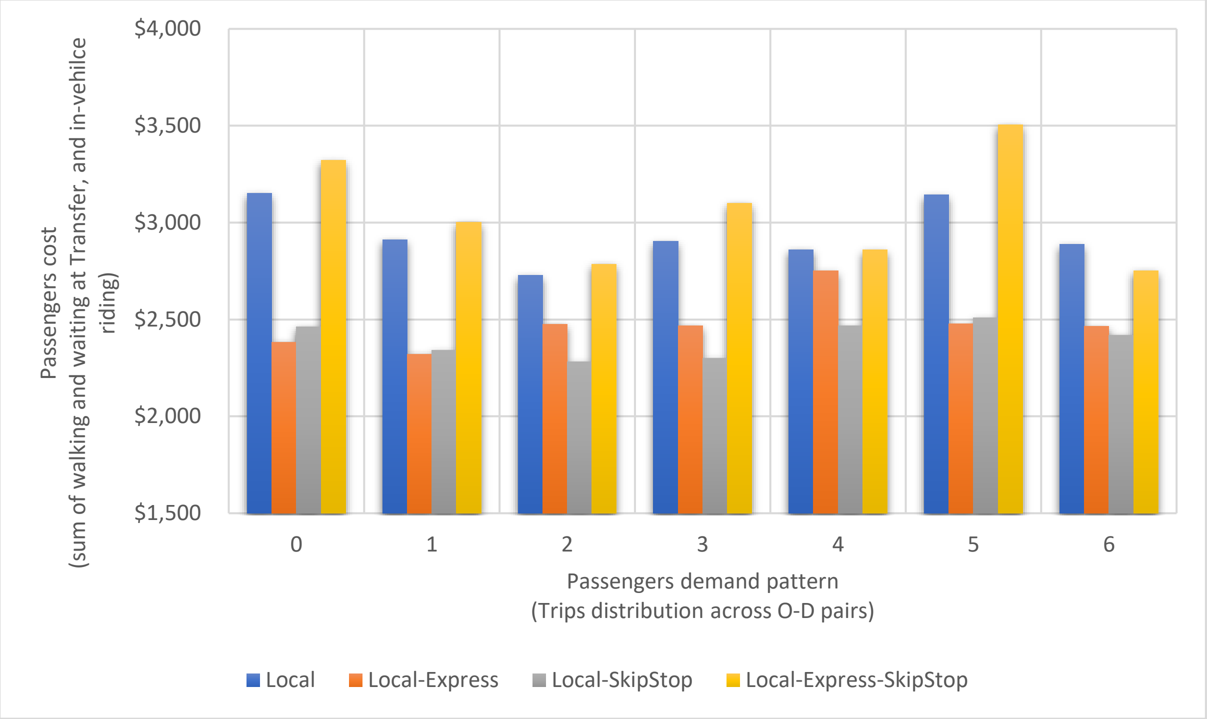


Figure 6.8: Bus bridging strategies evaluation under changing passengers' OD demand pattern based on the discrete passengers' route choice approach

As shown in Figure 6.9, passenger demand increased gradually, by 50 passengers, along with the ridership pattern, and it was observed that all the proposed bus bridging routing strategies alternative to the single route (local) outperformed the conventional local bus bridging strategy. Strategy 2, 3 and 4 caused 15%, 15%, and 13% less passenger total cost than local strategy-1 (local), respectively. The model suggests optimal headways for each route in a bus bridging strategy. This information is provided in *Table 6.7* separately for all four strategies tested in this study.

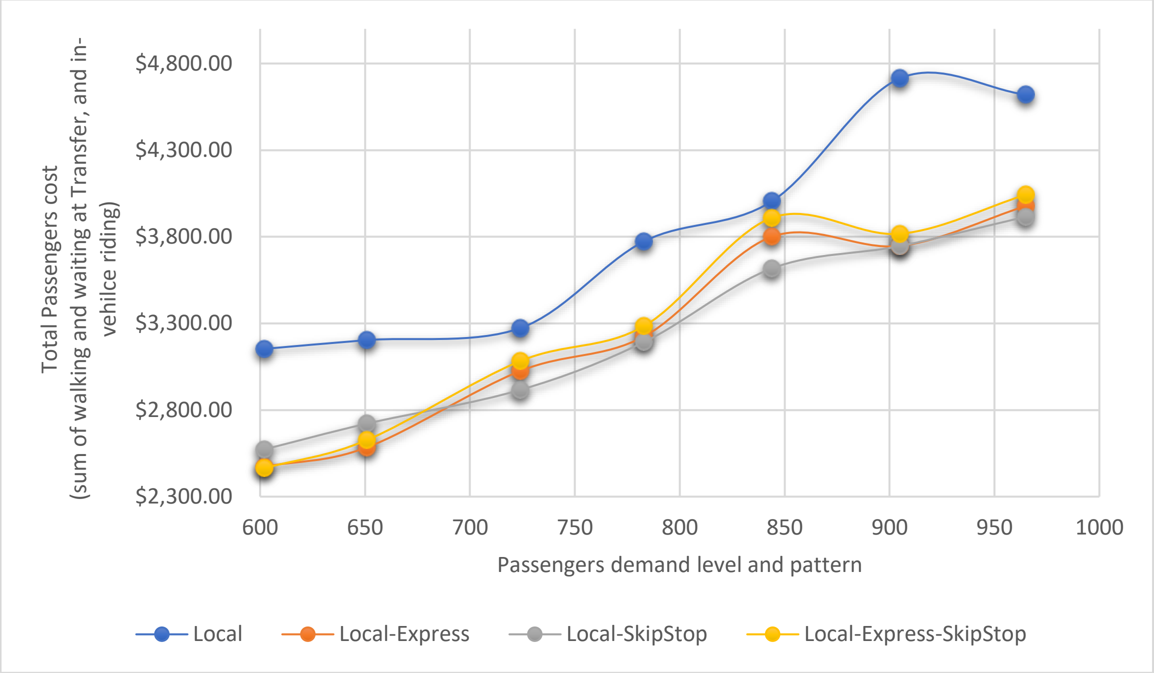


Figure 6.9: Bus bridging strategies evaluation under increasing ridership demand and changing passengers' OD demand pattern based on the based on the discrete passengers' route choice approach

Table 6.7: Optimal routes headways and required fleet size as suggested by the model, using a discrete choice approach.

Passengers Demand (#)	Route Type	Local		Local-Express		Local-Skip		Local-Express-Skip	
		Headway (minutes)	Fleet size (# of buses)	Headway (minutes)	Fleet size (# of buses)	Headway (minutes)	Fleet size (# of buses)	Headway (minutes)	Fleet size (# of buses)
602	Local	11	5	22	3	26	2	23	2
	Express	-	-	19	2	-	-	19	2
	Skip	-	-	-	-	16	3	25	2
	Total Fleet size		5		5		6		7
651	Local	10	6	18	3	22	3	21	3

	Express	-	-	21	2	-	-	21	2
	Skip	-	-	-	-	17	2	51	1
	Total Fleet size		6		6		6		6
723	Local	9	6	12	5	18	3	17	3
	Express	-	-	30	1	-	-	26	1
	Skip	-	-	-	-	17	2	27	2
	Total Fleet size		6		6		6		7
784	Local	8	7	13	4	18	3	17	3
	Express	-	-	21	2	-	-	21	2
	Skip	-	-	-	-	14	3	32	1
	Total Fleet size		7		7		6		7
844	Local	8	7	10	6	13	4	12	5
	Express	-	-	24	1	-	-	26	1
	Skip	-	-	-	-	16	3	27	2
	Total Fleet size		8		8		8		9
905	Local	7	8	15	4	21	3	18	3
	Express	-	-	15	2	-	-	18	2
	Skip	-	-	-	-	10	4	35	1
	Total Fleet size		8		7		8		8
965	Local	7	8	11	5	16	3	14	4
	Express	-	-	17	2	-	-	18	2
	Skip	-	-	-	-	12	4	27	2
	Total Fleet size		9		8		9		8

6.4.2 Effect of uncertainty in choice probabilities based on the discrete passengers' route choice approach:

In this sensitivity analysis, total ridership and demand patterns were kept unchanged along the bus bridging corridor. Still, uncertainty in the passengers' choice (i.e., scaling parameter θ) among the available strategies was changed from 0.025 to 1 to reflect the quality of the information received, with 1 indicating perfect information. Route headways were assumed to remain unchanged. This analysis suggests that the route choice behaviour of diverse types of passengers among the bus bridging strategies is similar (*Figure 6.10)*. In other words, strategy-2 (local-express) and strategy-3 (local-skip stop) are perceived to be the most attractive strategies by all types of passengers (passengers with diverse choice tastes). This implies that despite the wider spread of passengers (i.e., passengers with diverse demographics and choice tastes), the recommended bus bridging strategy suggested by the model would not change much.

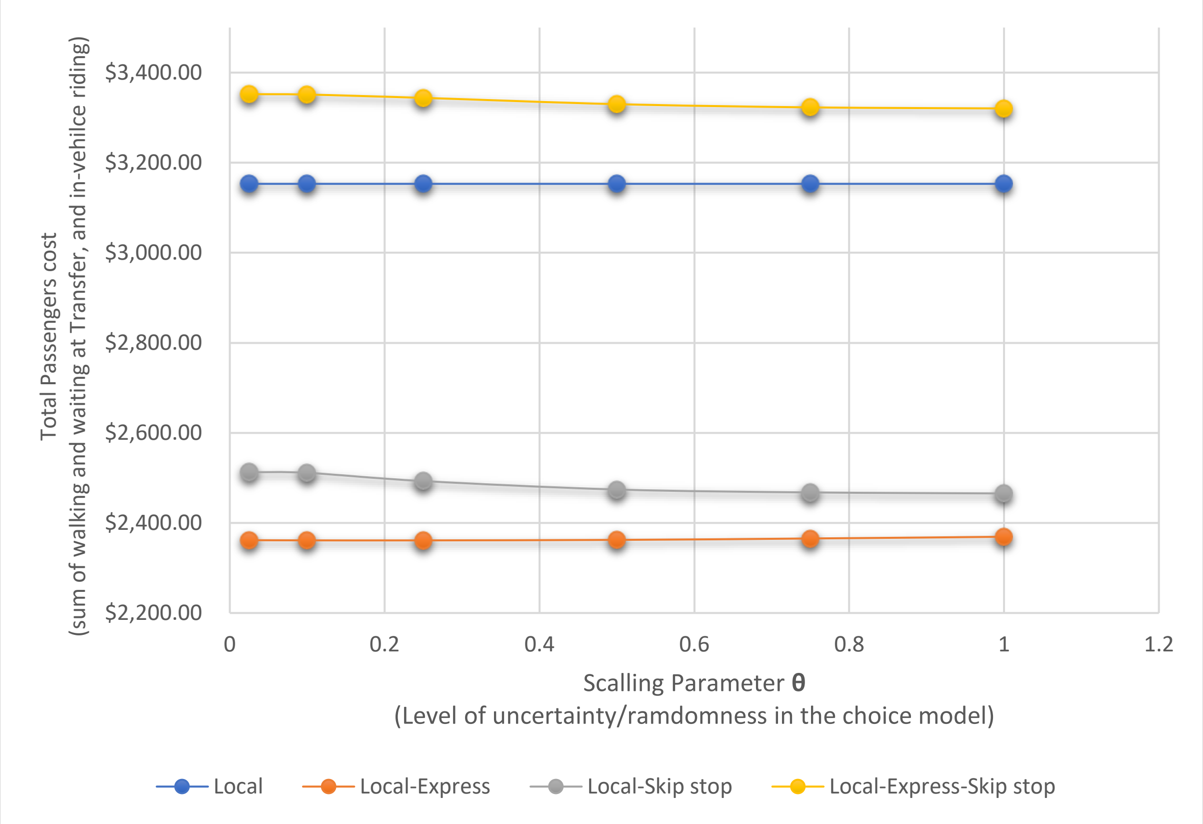


Figure 6.10: Bus bridging strategies evaluation under variability of choice probabilities, expressed by scaling parameter based on the discrete passengers' route choice approach

6.4.2 Effect of passenger demand pattern using the deterministic approach

In this analysis, total ridership was kept unchanged along the bus bridging corridor, but the passenger demand pattern was changed randomly for all OD pairs. Route headways were assumed to remain unchanged. The random OD demand was generated using random number generator with a condition to keep the total ridership same along the bus bridging corridor. Various patterns were generated and the chosen the ones that provided different scenarios such as evenly distributed demand along the corridors, heavy demand on certain stations (for example one terminal station to the other terminal, at middle station).

In the *Figure 6.11* passenger demand patterns are shown on the horizontal axis, where “0” indicates the base demand pattern and “1” to “6” indicates other demand patterns with different OD passengers demand along the corridor. The vertical axis shows the total passengers cost on a certain routing strategy which is sum of walking time, waiting time, transfer time and riding time, of the strategy. The figure describes that the total passenger cost of strategy-2 (local-express), strategy-3, and strategy-4 (local-express-Skip Stop) have always been lower than that of strategy-1 (local). Total passengers cost in strategy-2 and 4 are very close and for some demand patterns, strategies-1, 2, and 3 offer similar optimal total passengers cost. That being said, the local-Express-Skip stop strategy performs best and provides up to 33% better service to passengers (lower total passengers cost) than the current local only strategy, with 30% overall average passengers total cost savings. Local-express strategy provides up to 32% better passenger service than the current local only strategy with 29% average passengers total cost savings. The results of this analysis show that the proposed methodology is responsive to the changes in ridership patterns along the bus bridging corridor. The results also suggest that the bus bridging strategy, which impacts the passengers the least without increasing the operating cost of the bus bridging service to the transit agency, is recommended.

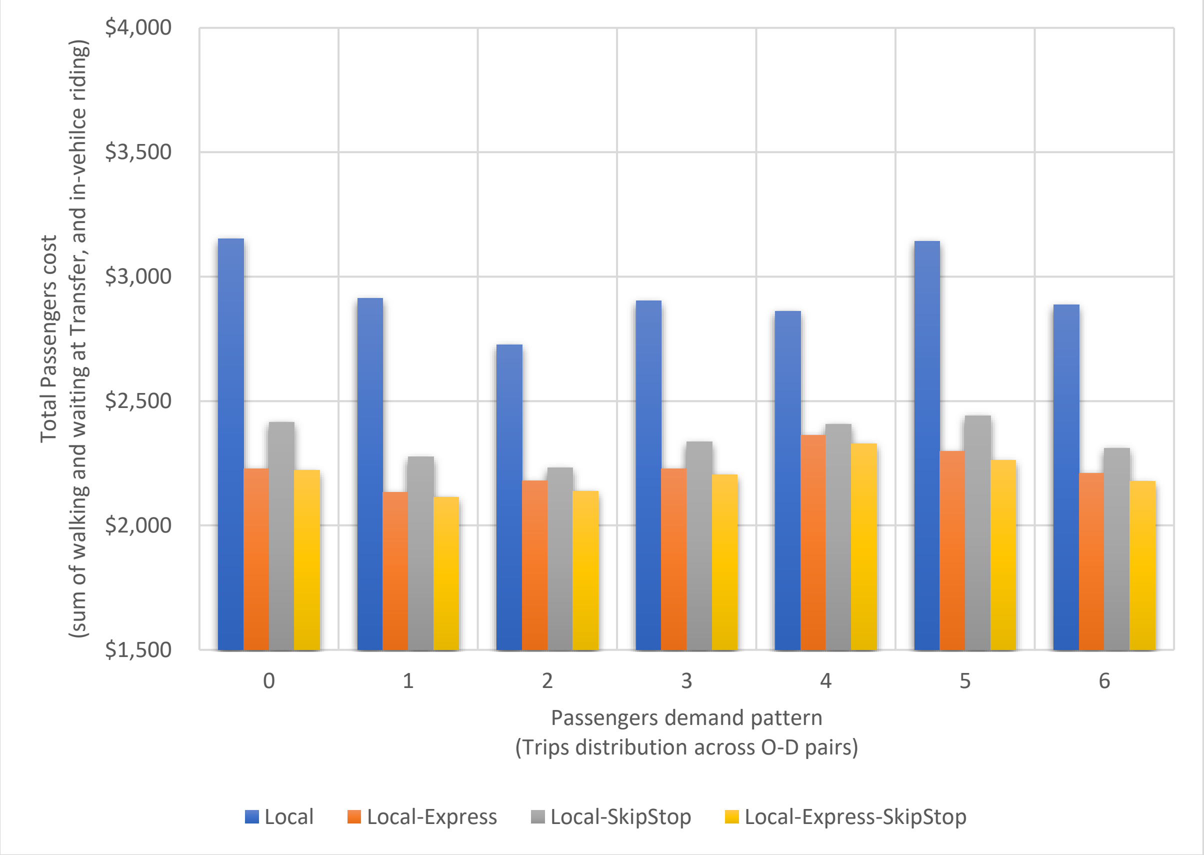


Figure 6.11: Bus bridging strategies evaluation under changing passengers' OD demand pattern based on the deterministic transit assignment approach.

As shown in *Figure 6.12*, passenger demand was increased gradually along with the ridership pattern and observed that all the proposed bus bridging routing strategies alternative to the single route (local) outperformed the conventional local bus bridging strategy. Strategy 2, 3 & 4 cause 16%, 24%, and 26% less passengers total cost than the local strategy-1 (local), respectively. Strategy-3 and strategy-4 offer least passengers cost as compared to the Strategy-2. The dip in the graph of passenger costs for strategy-3 and strategy-4 may be due to passenger's demand more to/from the terminal, and middle stations, which are serviced by skip-stop route provided. The model suggests optimal headways for each route in a bus bridging strategy. This information is provided in *Table 6.8* separately for all four strategies tested in this study.

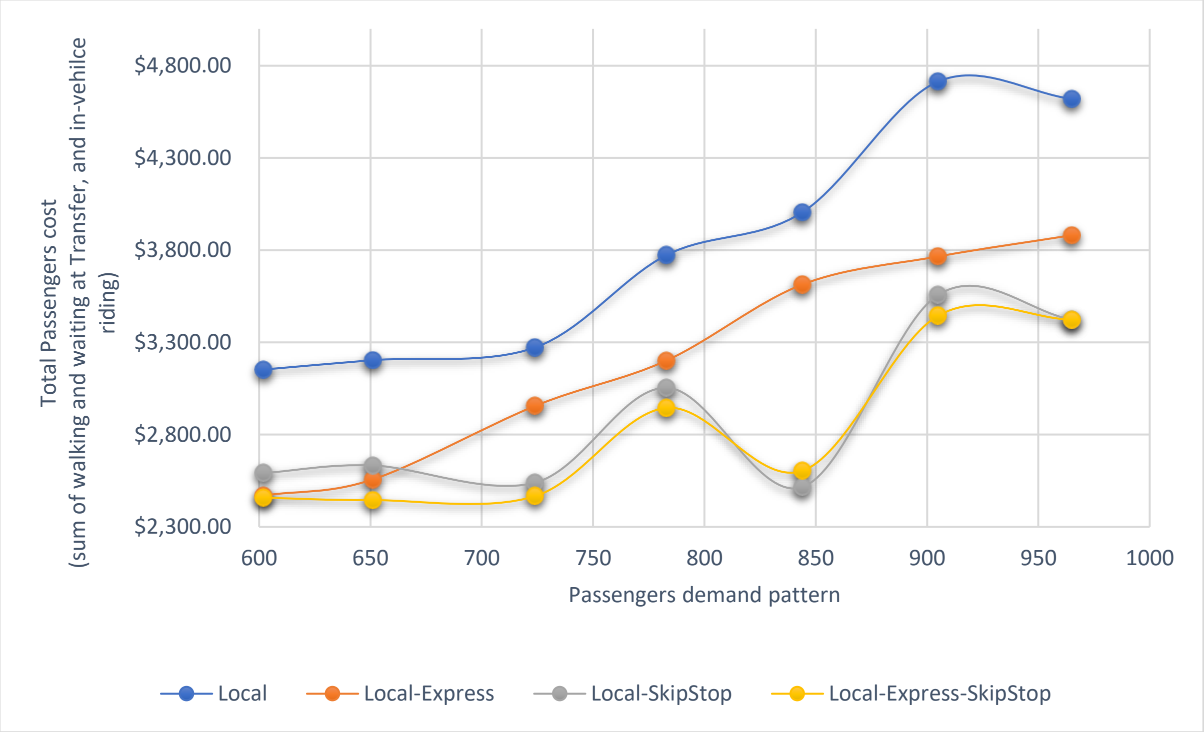


Figure 6.12: Bus bridging strategies evaluation under increasing ridership demand and changing passengers' OD demand pattern based on the deterministic transit assignment approach

Table 6.8: Optimal routes headways and required fleet size as suggested by the model, using the deterministic transit assignment approach.

Passengers' Demand (#)	Route Type	Local		Local-Express		Local-Skip		Local-Express-Skip	
		Headway (minutes)	Fleet size (# of buses)	Headway (minutes)	Fleet size (# of buses)	Headway (minutes)	Fleet size (# of buses)	Headway (minutes)	Fleet size (# of buses)
602	Local	11	5	22	3	26	2	23	2
	Express	-	-	19	2	-	-	19	2
	Skip	-	-	-	-	16	3	25	2
	Total Fleet size		5		5		6		7
651	Local	10	6	18	3	22	3	21	3
	Express	-	-	21	2	-	-	21	2

	Skip	-	-	-	-	17	2	51	1
	Total Fleet size		6		6		6		6
723	Local	9	6	12	5	12	5	12	5
	Express	-	-	35	1	-	-	27	1
	Skip	-	-	-	-	22	2	40	1
	Total Fleet size		6		6		7		7
784	Local	8	7	13	4	18	3	13	4
	Express	-	-	22	1	-	-	22	1
	Skip	-	-	-	-	14	3	50	1
	Total Fleet size		7		7		8		8
844	Local	8	7	10	6	12	5	10	6
	Express	-	-	24	1	-	-	26	1
	Skip	-	-	-	-	13	3	27	2
	Total Fleet size		8		8		9		10
905	Local	7	8	15	4	21	3	16	3
	Express	-	-	15	2	-	-	13	2
	Skip	-	-	-	-	10	4	37	1
	Total Fleet size		8		7		8		9
965	Local	7	8	10	6	12	5	10	6
	Express	-	-	18	2	-	-	14	2
	Skip	-	-	-	-	12	4	37	1
	Total Fleet size		9		8		9		10

For the sensitivity analysis, it is found that the discrete passengers' route choice approach of passenger assignment on various routes of routing strategy represents is more realistic in modelling the level of uncertainty (θ) and can incorporate the effect of passengers diverse demographics and level of information accuracy. The deterministic transit assignment approach, on the other hand, does not have this capability as it represents an ideal scenario where all passengers have complete information about the available route alternatives.

6.5 Chapter Summary

In this chapter, we proposed a methodology to design an optimal bus bridging strategy for improving passenger level of services to compensate for the inconvenience they face during the PSDs. Extensive work has been done for route design in case of planned and unplanned transit disruption. However, no previous work is available on bus bridging strategy design in the context of short-term LRT PSDs. Deterministic and discrete choice approaches of passenger assignment models were proposed considering passengers impacts (wait time and walking time at transfer stations, riding time, which is a combination of cruising and dwelling time). The methodology recommends the bus bridging strategy that causes the least passengers inconvenience system-wide by comparing various types of bus routing strategies and suggesting bus headways and fleet size required for all the routes in the recommended routing strategy.

The methodology proposed in this chapter is based on the classical model proposed by Spiess and Florian back in 1989 (Spiess and Florian 1989). MNL logit model was introduced in the passenger assignment for modelling realistic passengers' perceived choice behaviour to choose among the available routes. Values of time for parameters such as waiting time, walking time and riding time were used, which were estimated for the city where the case study was conducted. The proposed model was tested with variation in passenger demand levels and passenger distribution along a disrupted section. The model was found to be robust and can determine optimal bus bridging for disrupted sections of short-term PSD successfully. The proposed model is developed in consideration of shorter sections (covering 2-5 stations) of disrupted PSD along a single mass transit line, which can be a limitation of this model. Following are a few suggestions for future work:

- Exploring alternate technologies to quantify short-term PSDs' impacts, such as Automated Fare Collection (AFC) and WiFi sensing technology. WiFi sensing technology for inferring transit passenger activity and system performance is an emerging research topic. Much research is required to explore the potential of this technology further to generate more accurate data without compromising the privacy of smartphone users.
- Providing bus bridging service at the LRT network level during LRT short-term PSD to connect the busy LRT stations which are not on the same line [e.g., between busy stations of the Red line and Blue line]. This type of service may offer better service and save travel time than the original LRT service, where passengers make transfers downtown to other LRT lines. Good quality origin-destination historical information would be required to identify busy stations in the LRT network.
- Using a bus fleet of different capacities on bus bridging routes during short-term planned service disruptions, a combination of mini, standard-size buses and articulated buses.

Chapter-7

Conclusion and Recommendations for Future Work

7.1 Conclusions

This research examined LRT (Light Rail Transit) users' travel mode choice preferences in the event of short-term LRT Planned Service Disruptions (PSDs) and proposed methodology for designing an optimal bus bridging strategy for providing improved level of service to the passengers during the short-term LRT PSD.

In the first part of this thesis, a detailed combined revealed preference (RP) and stated preference survey was designed and distributed to collect information on passengers' behaviour on mode choice responses under a set of hypothetical short-term LRT PSD scenarios in the City of Calgary, AB, Canada. A mixed multinomial logit (MNL) model was calibrated using the collected data to identify the factors contributing to the presented alternative mode choices. A sensitivity analysis was also conducted to examine the impact of variations in transit fare, carshare fare and wait time at the transfer stations for the express shuttle on the mode choice probabilities.

The findings of this part of the research improve the understanding of transit passengers' behavioural choices under short-term LRT PSDs. The results of the analysis show that, in the context of the short-term LRT PSD choice situation we investigated, LRT ridership can be reduced by up to 35%. More specifically, respondents who stated that they would avoid the LRT during the hypothetical disruption are likely to consider alternative travel mode, e.g. alternate transit bus route (17%), driving personal vehicle (6%), taxi/Uber (7%) or cancel/reschedule their trip (9%). The customers who use transit payment passes (monthly, seniors, students, juniors, employees, etc.) who are frequent weekend LRT users are more likely to stay with the LRT mode even during a short-term PSD. If customers are provided with alternative modes (express shuttle bus and carsharing) in addition to regular shuttle bus service, they would likely use those alternative modes (express shuttle bus and car sharing) to shorten their travel time. LRT users that belong to the high-income category are less likely to take transit during a short-term LRT PSD. The value of time was found to be 11.76 $/hr and 13.0 $/hr for travel time and wait time during travel, respectively.

The outcomes from the sensitivity analysis provide valuable information to transport planners in proposing potential measures to alleviate the impact on travellers due to service disruptions. The sensitivity analysis of important variables considered in this study showed that improving the level of shuttle bus service (bus bridging) would increase customers' choice probability for LRT. In-vehicle, travel time and wait time are found to be key components of bus bridging service.

In the second part of this research, we developed a methodology to design an optimal bus bridging strategy for improving passenger level of services to compensate for the inconvenience they face during the PSDs. Extensive work has been done for route design in case of planned and unplanned transit disruption. However, no previous work is available on bus bridging strategy design in the context of short-term LRT PSDs while anticipating the impacts of these strategies on passengers' route choice. A bilevel optimization model was developed. The upper-level recommends the bus bridging strategy that causes the least passengers inconvenience system-wide by suggesting bus headways and fleet size. At the same time, the lower level takes the form of either a deterministic or discrete choice approach of passengers assignment models to consider passengers related impacts (wait time and walking time at transfer stations, riding time which is combination of cruising and dwelling time). Thus, the deterministic model assigns passengers to bridging route choices based on a classical model proposed by Spiess and Florian back in 1989 (Spiess and Florian 1989). The discrete choice model uses an MNL logit model to assign passengers with a more realistic passengers perceived choice behaviour to choose among the available routes. Values of time for parameters such as waiting time, walking time and riding time were used, which were estimated for the city where the case study was conducted. The proposed model was tested with variation in passengers demand levels and passengers distribution along a disrupted section. The model was found to be robust and can determine optimal bus bridging for disrupted sections of short-term PSD successfully. The proposed model is developed in consideration of shorter sections (covering 2-5 stations) of disrupted PSD along a single mass transit line, which can be a limitation of this model. Results of the case study conducted in Calgary, AB, Canada, suggested that the proposed model for the bus bridging service design outperformed the conventional local route strategy and reduced passenger cost by up to 25%. The study contributes valuable insights and practical recommendations for enhancing transit services during short-term LRT disruptions.

7.2 Recommendations

- Provide car or ride-hailing options for the LRT customers during the short-term LRT planned service disruption at LRT stations located at the end of the closed LRT section. Car2Go or other similar service providers like Common auto or Uber/Lyft can be brought on board to provide this service. Subsidizing these services could also be considered.
- Wait time at the transfer station is an important component of transit users' perceived utility. Consider running an express bus shuttle in bus bridging. The schedule of the express shuttle service should be aligned with the LRT arrival at the stations where the bus bridging service is to be provided.
- Consider providing bus bridging service at the LRT network level during LRT short-term PSD to connect the busy LRT stations which are not on the same line (i.e., between

busy stations of the Red Line and Blue Line). This type of service may offer better service and save travel time than the original LRT service, where passengers make transfers downtown to other LRT lines. Good quality origin-destination historical information would be required to identify busy stations in the LRT network.

- Bus bridging level of service can be improved significantly by providing an express shuttle service that skips intermediate stations and offers shorter travel time (in addition to the regular shuttle service). This also reduces customers' wait time at transfer stations by increasing the frequency of the bus service and by improving the bus bridging schedule such that a bus should be available at the transfer station when LRT arrives. Other policies, like making the LRT free during the PSD and/or subsidizing carsharing, ride-hailing or e-scooter service can further improve the attractiveness of LRT during short-term PSDs. These initiatives would also help promote the mobility options (carsharing, ride-hailing and e-scooters)

7.3 Limitations and Future Research

Research conducted in this thesis was the first step for developing a methodology to design bus bridging service in the context of short-term LRT PSD. This work, while comprehensive, does acknowledge certain limitations which present opportunities for future research. The identified limitations and prospective research directions are as follows:

- In this study, a single route was considered for all respondents in the SP survey to cross the disrupted LRT section. So, there is a bias that LRT users would prefer to use the express shuttle bus service to travel around the disrupted section. So, this study can be redone by collecting more realistic data for mode choice analysis in a hypothetical scenario that can be pivoted around each respondent's actual route. Cell phone and WiFi data can also be used to complement the study by collecting real long-term ridership and mode choice data to examine the short, medium, and longer-term impact of transit PSDs.

- Automatic Passengers Counts (APC) data was used in this research to infer passengers' origin destination information. For quantifying the impacts of short-term PSDs, alternate technologies should be explored, such as Automated Fare Collection (AFC) and WiFi sensing technology. WiFi sensing technology for inferring transit passenger activity and system performance is an emerging research topic. Much research is required to explore the potential of this technology further to generate more accurate data without compromising the privacy of smartphone users.
- To model passengers' more realistic choice behaviour within the proposed framework of this study, it is advisable to utilize observed passenger data. This data, pertaining to various path choices made during travel along a disrupted section of rapid transit, can be effectively inferred from Automated Fare Collection (AFC) systems. Such systems, which include both tap-in and tap-out data, offer valuable insights into real-world passenger behaviour.
- A mixed Multinomial Logit model can be calibrated to capture more realistic passenger route choice behaviour for passengers' assignment in the context of the bus bridging strategies. MMNL effectively complies with the IIA and IID assumptions of the simpler MNL logit model, thereby ensuring a more robust passenger assignment onto various routes.
- In this research non-transit mode options (car, ride hail service etc.) were also provided to the survey respondents, which may not be practically feasible, such as transferring from LRT to transit shuttle bus (either low or high frequency) as compared to transferring from LRT to ride hail service. For future the study can be repeated with

offering the survey respondents with transit modes only, such as low frequency shuttle bus, high frequency shuttle bus, skip stop, or Express shuttle route etc.

APPENDICES

Appendix-A1: Figures related to the Survey

(Figures related outcome of the Survey conducted for this study)

Figure A1: The Survey invitation card designed for this study

Calgary Transit

UNIVERSITY OF CALGARY

CTrain Planned Disruptions Survey

We would like to hear from you!

(You will receive a free Starbucks Coffee gift card upon completing this survey)

CTrain service is disrupted at certain stations along the line for maintenance and upgrade work during some weekends. Please share your transit travel experience during a weekend CTrain service disruption.

Direct link to survey:

https://survey.ucalgary.ca/jfe/form/SV_1HoaZM3ls4UEju5

Survey is open **September 7** to **October 26, 2019**

For more information, please contact 403-966-4800 or Muhammad.asim@ucalgary.ca

The University of Calgary Conjoint Faculties Research Ethics Board has approved this study (REB19_0752)

Figure A2: Age distribution of individuals participated in the study

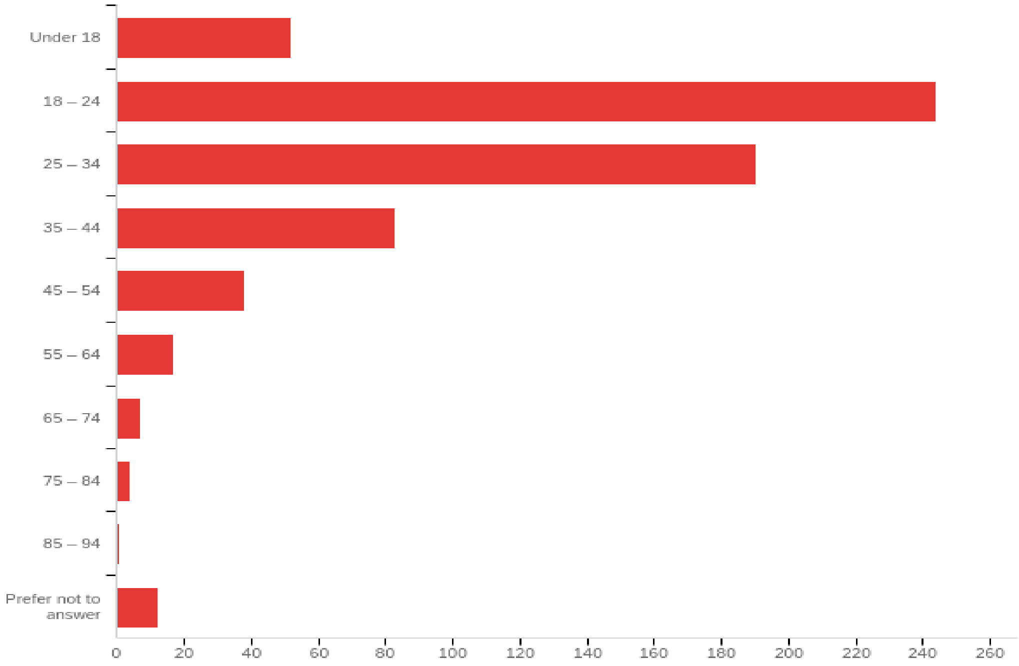


Figure A4: Occupation of the survey participants

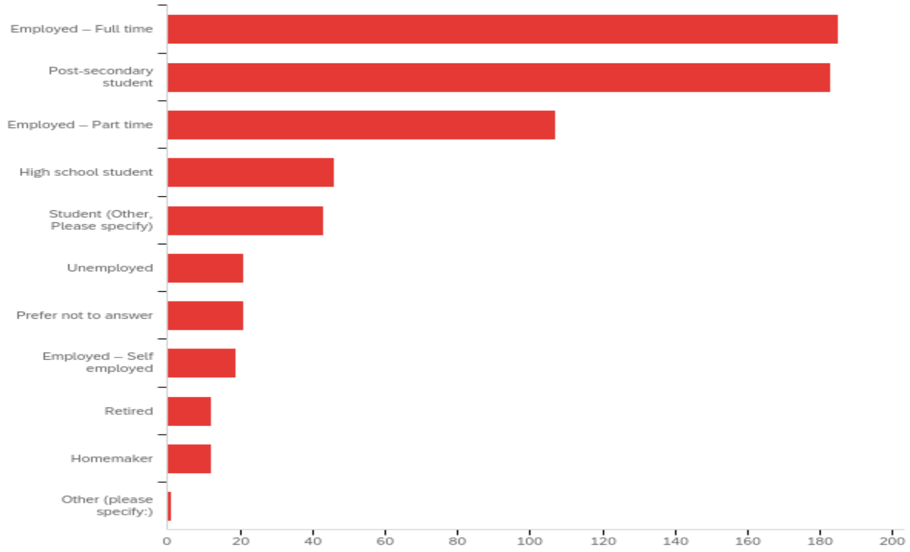
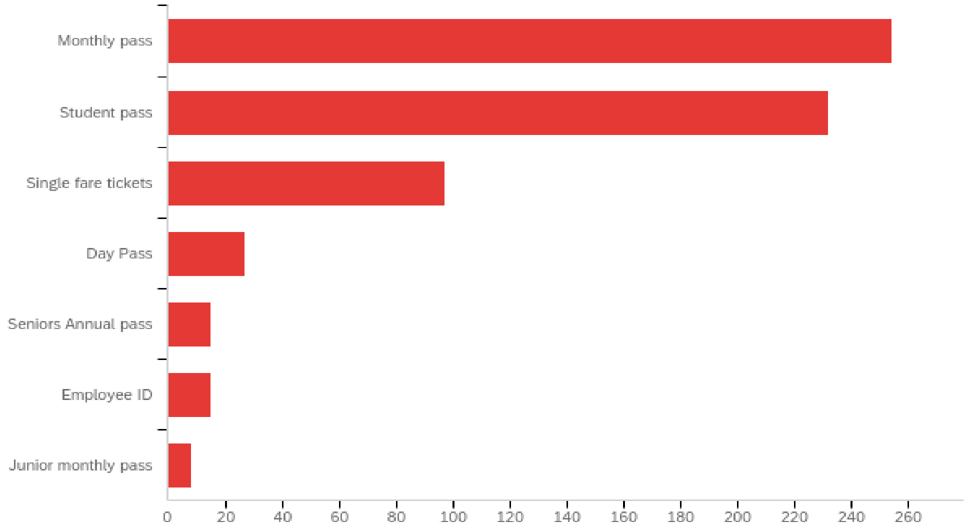


Figure A4: Transit fare types used by the survey participants



Appendix-A2: Ngene model and results

(Coding of the Ngene model to generate choice situations for MNL model)

All prior parameters estimate values were uniformly distributed with upper and lower bounds.
Access/Walk time: (u,-0.04,-0.02)
Wait time: (u,-0.05,-0.03)
Travel time (Shuttle bus, Train, car2Go,bus, drive, Taxi): (u,-0.03,-0.01)
Travel Cost (Car2Go): (u,-0.08,-0.02)

```
? *** CUSTOMERS EXPERIENCE WITH LRT DISRUPTED SERVICE (stated Preference Survey
Design)***
?Alternative Definitions:
? LRTdis_Shuttle_n = LRT disruption Shuttle bus stopping at intermediate stations
? LRTdis_Shuttle_h = LRT distruption shuttle non-stop/end-to-end
? LRTdis_C2G = Subsidized Car2Go service along disrupted LRT section
? Alt_Bus = Alternate Transit Bus route
? Pers_Car = Personal car from origin to destination.
? Taxi_Uber = Taxi or Uber along the disrupted LRT section
? Trip_Cancel = Trip Cancellation or rescheduling

?Attributes:
? C = Cost/Fare ($)
? Trans = Additional numberof Transfers (#)
? Tacc = Access Time to origin station (minutes)
? Tveh = In-Vehicle Travel Time (minutes)
? Twait = Waiting Time at Transfer points (minutes)
? Twalk = Walking Time between Transfers (minutes)
? Tegg = Egress time from destination station (minutes)
? TT = Total Travel Time (minutes)
?
*****************************************************************************************
**********

                        ?   ********************* Scenario - 1 **********************
 ;Design
;alts = LRTdis_Shuttle_n, LRTdis_Shuttle_h, LRTdis_C2G, Alt_Bus, Pers_Car, Taxi_Uber, Trip_Cancel

;rows = 24
;block = 4

?Efficinet Design parametter
;eff = (mnl,d)
;bdraws = halton(100)

 ;model:
U(LRTdis_Shuttle_n)        =      bWalk[(u,-0.04,-0.02)]*TaccSN[10, 15] + bWait[(u,-0.05,-0.03)]*TwaitN[0,
5, 10] + BttB[(u,-0.03,-0.01)]*ttSN[15,25] + BttT[(u,-0.03,-0.01)]* ttT[20,25]  /

U(LRTdis_Shuttle_h)        =      bWalk[(u,-0.04,-0.02)]*TaccSH[10, 15] + bWait[(u,-0.05,-0.03)]*TwaitH[0,
7.5, 15] + BttB[(u,-0.03,-0.01)] * ttSH[10,20] + BttT[(u,-0.03,-0.01)]* ttT[20,25]  /

U(Alt_Bus)              =      bwalk[(u,-0.04,-0.02)]*TaccB[3, 5] + bWait[(u,-0.05,-0.03)]*Twaitb[10, 15] +
BttB[(u,-0.03,-0.01)]*[50,60]/

U(Taxi_Uber)             =      BttD[(u,-0.03,-0.01)]*Tveh[25, 30] + Btc[(u,-0.08,-0.02)]*tcTU[30,40]  /

U(trip_cancel)           =      BNegativeConstant[-1.75]
```

```
 $

                         ?   ********************* Scenario - 2 ***********************

;Design
;alts = LRTdis_Shuttle_n, LRTdis_Shuttle_h, LRTdis_C2G, Alt_Bus, Pers_Car, Taxi_Uber, Trip_Cancel

;rows = 24
;block = 4

?Efficinet Design parametter
;eff = (mnl,d)
;bdraws = halton(100)

if(LRTdis_C2G.TTC2G=10, LRTdis_C2G.TC=[4.4,5.4]),
if(LRTdis_C2G.TTC2G=15, LRTdis_C2G.TC=[4.9,6.4])

;model:
U(LRTdis_Shuttle_n)        =       bWalk[(u,-0.04,-0.02)]*TaccSN[10, 15] + bWait[(u,-0.05,-0.03)]*TwaitN[0,
5, 10] + BttB[(u,-0.03,-0.01)]*ttSN[15,25] + BttT[(u,-0.03,-0.01)]* ttT[20,25]  /

U(LRTdis_Shuttle_h)        =       bWalk[(u,-0.04,-0.02)]*TaccSH[10, 15] + bWait[(u,-0.05,-0.03)]*TwaitH[0,
7.5, 15] + BttB[(u,-0.03,-0.01)] * ttSH[10,20] + BttT[(u,-0.03,-0.01)]* ttT[20,25]  /

U(LRTdis_C2G)              =       bWalk[(u,-0.04,-0.02)]*TaccC2G[10, 15] + bttD[(u,-0.03,-0.01)] *
TTC2G[10,15] + Btc[(u,-0.08,-0.02)] * TC[4.4,4.9,5.4,6.4] + BttT[(u,-0.03,-0.01)]* ttTFL[15,20] /

U(Alt_Bus)                 =       bwalk[(u,-0.04,-0.02)]*TaccB[3, 5] + bWait[(u,-0.05,-0.03)]*Twaitb[10, 15] +
BttB[(u,-0.03,-0.01)]*ttB[50,60]/

U(Taxi_Uber)               =       BttD[(u,-0.03,-0.01)]*Tveh[25, 30] + Btc[(u,-0.08,-0.02)]*tcTU[30,40]  /

U(trip_cancel)             =       BNegativeConstant[-1.75]

 $

                         ?   ********************* Scenario - 3 ***********************

;Design
;alts = LRTdis_Shuttle_n, LRTdis_Shuttle_h, LRTdis_C2G, Alt_Bus, Pers_Car, Taxi_Uber, Trip_Cancel

;rows = 24
;block = 4

?Efficinet Design parametter
;eff = (mnl,d)

if(LRTdis_C2G.TTC2G=10, LRTdis_C2G.TC=[4.4,5.4]),
if(LRTdis_C2G.TTC2G=15, LRTdis_C2G.TC=[4.9,6.4])

;bdraws = halton(100)

;model:
U(LRTdis_Shuttle_n)        =       bWalk[(u,-0.04,-0.02)]*TaccSN[10, 15] + bWait[(u,-0.05,-0.03)]*TwaitN[0,
5, 10] + BttB[(u,-0.03,-0.01)]*ttSN[15,25] + BttT[(u,-0.03,-0.01)]* ttT[20,25]  /

U(LRTdis_Shuttle_h)        =       bWalk[(u,-0.04,-0.02)]*TaccSH[10, 15] + bWait[(u,-0.05,-0.03)]*TwaitH[0,
7.5, 15] + BttB[(u,-0.03,-0.01)] * ttSH[10,20] + BttT[(u,-0.03,-0.01)]* ttT[20,25]  /
```

```
U(LRTdis_C2G)            =      bWalk[(u,-0.04,-0.02)]*TaccC2G[10, 15] + bttD[(u,-0.03,-0.01)] *
TTC2G[10,15] + Btc[(u,-0.08,-0.02)] * TC[4.4,4.9,5.4,6.4] + BttT[(u,-0.03,-0.01)]* ttTFL[15,20] /

U(Alt_Bus)               =      bwalk[(u,-0.04,-0.02)]*TaccB[3, 5] + bWait[(u,-0.05,-0.03)]*Twaitb[10, 15] +
BttB[(u,-0.03,-0.01)]*ttB[50,60]/

U(Pers_Car)              =      BttD[(u,-0.03,-0.01)]*Tveh[25, 30] /

U(Taxi_Uber)             =       BttD[(u,-0.03,-0.01)]*Tveh[25, 30] + Btc[(u,-0.08,-0.02)]*tcTU[30,40]  /

U(trip_cancel)           =      BNegativeConstant[-1.75]


 $
                                   ******************************
```

Ngene results

(Ngene Results for the MNL measures for the experiment Design)

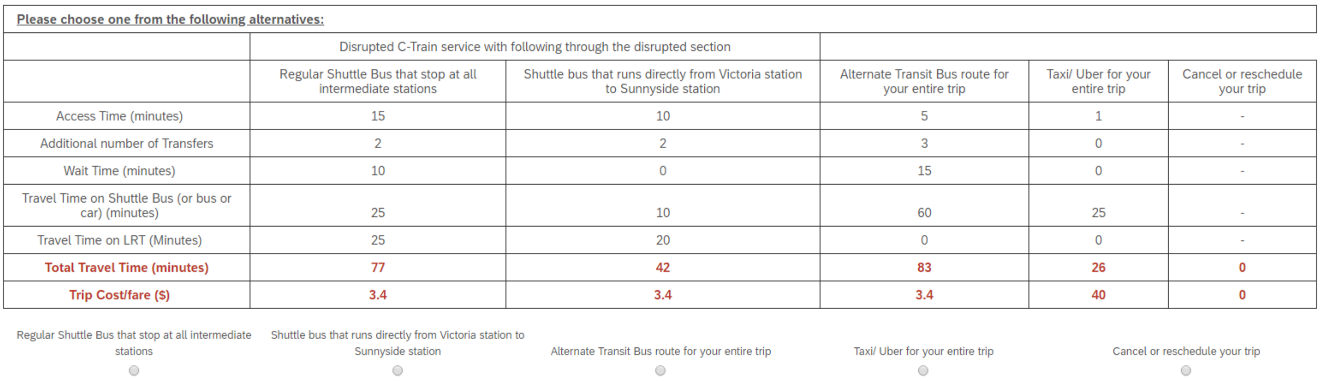
	Fixed (Bayesian)	**Mean**	**Std**	**dev.**	**Median**	**Minimum**	**Maximum**	
Scenario - 1	**D-error**	0.00	0.00	0.00	0.00	0.00	0.01	
	A-error	0.68	0.69	0.05	0.68	0.62	0.84	
	B-estimate	73.19	65.79	17.00	67.52	26.18	92.45	
	S-estimate	132.95	197.08	128.68	165.83	53.73	661.71	
	Prior	**Bwalk (Access)**	**Bwait (wait)**	**Bttb (Travel time on shuttle)**	**Bttt (Travel time on Train)**	**Bttd (Travel time Taxi/bus)**	**Btc (Cost)**	**bnegative constant**
	Fixed prior value	-0.03	-0.04	-0.02	-0.02	-0.02	-0.05	-1.75
	Sp- estimate	44.176	6.306	10.713	35.097	132.946	12.223	5.898
	Sp t-ratios	0.295	0.780	0.599	0.331	0.170	0.561	0.807
	Sb mean Estimates	50.07	6.83	14.24	45.76	194.53	15.61	6.03
	Sb mean T-ratios	0.29	0.77	0.59	0.33	0.17	0.52	0.80
Scenario - 2	**Fixed (Bayesian)**	**Mean**	**Std**	**dev.**	**Median**	**Minimum**	**Maximum**	
	D-error	0.00	0.00	0.00	0.00	0.00	0.00	
	A-error	0.58	0.59	0.03	0.58	0.54	0.69	
	B-estimate	66.29	59.55	15.70	60.61	24.59	87.67	
	S-estimate	55.91	82.39	42.96	67.89	28.98	211.82	
	Prior	**Bwalk (Access)**	**Bwait (wait)**	**Bttb (Travel time on**	**Bttt (Travel time**	**Bttd (Travel time**	**Btc (Cost)**	**bnegative constant**

				shuttle)	on Train)	Taxi/bus)		
	Fixed prior value	-0.03	-0.04	-0.02	-0.02	-0.02	-0.05	-1.75
	Sp- estimate	33.840	7.441	9.075	30.221	55.911	4.718	5.032
	Sp t-ratios	0.337	0.719	0.651	0.357	0.262	0.902	0.874
	Sb mean Estimates	38.22	8.01	12.03	39.72	73.94	6.31	5.12
	Sb mean T-ratios	0.33	0.71	0.65	0.35	0.26	0.87	0.87
Scenario - 3	**Fixed (Bayesian)**	**Mean**	**Std**	**dev.**	**Median**	**Minimum**	**Maximum**	
	D-error	0.00	0.00	0.00	0.00	0.00	0.00	
	A-error	0.63	0.64	0.02	0.64	0.59	0.70	
	B-estimate	38.10	35.11	13.35	32.87	13.37	65.62	
	S-estimate	50.67	80.10	40.23	68.85	28.76	202.05	
	Prior	**Bwalk (Access)**	**Bwait (wait)**	**Bttb (Travel time on shuttle)**	**Bttt (Travel time on Train)**	**Bttd (Travel time Taxi/bus)**	**Btc (Cost)**	**bnegative constant**
	Fixed prior value	-0.03	-0.04	-0.02	-0.02	-0.02	-0.05	-1.75
	Sp- estimate	34.527	10.318	10.973	35.469	50.671	1.115	5.525
	Sp t-ratios	0.334	0.610	0.592	0.329	0.275	1.856	0.834
	Sb mean Estimates	38.91	11.10	14.34	45.92	67.29	1.38	5.59
	Sb mean T-ratios	0.33	0.61	0.59	0.33	0.28	1.75	0.83

Appendix-A3: SP Survey choice situation sample

(Example choice situations used in the SP part of the survey)

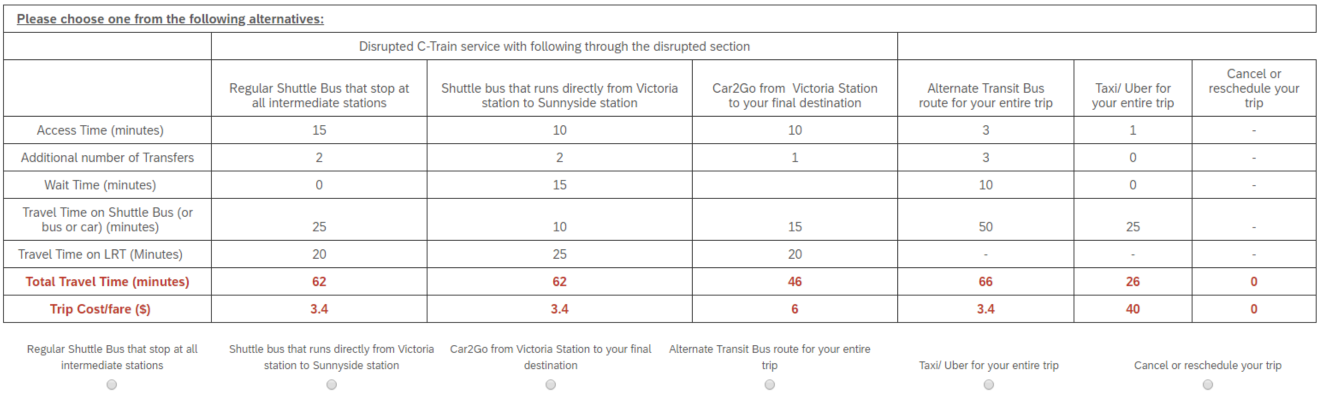
Scenario-1



Please choose one from the following alternatives:					
	Disrupted C-Train service with following through the disrupted section				
	Regular Shuttle Bus that stop at all intermediate stations	Shuttle bus that runs directly from Victoria station to Sunnyside station	Alternate Transit Bus route for your entire trip	Taxi/ Uber for your entire trip	Cancel or reschedule your trip
Access Time (minutes)	15	10	5	1	-
Additional number of Transfers	2	2	3	0	-
Wait Time (minutes)	10	0	15	0	-
Travel Time on Shuttle Bus (or bus or car) (minutes)	25	10	60	25	-
Travel Time on LRT (Minutes)	25	20	0	0	-
Total Travel Time (minutes)	**77**	**42**	**83**	**26**	**0**
Trip Cost/fare ($)	**3.4**	**3.4**	**3.4**	**40**	**0**

Regular Shuttle Bus that stop at all intermediate stations	Shuttle bus that runs directly from Victoria station to Sunnyside station	Alternate Transit Bus route for your entire trip	Taxi/ Uber for your entire trip	Cancel or reschedule your trip
○	○	○	○	○

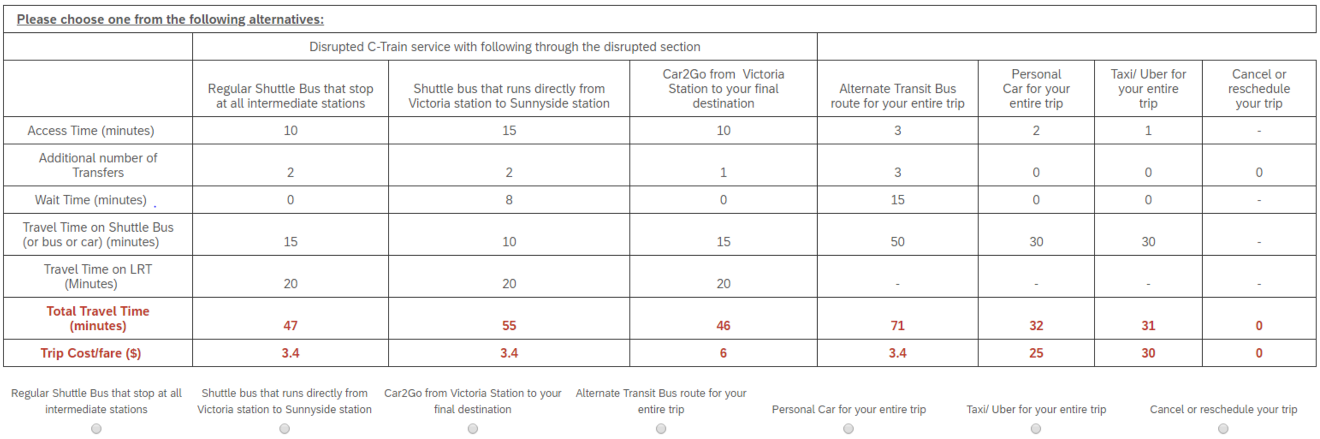
Scenario-2



Please choose one from the following alternatives:						
	Disrupted C-Train service with following through the disrupted section					
	Regular Shuttle Bus that stop at all intermediate stations	Shuttle bus that runs directly from Victoria station to Sunnyside station	Car2Go from Victoria Station to your final destination	Alternate Transit Bus route for your entire trip	Taxi/ Uber for your entire trip	Cancel or reschedule your trip
Access Time (minutes)	15	10	10	3	1	-
Additional number of Transfers	2	2	1	3	0	-
Wait Time (minutes)	0	15		10	0	-
Travel Time on Shuttle Bus (or bus or car) (minutes)	25	10	15	50	25	-
Travel Time on LRT (Minutes)	20	25	20	-	-	-
Total Travel Time (minutes)	**62**	**62**	**46**	**66**	**26**	**0**
Trip Cost/fare ($)	**3.4**	**3.4**	**6**	**3.4**	**40**	**0**

Regular Shuttle Bus that stop at all intermediate stations	Shuttle bus that runs directly from Victoria station to Sunnyside station	Car2Go from Victoria Station to your final destination	Alternate Transit Bus route for your entire trip	Taxi/ Uber for your entire trip	Cancel or reschedule your trip
○	○	○	○	○	○

Scenario-3



Please choose one from the following alternatives:							
	Disrupted C-Train service with following through the disrupted section						
	Regular Shuttle Bus that stop at all intermediate stations	Shuttle bus that runs directly from Victoria station to Sunnyside station	Car2Go from Victoria Station to your final destination	Alternate Transit Bus route for your entire trip	Personal Car for your entire trip	Taxi/ Uber for your entire trip	Cancel or reschedule your trip
Access Time (minutes)	10	15	10	3	2	1	-
Additional number of Transfers	2	2	1	3	0	0	0
Wait Time (minutes)	0	8	0	15	0	0	-
Travel Time on Shuttle Bus (or bus or car) (minutes)	15	10	15	50	30	30	-
Travel Time on LRT (Minutes)	20	20	20	-	-	-	-
Total Travel Time (minutes)	**47**	**55**	**46**	**71**	**32**	**31**	**0**
Trip Cost/fare ($)	**3.4**	**3.4**	**6**	**3.4**	**25**	**30**	**0**

Regular Shuttle Bus that stop at all intermediate stations	Shuttle bus that runs directly from Victoria station to Sunnyside station	Car2Go from Victoria Station to your final destination	Alternate Transit Bus route for your entire trip	Personal Car for your entire trip	Taxi/ Uber for your entire trip	Cancel or reschedule your trip
○	○	○	○	○	○	○

Appendix-A4: Biogeme Code

Biogeme Coding

```
// This file has automatically been generated.
// 05/10/20 13:07:12
// Michel Bierlaire, EPFL 2001-2008
// BIOGEME Version 1.8 [Sat Mar 7 14:36:56 CEST 2009]
// Michel Bierlaire, EPFL
[Choice]
CHOICE
[Weight]
$NONE
[PanelData]
$NONE
[Beta]
// Name Value  LowerBound UpperBound  status (0=variable, 1=fixed)
ASC1    0           -10000   10000    1
ASC2    -0.11119-10000   10000    0
ASC3    -1.65351-10000   10000    0
ASC4    -0.0577461          -10000   10000    0
ASC5    3.00306 -10000   10000    0
ASC6    0.350835            -10000   10000    0
ASC7    -2.11468-10000   10000    0
B_Age25-44_5    0.789344            -10000   10000    0
B_C     -0.102131           -10000   10000    0
B_Employee_1    -0.220527           -10000   10000    0
B_Employee_2    -0.163581           -10000   10000    0
B_Freq_Weekend1         0.0262929           -10000   10000    0
B_Freq_Weekend2         0.0860686           -10000   10000    0
B_Freq_Weekend3         0.149401            -10000   10000    0
B_Freq_Weekend4         0.0726892           -10000   10000    0
B_Income40-150_4        -0.415841           -10000   10000    0
B_IncomeAbove150_1      -2.53821-10000   10000    0
B_IncomeAbove150_2      -1.63595-10000   10000    0
B_IncomeAbove150_3      -1.8153  -10000   10000    0
```

```
B_IncomeAbove150_4      -2.58864-10000   10000    0
B_IncomeAbove150_7      -1.6583  -10000   10000    0
B_Male4        -0.332814        -10000   10000    0
B_Male5        -0.709698        -10000   10000    0
B_Male6        -0.645582        -10000   10000    0
B_Male7        -0.644078        -10000   10000    0
B_PassFare_1   0.841489         -10000   10000    0
B_PassFare_2   0.717173         -10000   10000    0
B_PassFare_3   0.656948         -10000   10000    0
B_PassFare_5   -1.47185-10000   10000    0
B_SingleFare_5 -2.48676-10000   10000    0
B_Student_1    -0.608224        -10000   10000    0
B_Student_2    -0.339471        -10000   10000    0
B_TT    -0.0199575       -10000   10000    0
B_Twait-0.0220753        -10000   10000    0
SIGMA1         -0.0743184       -10000   10000    0
[LaTeX]
$NONE
[OrdinalLogit]
$NONE
[Mu]
// In general, the value of mu must be fixed to 1. For testing purposes, you
// may change its value or let it be estimated.
// Value LowerBound UpperBound Status
1        0        1        1
[IIATest]
// Description of the choice subsets to compute the new variable for McFadden's IIA test
$NONE
[SampleEnum]
// Number of simulated choices to include in the sample enumeration file
0
[Utilities]
// Id Name  Avail  linear-in-parameter expression (beta1*x1 + beta2*x2 + ... )
7        Cancel_trip        Av7      ASC7 * one + B_IncomeAbove150_7 * Income_150nAbove + B_Male7 * 
Male
```

```
4	alt_bus	Av4	ASC4 * one + B_TT * TT4 + B_Twait * X43 + B_C [ SIGMA1 ]  * X47 + B_Income40-150_4 * Income_40-150 + B_IncomeAbove150_4 * Income_150nAbove + B_Male4 * Male + B_Freq_Weekend4 * lrt_used_frequency
3	lrtdis_c2g	Av3	ASC3 * one + B_TT * TT3 + B_Twait * X33 + B_C [ SIGMA1 ]  * X37 + B_IncomeAbove150_3 * Income_150nAbove + B_PassFare_3 * Fare_Pass + B_Freq_Weekend3 * lrt_used_frequency
2	lrtdis_shuttle_h	Av2	ASC2 * one + B_TT * TT2 + B_Twait * X23 + B_C [ SIGMA1 ]  * X27 + B_IncomeAbove150_2 * Income_150nAbove + B_Student_2 * Student + B_Employee_2 * Employed + B_PassFare_2 * Fare_Pass + B_Freq_Weekend2 * lrt_used_frequency
1	lrtdis_shuttle_n	Av1	ASC1 * one + B_TT * TT1 + B_Twait * X13 + B_C [ SIGMA1 ]  * X17 + B_IncomeAbove150_1 * Income_150nAbove + B_Student_1 * Student + B_Employee_1 * Employed + B_PassFare_1 * Fare_Pass + B_Freq_Weekend1 * lrt_used_frequency
5	pers_car	Av5	ASC5 * one + B_TT * TT5 + B_Twait * X53 + B_C [ SIGMA1 ]  * X57 + B_Male5 * Male + B_Age25-44_5 * Age_25-44 + B_SingleFare_5 * Fare_Single + B_PassFare_5 * Fare_Pass
6	taxi_uber	Av6	ASC6 * one + B_TT * TT6 + B_Twait * X63 + B_C [ SIGMA1 ]  * X67 + B_Male6 * Male
[GeneralizedUtilities]
$NONE
[SNP]
$NONE
[AggregateLast]
$NONE
[AggregateWeight]
$NONE
[SelectionBias]
$NONE
[ParameterCovariances]
// Par_i Par_j Value  LowerBound UpperBound  status (0=variable, 1=fixed)
$NONE
[Expressions]
// Define here arithmetic expressions for name that are not directly
// available from the data
one  = 1
TT1  = (  X11   +  X14   ) +  X15
TT2  = (  X21   +  X24   ) +  X25
TT3  = (  X31   +  X34   ) +  X35
TT4  = (  X41   +  X44   ) +  X45
TT5  = (  X51   +  X54   ) +  X55
TT6  = (  X61   +  X64   ) +  X65
[Draws]
```

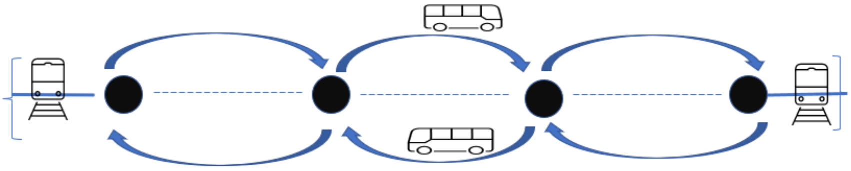
```
1000
[Group]
1
[Exclude]
$NONE
[Model]
// Currently, the following models are available
// Uncomment exactly one of them
//$BP  // Binary Probit Model
//$OL // Ordinal logit
$MNL  // Multinomial Logit Model
//$NL  // Nested Logit Model
//$CNL  // Cross-Nested Logit Model
//$NGEV // Network GEV Model
[Scale]
// The sample can be divided in several groups of individuals. The
//utility of an individual in a group will be multiplied by the scale factor
//associated with the group.
// Group_number  scale LowerBound UpperBound status

1       1       1       1       1
[NLNests]
// Name paramvalue  LowerBound UpperBound  status list of alt
$NONE
[CNLNests]
// Name paramvalue LowerBound UpperBound  status
$NONE
[CNLAlpha]
// Alt Nest value LowerBound UpperBound  status
$NONE
[Ratios]
// List of ratios of estimated coefficients that must be produced in
// the output. The most typical is the value-of-time.
// Numerator   Denominator  Name
$NONE
[LinearConstraints]
```

```
$NONE
[NonLinearEqualityConstraints]
$NONE
[NonLinearInequalityConstraints]
// At this point, BIOGEME is not able to handle nonlinear inequality
// constraints yet. It should be available in a future version.
$NONE
[NetworkGEVNodes]
// All nodes of the Network GEV model, except the root,
// must be listed here, with their associated parameter.
// If the nodes corresponding to alternatives are not listed,
// the associated parameter is constrained to 1.0 by default
// Name  mu_param_value LowerBound       UpperBound       status
$NONE
[NetworkGEVLinks]
// There is a line for each link of the network.
// The root node is denoted by __ROOT
// All other nodes must be either an alternative or a node listed in
// the section [NetworkGEVNodes]
// Note that an alternative cannot be the a-node of any link,
// and the root node cannot be the b-node of any link.
// a-node  b-node alpha_param_value LowerBound UpperBound  status
$NONE
[ZhengFosgerau]
// This section is used only by biosim for simulation, not by biogeme for estimation
// Syntax: expression  bandwith lb  ub name
// Expression must be a probability ($P) or an expression from the data ($E)
// Examples:
// $P { Alt1 } 1 0 1 "P1"
// $E { x31 } 1 -1000 1000 "x31"
//
$NONE
```

Appendix-A5: Bus bridging optimization analytical models

(Analytical models of various bus bridging service optimization)

i) Regular/All stop service scenario:



- $Passengers\ waiting\ time\ cost$: $k\ .\ \boldsymbol{h(t)}.\ \boldsymbol{P(t)}\ .\boldsymbol{\gamma_\omega}$

$$= k\ .\ \frac{1}{g(t)}\ .\ \boldsymbol{P(t)}\ .\boldsymbol{\gamma_\omega}$$

- Agency's Operating cost: $\boldsymbol{\lambda}$/h(t) = $\boldsymbol{\lambda}$. g(t)
- Objective/cost function:
- Z(t) = $\boldsymbol{\lambda}$. g(t) + $k\ /\boldsymbol{g(t)}.\ \boldsymbol{P(t)}\ .\boldsymbol{\gamma_\omega}$
- Total Cost function in a time T:

$$\int_T z(t)\cdot \mathrm{d}t$$

Derivative of Z(t) w.r.t g(t) to achieve minimum of the cost function

$$\frac{\mathrm{d}z(t)}{g(t)} = \lambda_D - k\gamma_\omega P(t)\cdot\frac{1}{g2(t)} = 0$$

$$g(t) = \sqrt{\frac{k\,\gamma_\omega P(t)}{\lambda_D}} \quad \text{-------------------} \ \text{(i)}$$

$$\mathrm{h}(t) = \sqrt{\frac{\lambda_D}{k\,\gamma_\omega P(t)}}$$

2nd Derivative

$$\frac{\mathrm{d}2z(t)}{g(t)2} = 0 - \ (-2)\ k\,\gamma_\omega P(t)\cdot\frac{1}{g3(t)}$$

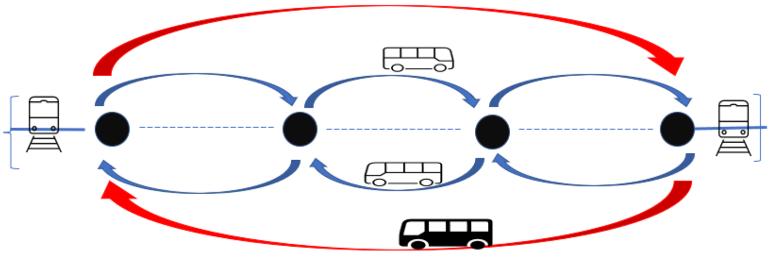
$$= 2\ k\,\gamma_\omega P(t)\cdot\frac{1}{g3(t)} > 0$$

The function is minimum at $g(t) = \sqrt{\frac{k\,\gamma_\omega P(t)}{\lambda_D}}$ $\qquad g(t)\ \alpha\ \sqrt{P(t)}$

- When unlimited fleet of large buses is available, they are dispatched at a rate directly proportional to the square root of passengers' demand per unit time.
- Optimal dispatch rate = $g(t) = \sqrt{\frac{k\,\gamma_\omega P(t)}{\lambda_D}}$
- Passengers Waiting time cost at optimal dispatch = $k\ .\ \boldsymbol{P(t)}\ .\boldsymbol{\gamma_\omega}\ .$ $\frac{1}{g(t)} = \sqrt{\lambda_D\,\gamma_\omega k\,P(t)}$

- Optimal total dispatch cost per hour = λ_D/h(t) = λ_D . g(t) = $\sqrt{\lambda_D\, \gamma_\omega k\, P(t)}$
- No. of passengers in a bus dispatched at time “t” in optimal case= $P(t)$ h*(t) $= \sqrt{\frac{P(t)\,\lambda_D}{k\,\gamma_\omega}}$
- Objective cost function,
- $Z(t) = \boldsymbol{\lambda D}\, .\, g(t) + k\, .\, \boldsymbol{P(t)}\, .\boldsymbol{\gamma_\omega} \cdot \frac{1}{g(t)}$
- Minimized Total Cost function in a time T, substituting value of g(t) using Equation(i):
- $\int_T z(t) \cdot dt = \boldsymbol{\lambda D}\, .\, \sqrt{\frac{k\,\gamma_\omega P(t)}{\lambda_D}} + k\, .\, \boldsymbol{P(t)}\, .\boldsymbol{\gamma_\omega} \cdot \sqrt{\frac{\lambda_D}{k\,\gamma_\omega P(t)}}$
- $= \int_{\boldsymbol{T}} 2\sqrt{k\, \boldsymbol{\lambda D}\ \ \boldsymbol{P(t)}\, .\boldsymbol{\gamma_\omega}}$

ii) Regular-Express route Scenario



Total passenger demand = **P(t)** = **P**$_{\mathbf{R}}$(t) + **P**$_{\mathbf{E}}$(t)

Total Passengers Waiting time cost: $\gamma_\omega[k_R \frac{1}{g_R(t)} \boldsymbol{P_R(t)} + k_E \frac{1}{g_E(t)} \boldsymbol{P_E(t)} + k_E \frac{1}{g_E(t)} \boldsymbol{\alpha'}\, \boldsymbol{P_R(t)} + k_R \frac{1}{g_R(t)} \boldsymbol{\alpha}\, \boldsymbol{P_E(t)}]$

Agency’s Operating cost = $\boldsymbol{\lambda_D}\ [\boldsymbol{g_R(t)} + \boldsymbol{g_E(t)}]$

-

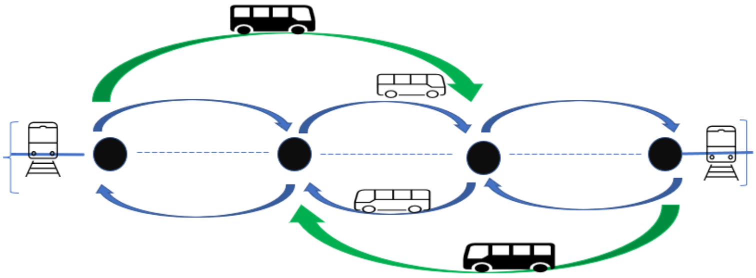
Objective/cost function: Z(t) = $\boldsymbol{\lambda_D}\ [\boldsymbol{g_R(t)} + \boldsymbol{g_E(t)}] + \boldsymbol{\gamma_\omega}[k_R \frac{1}{g_R(t)} \boldsymbol{P_R(t)} + k_E \frac{1}{g_E(t)} \boldsymbol{P_E(t)} + k_E \frac{1}{g_E(t)} \boldsymbol{\alpha'}\, \boldsymbol{P_R(t)} + k_R \frac{1}{g_R(t)} \boldsymbol{\alpha}\, \boldsymbol{P_E(t)}]$

Differentiating total cost function with respect to $g_R(t)$ and $g_E(t)$ separately and equating to zero, i.e.. $\frac{\mathrm{d}z(t)}{g(t)}$ = 0, the optimal dispatch rate is

- For Express route: $g_E(t) = \sqrt{\boldsymbol{\gamma_w}\, k_E \frac{\boldsymbol{P_E(t)} + \boldsymbol{\alpha\prime}\, \boldsymbol{P_R(t)}}{\lambda_D}}$ ………… *(x)*

- For local route: $g_R(t) = \sqrt{\boldsymbol{\gamma_w}\, k_R \frac{\boldsymbol{P_R(t) + \alpha P_E(t)}}{\lambda_D}}$ ………… *(y)*

iii) Local-skip stop bus bridging service with Transfers:



Total Passengers Wait time cost: $\gamma_\omega[k_R \frac{1}{g_R(t)} \boldsymbol{P_R(t)} + k_S \frac{1}{g_S(t)} \boldsymbol{P_S(t)} + k_S \frac{1}{g_S(t)} \boldsymbol{\beta' P_R(t)} + k_R \frac{1}{g_R(t)} \boldsymbol{\beta P_R(t)}\,]$

Operating cost: $\boldsymbol{\lambda_D}\, [\boldsymbol{g_R}(\quad) + \boldsymbol{g_S(t)}]$

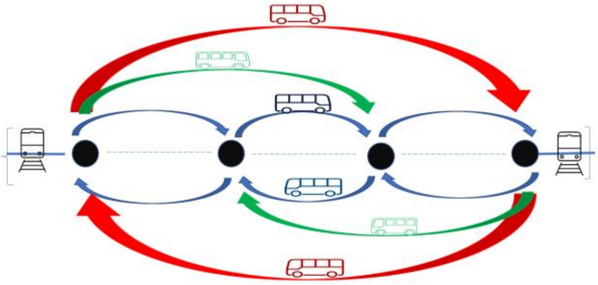
Total cost function: Z(t) = $\boldsymbol{\lambda_D}\, [\boldsymbol{g_R(t)} + \boldsymbol{g_S(t)}] + \boldsymbol{\gamma_\omega}[k_R \frac{1}{g_R(t)} \boldsymbol{P_R(t)} + k_S \frac{1}{g_S(t)} \boldsymbol{P_S(t)} + k_S \frac{1}{g_S(t)} \boldsymbol{\beta' P_R(t)} + k_R \frac{1}{g_R(t)} \boldsymbol{\beta P_S(t)}$

Differentiating total cost function with respect to $g_R(t)$ and $g_S(t)$ separately and equating to zero, i.e.. $\frac{\mathrm{dz}(t)}{g(t)}$ = 0, the optimal dispatch rate is

$$g_S(t) = \sqrt{\boldsymbol{\gamma_w}\, k_S \frac{\boldsymbol{P_S(t) + \beta P_R(t)}}{\lambda_D}} \text{ ………… } \textbf{\textit{(a)}}$$

$$g_R(t) = \sqrt{\boldsymbol{\gamma_w}\, k_R \frac{\boldsymbol{P_R(t) + \beta\prime P_S(t)}}{\lambda_D}} \text{ ………… } \textbf{\textit{(b)}}$$

iv) Local-express-ekip stop bus bridging service:



Total passenger demand = $\boldsymbol{P(t)} = \boldsymbol{P_R(t)} + \boldsymbol{P_E(t)} + \boldsymbol{P_S(t)}$

$Passengers\ total\ waiting\ time\ cost\ = \ \boldsymbol{\gamma_\omega}[k_R \frac{1}{\boldsymbol{g_R(t)}} \cdot \boldsymbol{P_R(t)} + k_E \cdot \frac{1}{g_E(t)} \cdot \boldsymbol{P_E(t)} + k_S \cdot \frac{1}{g_S(t)} \cdot \boldsymbol{P_S(t)} + k_R \cdot \frac{1}{g_R(t)} (\boldsymbol{\alpha\, P_E(t) + \beta\, P_S(t)}) + k_E \cdot \frac{1}{g_E(t)} \boldsymbol{\alpha'\, P_R(t)} + k_S \cdot \frac{1}{g_S(t)} \boldsymbol{\beta'\, P_R(t)}]$

Operating cost: $\boldsymbol{\lambda D}\ [\boldsymbol{g_R(t)} + \boldsymbol{g_E(t)} + \boldsymbol{g_S(t)}]$

Total cost function: $Z(\mathrm{t}) = \boldsymbol{\lambda D}\ [\boldsymbol{g_R(t)} + \boldsymbol{g_E(t)} + \boldsymbol{g_S(t)}] + \boldsymbol{\gamma_\omega}[k_R \frac{1}{\boldsymbol{g_R(t)}} \cdot \boldsymbol{P_R(t)} + k_E \cdot \frac{1}{g_E(t)} \cdot \boldsymbol{P_E(t)} + k_S \cdot \frac{1}{g_S(t)} \cdot \boldsymbol{P_S(t)} + k_R \cdot \frac{1}{g_R(t)} (\boldsymbol{\alpha\, P_E(t) + \beta\, P_S(t)}) + k_E \cdot \frac{1}{g_E(t)} \boldsymbol{\alpha'\, P_R(t)} + k_S \cdot \frac{1}{g_S(t)} \boldsymbol{\beta'\, P_R(t)}]$

Differentiating total cost function with respect to $g_R(t)$, $g_E(t)$ and $g_S(t)$ separately and equating to zero, i.e.. $\frac{\mathrm{d}z(t)}{g(t)} = 0$

- $g_R(t) = \sqrt{\boldsymbol{\gamma_w}\, k_R \frac{\boldsymbol{P_R(t) + \alpha\, P_E(t) + \beta\, P_S(t)}}{\lambda_D}}$ ………… ***(c)***
- $g_E(t) = \sqrt{\boldsymbol{\gamma_w}\, k_E \frac{\boldsymbol{P_E(t) + \alpha' P_R(t)}}{\lambda_D}}$ ………… ***(d)***
- $g_S(t) = \sqrt{\boldsymbol{\gamma_w}\, k_S \frac{\boldsymbol{P_S(t) + \beta' P_R(t)}}{\lambda_D}}$ ………… ***(e)***

Appendix-A6: Python Codes for passenger’s assignment model

Python Code of Passengers Assignment Model

Local-Express-Skip Stop Strategy:

Passenger Assignment Model

```
#Bus Bridging service During LRT Planned Service Disruption



import pandas as pd
from pyomo.environ import *

# Read passenger demand from Excel file
demand_data = pd.read_excel('Pass_Demand.xlsx', index_col=0, na_values='-')
demand = {(row, col): demand_data.at[row, col]
for row in demand_data.index for col in demand_data.columns if not pd.isna(demand_data.at[row, col])}
print(demand_data)

# Read bus capacity data from Excel file
capacity_data = pd.read_excel('Bus_capacity.xlsx')
capacity = {row['Route']: row['Bus Capacity'] for _, row in capacity_data.iterrows()}

# Read unit cost matrices from Excel files for each route
local_cost_data = pd.read_excel('St2_L_Cost.xlsx', index_col=0, na_values='-')
express_cost_data = pd.read_excel('St2_E_Cost.xlsx', index_col=0, na_values='-')
local_express_cost_data = pd.read_excel('St2_LE_Cost.xlsx', index_col=0, na_values='-')
skip_cost_data = pd.read_excel('St3_S_Cost.xlsx', index_col=0, na_values='-')
local_skip_cost_data = pd.read_excel('St4_LS_Cost.xlsx', index_col=0, na_values='-')

# Read route availability matrices from Excel files for each route
local_routes_data = pd.read_excel('St2_L_route.xlsx', index_col=0, na_values='-')
express_routes_data = pd.read_excel('St2_E_route.xlsx', index_col=0, na_values='-')
local_express_routes_data = pd.read_excel('St2_LE_route.xlsx', index_col=0, na_values='-')
skip_routes_data = pd.read_excel('St3_S_route.xlsx', index_col=0, na_values='-')
local_skip_routes_data = pd.read_excel('St4_LS_route.xlsx', index_col=0, na_values='-')


# Create a dictionary to store cost matrices for all routes
route_costs = {
    'Local': {(row, col): local_cost_data.at[row, col]
for row in local_cost_data.index for col in local_cost_data.columns if not pd.isna(local_cost_data.at[row,
col])},
    'Express': {(row, col): express_cost_data.at[row, col]
for row in express_cost_data.index for col in express_cost_data.columns if not pd.isna(express_cost_data.
at[row, col])},
    'Local-Express': {(row, col): local_express_cost_data.at[row, col]
for row in local_express_cost_data.index for col in local_express_cost_data.columns if not pd.isna(local_
express_cost_data.at[row, col])},
    'Skip': {(row, col): skip_cost_data.at[row, col]
for row in skip_cost_data.index for col in skip_cost_data.columns if not pd.isna(skip_cost_data.at[row,
col])},
```

```
    'Local-Skip': {(row, col): local_skip_cost_data.at[row, col]
for row in local_skip_cost_data.index for col in local_skip_cost_data.columns if not pd.isna(local_skip_cost_data.at[row, col])}
}

# Create a single dictionary for route availability matrices
route_availability = {
    'Local': {(row, col): local_routes_data.at[row, col]
for row in local_routes_data.index for col in local_routes_data.columns if not pd.isna(local_routes_data.at[row, col])},
    'Express': {(row, col): express_routes_data.at[row, col]
for row in express_routes_data.index for col in express_routes_data.columns if not pd.isna(express_routes_data.at[row, col])},
    'Local-Express': {(row, col): local_express_routes_data.at[row, col]
for row in local_express_routes_data.index for col in local_express_routes_data.columns if not pd.isna(local_express_routes_data.at[row, col])},
    'Skip': {(row, col): skip_routes_data.at[row, col]
for row in skip_routes_data.index for col in skip_routes_data.columns if not pd.isna(skip_routes_data.at[row, col])},
    'Local-Skip': {(row, col): local_skip_routes_data.at[row, col]
for row in local_skip_routes_data.index for col in local_skip_routes_data.columns if not pd.isna(local_skip_routes_data.at[row, col])}
}



#-------------------------------  PYOMO MODEL  ---------------------------------

# --- Create a ConcreteModel ---

model = ConcreteModel()

# --- Sets ----

model.od_pairs = Set(initialize=demand.keys())
model.routes = Set(initialize=route_availability.keys())

# -------- Parameters ------

model.demand = Param(model.od_pairs, initialize=demand, within=Any)
model.capacity = Param(model.routes, initialize=capacity)

# Parameters for route costs and availability
model.route_costs = Param(model.routes, model.od_pairs, initialize={
    (route, (origin, destination)): cost
    for route in model.routes
    for (origin, destination), cost in route_costs[route].items()
})

# Parameters for route availability
model.route_availability = Param(model.routes, model.od_pairs, within=Binary, initialize={
    (route, (origin, destination)): 1 if (origin, destination) in route_availability[route] else 0
    for route in model.routes
    for (origin, destination) in model.od_pairs
})


# ----- Decision Variables-------
```

```
model.x = Var(model.routes, model.od_pairs, within=NonNegativeReals)


# ------- Objective Function -------

def total_cost_rule(model):
    total_cost = sum(
        model.x[r, i, j] * model.route_costs[r, (i, j)]
        for i, j in model.od_pairs
        for r in model.routes
    )
    return total_cost

model.total_cost = Objective(rule=total_cost_rule, sense=minimize)

# ------------ CONSTRAINTS ------------

# Constraint-1:Passenger flow conservation constraint - Sum of passengers on all available routes for a certain OD pair should be equal to the total demand on that OD pair
def passenger_flow_rule(model, i, j):
    return sum(model.x[r, i, j] for r in model.routes) == model.demand[i, j]

model.passenger_flow = Constraint(model.od_pairs, rule=passenger_flow_rule)


# Constraint-2: Bus capacity constraint - Total passengers assigned to a bus for should not be greater than the bus passenger caring capacity.
#def bus_capacity_rule(model, r):
#    return sum(model.x[r, i, j] for (i, j) in model.od_pairs) <= model.capacity[r]

#model.bus_capacity = Constraint(model.routes, rule=bus_capacity_rule)


# Constraint-3: Total optimized cost must be greater than zero
def total_cost_positive_rule(model):
    return model.total_cost >= 0

model.total_cost_positive = Constraint(rule=total_cost_positive_rule)


# Constraint-4:Constraint to skip elements where route availability is not 1
def skip_elements_rule(model, r, origin, destination):
    if model.route_availability[r, (origin, destination)] == 1:
        return Constraint.Skip
    else:
        # Include a default return statement to avoid the "None" error
        return model.x[r, origin, destination] ==0

model.skip_elements_constraint = Constraint(model.routes, model.od_pairs, rule=skip_elements_rule)



# ------------------------- SOLVER ----------------------

# Solve the linear program using a solver (e.g., GLPK)
solver = SolverFactory('glpk')
results = solver.solve(model, tee=True)
```

```
#------------------------ PRINTING RESULTS ---------------------------
# Print variable values in every step
for od in model.od_pairs:
    for r in model.routes:
        i, j = od
        print(f"x[{i}, {j}, {r}] = {model.x[r, i, j].value}")


# Check the solver termination condition
print(f"Solver Termination Condition: {results.solver.termination_condition}")



    # Empty list to store the results
results_list = []

if results.solver.termination_condition == TerminationCondition.optimal:
    print("Optimal Solution Found")
    for od in model.od_pairs:
        for route in model.routes:
            for r in model.routes:
                if (od[0], od[1], r) in model.x:
                    passenger_count = model.x[od[0], od[1], r].value
                    results_list.append({
                        'Origin': od[0],
                        'Destination': od[1],
                        'Route': r,
                        'Passenger Count': passenger_count
                    })

    print(f"Total Minimized Cost: {model.total_cost()}")

   # DataFrame from the results_list
    results_df = pd.DataFrame(results_list)

    # Export the DataFrame to an Excel file
    results_df.to_excel('Passenger_Assignment.xlsx', index=False)
else:
    print("No Optimal Solution Found")


 # Create an empty dictionary to store total passengers assigned for each route
total_passengers_by_route = {}

# Print variable values in every step
for route in model.routes:
    print(f"Route: {route}")

    # Create an empty dictionary to store the origin-destination table
    origin_destination_table = {}

    # Calculate total passengers assigned for this route
    total_passengers = sum(model.x[route, i, j].value for i, j in model.od_pairs)

    # Store the total passengers for this route
    total_passengers_by_route[route] = total_passengers
```

```
    # Print variable values for this route
    for od in model.od_pairs:
        i, j = od
        value = model.x[route, i, j].value
        origin_destination_table[(i, j)] = value

    # Create a DataFrame for the origin-destination table
    origin_destination_df = pd.DataFrame(
        data={'Origin-Destination': list(origin_destination_table.keys()), 'Passenger Count':
list(origin_destination_table.values())}
    )

    # Print the DataFrame
    print(origin_destination_df)

    # Export the origin-destination DataFrame to an Excel file for this route
    origin_destination_df.to_excel(f'Origin_Destination_Table_Route_{route}.xlsx', index=False)

# Print total passengers assigned for each route
print("\nTotal Passengers by Route:")
for route, total_passengers in total_passengers_by_route.items():
    print(f"Route {route}: {total_passengers}")
```

Local- Skip Stop Strategy

Passenger Assignment Model

```
#Bus Bridging service During LRT Planned Service Disruption


import pandas as pd
from pyomo.environ import *

# Read passenger demand from Excel file
demand_data = pd.read_excel('Pass_Demand.xlsx', index_col=0, na_values='-')
demand = {(row, col): demand_data.at[row, col]
for row in demand_data.index for col in demand_data.columns if not pd.isna(demand_data.at[row, col])}

# Read bus capacity data from Excel file
capacity_data = pd.read_excel('Bus_capacity_LS.xlsx')
capacity = {row['Route']: row['Bus Capacity'] for _, row in capacity_data.iterrows()}

# Read unit cost matrices from Excel files for each route
local_cost_data = pd.read_excel('St2_L_Cost.xlsx', index_col=0, na_values='-')
skip_cost_data = pd.read_excel('St3_S_Cost.xlsx', index_col=0, na_values='-')
local_skip_cost_data = pd.read_excel('St4_LS_Cost.xlsx', index_col=0, na_values='-')

# Read route availability matrices from Excel files for each route
local_routes_data = pd.read_excel('St2_L_route.xlsx', index_col=0, na_values='-')
skip_routes_data = pd.read_excel('St3_S_route.xlsx', index_col=0, na_values='-')
local_skip_routes_data = pd.read_excel('St4_LS_route.xlsx', index_col=0, na_values='-')
```

```
# Create a dictionary to store cost matrices for all routes
route_costs = {
    'Local': {(row, col): local_cost_data.at[row, col]
for row in local_cost_data.index for col in local_cost_data.columns if not pd.isna(local_cost_data.at[row, col])},
    'Skip': {(row, col): skip_cost_data.at[row, col]
for row in skip_cost_data.index for col in skip_cost_data.columns if not pd.isna(skip_cost_data.at[row, col])},
    'Local-Skip': {(row, col): local_skip_cost_data.at[row, col]
for row in local_skip_cost_data.index for col in local_skip_cost_data.columns if not pd.isna(local_skip_cost_data.at[row, col])}
}


# Create a single dictionary for route availability matrices
route_availability = {
    'Local': {(row, col): local_routes_data.at[row, col]
for row in local_routes_data.index for col in local_routes_data.columns if not pd.isna(local_routes_data.at[row, col])},
    'Skip': {(row, col): skip_routes_data.at[row, col]
for row in skip_routes_data.index for col in skip_routes_data.columns if not pd.isna(skip_routes_data.at[row, col])},
    'Local-Skip': {(row, col): local_skip_routes_data.at[row, col]
for row in local_skip_routes_data.index for col in local_skip_routes_data.columns if not pd.isna(local_skip_routes_data.at[row, col])}
}


#------------------------------  PYOMO MODEL  --------------------------------

# --- Create a ConcreteModel ---

model = ConcreteModel()

# --- Sets ----

model.od_pairs = Set(initialize=demand.keys())
model.routes = Set(initialize=route_availability.keys())

# -------- Parameters ------

model.demand = Param(model.od_pairs, initialize=demand, within=Any)
model.capacity = Param(model.routes, initialize=capacity)

# Parameters for route costs and availability
model.route_costs = Param(model.routes, model.od_pairs, initialize={
    (route, (origin, destination)): cost
    for route in model.routes
    for (origin, destination), cost in route_costs[route].items()
})

# Parameters for route availability
model.route_availability = Param(model.routes, model.od_pairs, within=Binary, initialize={
    (route, (origin, destination)): 1 if (origin, destination) in route_availability[route] else 0
    for route in model.routes
    for (origin, destination) in model.od_pairs
})
```

```python
# ----- Decision Variables-------

model.x = Var(model.routes, model.od_pairs, within=NonNegativeReals)


# ------- Objective Function -------

def total_cost_rule(model):
    total_cost = sum(
        model.x[r, i, j] * model.route_costs[r, (i, j)]
        for i, j in model.od_pairs
        for r in model.routes
    )
    return total_cost

model.total_cost = Objective(rule=total_cost_rule, sense=minimize)

# ------------ CONSTRAINTS ------------

# Constraint-1:Passenger flow conservation constraint - Sum of passengers on all available routes for a certain OD pair should be equal to the total demand on that OD pair
def passenger_flow_rule(model, i, j):
    return sum(model.x[r, i, j] for r in model.routes) == model.demand[i, j]

model.passenger_flow = Constraint(model.od_pairs, rule=passenger_flow_rule)


# Constraint-2: Bus capacity constraint - Total passengers assigned to a bus for should not be greater than the bus passenger caring capacity.
#def bus_capacity_rule(model, r):
#    return sum(model.x[r, i, j] for (i, j) in model.od_pairs) <= model.capacity[r]

#model.bus_capacity = Constraint(model.routes, rule=bus_capacity_rule)


# Constraint-3: Total optimized cost must be greater than zero
def total_cost_positive_rule(model):
    return model.total_cost >= 0

model.total_cost_positive = Constraint(rule=total_cost_positive_rule)


# Constraint-4:Constraint to skip elements where route availability is not 1
def skip_elements_rule(model, r, origin, destination):
    if model.route_availability[r, (origin, destination)] == 1:
        return Constraint.Skip
    else:
        # Include a default return statement to avoid the "None" error
        return model.x[r, origin, destination] ==0

model.skip_elements_constraint = Constraint(model.routes, model.od_pairs, rule=skip_elements_rule)



# -------------------------- SOLVER -----------------------

# Solve the linear program using a solver (e.g., GLPK)
```

```
solver = SolverFactory('glpk')
results = solver.solve(model, tee=True)


#------------------------ PRINTING RESULTS ---------------------------
# Print variable values in every step
for od in model.od_pairs:
    for r in model.routes:
        i, j = od
        print(f"x[{i}, {j}, {r}] = {model.x[r, i, j].value}")


# Check the solver termination condition
print(f"Solver Termination Condition: {results.solver.termination_condition}")


    # Empty list to store the results
results_list = []

if results.solver.termination_condition == TerminationCondition.optimal:
    print("Optimal Solution Found")
    for od in model.od_pairs:
        for route in model.routes:
            for r in model.routes:
                if (od[0], od[1], r) in model.x:
                    passenger_count = model.x[od[0], od[1], r].value
                    results_list.append({
                        'Origin': od[0],
                        'Destination': od[1],
                        'Route': r,
                        'Passenger Count': passenger_count
                    })

    print(f"Total Minimized Cost: {model.total_cost()}")

   # DataFrame from the results_list
    results_df = pd.DataFrame(results_list)

    # Export the DataFrame to an Excel file
    results_df.to_excel('Passenger_Assignment.xlsx', index=False)
else:
    print("No Optimal Solution Found")


     # Create an empty dictionary to store total passengers assigned for each route
total_passengers_by_route = {}

# Print variable values in every step
for route in model.routes:
    print(f"Route: {route}")

    # Create an empty dictionary to store the origin-destination table
    origin_destination_table = {}

    # Calculate total passengers assigned for this route
    total_passengers = sum(model.x[route, i, j].value for i, j in model.od_pairs)

    # Store the total passengers for this route
```

```
    total_passengers_by_route[route] = total_passengers

    # Print variable values for this route
    for od in model.od_pairs:
        i, j = od
        value = model.x[route, i, j].value
        origin_destination_table[(i, j)] = value

    # Create a DataFrame for the origin-destination table
    origin_destination_df = pd.DataFrame(
        data={'Origin-Destination': list(origin_destination_table.keys()), 'Passenger Count':
list(origin_destination_table.values())}
    )

    # Print the DataFrame
    print(origin_destination_df)

    # Export the origin-destination DataFrame to an Excel file for this route
    origin_destination_df.to_excel(f'Origin_Destination_Table_Route_{route}.xlsx', index=False)

# Print total passengers assigned for each route
print("\nTotal Passengers by Route:")
for route, total_passengers in total_passengers_by_route.items():
    print(f"Route {route}: {total_passengers}")
```

Local-Express Strategy:

Passenger Assignment Model

```
#Bus Bridging service During LRT Planned Service Disruption


import pandas as pd
from pyomo.environ import *

# Read passenger demand from Excel file
demand_data = pd.read_excel('Pass_Demand.xlsx', index_col=0, na_values='-')
demand = {(row, col): demand_data.at[row, col]
for row in demand_data.index for col in demand_data.columns if not pd.isna(demand_data.at[row, col])}
print(demand_data)
print(" ")
print(demand)

# Read bus capacity data from Excel file
capacity_data = pd.read_excel('Bus_capacity_LE.xlsx')
capacity = {row['Route']: row['Bus Capacity'] for _, row in capacity_data.iterrows()}

# Read unit cost matrices from Excel files for each route
local_cost_data = pd.read_excel('St2_L_Cost.xlsx', index_col=0, na_values='-')
express_cost_data = pd.read_excel('St2_E_Cost.xlsx', index_col=0, na_values='-')
local_express_cost_data = pd.read_excel('St2_LE_Cost.xlsx', index_col=0, na_values='-')


# Read route availability matrices from Excel files for each route
```

```
local_routes_data = pd.read_excel('St2_L_route.xlsx', index_col=0, na_values='-')
express_routes_data = pd.read_excel('St2_E_route.xlsx', index_col=0, na_values='-')
local_express_routes_data = pd.read_excel('St2_LE_route.xlsx', index_col=0, na_values='-')


# Create a dictionary to store cost matrices for all routes
route_costs = {
    'Local': {(row, col): local_cost_data.at[row, col]
for row in local_cost_data.index for col in local_cost_data.columns if not pd.isna(local_cost_data.at[row,
col])},
    'Express': {(row, col): express_cost_data.at[row, col]
for row in express_cost_data.index for col in express_cost_data.columns if not pd.isna(express_cost_data.
at[row, col])},
    'Local-Express': {(row, col): local_express_cost_data.at[row, col]
for row in local_express_cost_data.index for col in local_express_cost_data.columns if not pd.isna(local_
express_cost_data.at[row, col])}
}


# Create a single dictionary for route availability matrices
route_availability = {
    'Local': {(row, col): local_routes_data.at[row, col]
for row in local_routes_data.index for col in local_routes_data.columns if not pd.isna(local_routes_data.at
[row, col])},
    'Express': {(row, col): express_routes_data.at[row, col]
for row in express_routes_data.index for col in express_routes_data.columns if not pd.isna(express_routes
_data.at[row, col])},
    'Local-Express': {(row, col): local_express_routes_data.at[row, col]
for row in local_express_routes_data.index for col in local_express_routes_data.columns if not pd.isna(lo
cal_express_routes_data.at[row, col])}
}

#------------------------------- PYOMO MODEL ------
# --- Create a ConcreteModel ---

model = ConcreteModel()

# --- Sets ----

model.od_pairs = Set(initialize=demand.keys())
model.routes = Set(initialize=route_availability.keys())

# -------- Parameters ------
model.demand = Param(model.od_pairs, initialize=demand, within=Any)
model.capacity = Param(model.routes, initialize=capacity)

# Parameters for route costs and availability
model.route_costs = Param(model.routes, model.od_pairs, initialize={
    (route, (origin, destination)): cost
    for route in model.routes
    for (origin, destination), cost in route_costs[route].items()
})

# Parameters for route availability
model.route_availability = Param(model.routes, model.od_pairs, within=Binary, initialize={
    (route, (origin, destination)): 1 if (origin, destination) in route_availability[route] else 0
    for route in model.routes
    for (origin, destination) in model.od_pairs
```

```
})

# ----- Decision Variables-------

model.x = Var(model.routes, model.od_pairs, within=NonNegativeReals)


# ------- Objective Function -------

def total_cost_rule(model):
    total_cost = sum(
        model.x[r, i, j] * model.route_costs[r, (i, j)]
        for i, j in model.od_pairs
        for r in model.routes
    )
    return total_cost

model.total_cost = Objective(rule=total_cost_rule, sense=minimize)

# ------------ CONSTRAINTS ------------

# Constraint-1:Passenger flow conservation constraint - Sum of passengers on all available routes for a certain OD pair should be equal to the total demand on that OD pair
def passenger_flow_rule(model, i, j):
    return sum(model.x[r, i, j] for r in model.routes) == model.demand[i, j]

model.passenger_flow = Constraint(model.od_pairs, rule=passenger_flow_rule)


# Constraint-2: Bus capacity constraint - Total passengers assigned to a bus for should not be greater than the bus passenger caring capacity.
#def bus_capacity_rule(model, r):
 #   return sum(model.x[r, i, j] for (i, j) in model.od_pairs) <= model.capacity[r]

#model.bus_capacity = Constraint(model.routes, rule=bus_capacity_rule)


# Constraint-3: Total optimized cost must be greater than zero
def total_cost_positive_rule(model):
    return model.total_cost >= 0

model.total_cost_positive = Constraint(rule=total_cost_positive_rule)


# Constraint-4:Constraint to skip elements where route availability is not 1
def skip_elements_rule(model, r, origin, destination):
    if model.route_availability[r, (origin, destination)] == 1:
        return Constraint.Skip
    else:
        # Include a default return statement to avoid the "None" error
        return model.x[r, origin, destination] ==0

model.skip_elements_constraint = Constraint(model.routes, model.od_pairs, rule=skip_elements_rule)


# ------------------------- SOLVER ----------------------

# Solve the linear program using a solver (e.g., GLPK)
```

```
solver = SolverFactory('glpk')
results = solver.solve(model, tee=True)


#------------------------ PRINTING RESULTS ---------------------------

# Check the solver termination condition
print(f"Solver Termination Condition: {results.solver.termination_condition}")

# Print variable values in every step
for od in model.od_pairs:
    for r in model.routes:
        i, j = od
        print(f"{i}, {j}, {r}, {model.x[r, i, j].value}")

# Empty list to store the results
results_list = []

if results.solver.termination_condition == TerminationCondition.optimal:
    print("Optimal Solution Found")
    for od in model.od_pairs:
        for route in model.routes:
            for r in model.routes:
                if (od[0], od[1], r) in model.x:
                    passenger_count = model.x[od[0], od[1], r].value
                    results_list.append({
                        'Origin': od[0],
                        'Destination': od[1],
                        'Route': r,
                        'Passenger Count': passenger_count
                    })

    print(f"Total Minimized Cost: {model.total_cost()}")



     # Create an empty dictionary to store total passengers assigned for each route
total_passengers_by_route = {}

# Print variable values in every step
for route in model.routes:
    print(f"Route: {route}")

    # Create an empty dictionary to store the origin-destination table
    origin_destination_table = {}

    # Calculate total passengers assigned for this route
    total_passengers = sum(model.x[route, i, j].value for i, j in model.od_pairs)

    # Store the total passengers for this route
    total_passengers_by_route[route] = total_passengers

    # Print variable values for this route
    for od in model.od_pairs:
        i, j = od
        value = model.x[route, i, j].value
        origin_destination_table[(i, j)] = value
```

```
    # Create a DataFrame for the origin-destination table
    origin_destination_df = pd.DataFrame(
        data={'Origin-Destination': list(origin_destination_table.keys()), 'Passenger Count': list(origin_destination_table.values())}
    )

    # Print the DataFrame
    print(origin_destination_df)

    # Export the origin-destination DataFrame to an Excel file for this route
    origin_destination_df.to_excel(f'Origin_Destination_Table_Route_{route}.xlsx', index=False)

# Print total passengers assigned for each route
print("\nTotal Passengers by Route:")
for route, total_passengers in total_passengers_by_route.items():
    print(f"Route {route}: {total_passengers}")
```

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