Paving over potential?

Evaluating the effect of freeways and transit-oriented growth in Vancouver, Canada

Niraj Dayanandan

Supervised by Dr. Craig Townsend

Department of Geography, Planning & Environment

URBS 491: Honours Thesis

April 24, 2025

Abstract

This thesis explores the relationship between transit-oriented development and freeway infrastructure in Vancouver from 2001-2021. We employed a correlation analysis to assess how population and employment density, transit frequency, and proximity to urban centres and to freeways all relate to each other. Moreover, we created a standardized metric titled Combined Density-Transit Frequency Index (CDTFI) to evaluate catchment areas around SkyTrain stations throughout the study period. Contrary to prior research, our findings reveal that transit frequency is not always an indicator of increasing densities in transit-oriented development areas (R^2 = -0.62). Throughout the study period, we measured significant correlations between transit frequency and employment density (R^2 = 0.64); population density and distance to the nearest interchange (R^2 = 0.52); employment density and distance to the nearest interchange (R^2 = -0.46); and distances to interchanges and distances to urban centres (R^2 = -0.50). The CDTFI metric illustrated a generally well-served SkyTrain network regarding supply and demand of transit, however, few stations showed drastic increases and decreases that were not explained by proximity to freeways. Further sample sizes are needed to find conclusive evidence of the CDTFI indicating proximity to freeways. However, both the correlation analysis and metric are useful and accessible data-driven tools for evaluating past, present, and future TOD areas. This paper offers a simplified approach to understanding the complicated relationship between land-use and the built environment.

Acknowledgements

This paper would not have been possible without the guidance from my supervisor Dr. Craig Townsend, whose continued support and patience has been invaluable throughout the ups and downs of research. I am equally grateful to Dr. Sarah Turner whose lectures and constructive feedback has not only made me a better researcher but enabled me to greatly improve my writing as I continue my journey in academia. Moreover, my friends and colleagues in the Urban Planning program who played a pivotal role at shaping me into who I am today, particularly Pema Davis, whose support has been especially meaningful in this journey. Lastly, I would like to express my sincerest gratitude to my mom, who has supported me through the many long nights of my undergraduate studies, including during this honour's thesis.

Table of Contents

List of Tables

List of Figures

List of Commonly Used Abbreviations

CBD – Central Business District

CDTFI – Combined Density-Transit Frequency Index

CT(s) – Census Tract(s)

DSR – Density-to-Service Ratio

GVRD – Greater Vancouver Regional District

TOD – Transit-Oriented Development

1. Introduction

Over the past century, North America has seen expansive developments in transportation, specifically in and around urban cores. The emergence of transportation technologies such as the streetcar and the automobile have led to monumental changes manifested in North American cities. Streetcars facilitated urban transportation in large numbers, allowing the public to live, work, and play along fixed routes, primarily limited to the urban core. This form of public transportation remedied the lack of mobility at the time, allowing urban growth to reach the periphery of cities through the development of streetcar suburbs. However, contemporary suburbanization intensified with the introduction of the automobile, which extended the urban boundary further than the limits of streetcar suburbs. In the United States and Canada, cities rapidly transformed with the automobile, specifically through high-capacity, controlled-access highways (freeways) dictating the growth of residential and employment opportunities through the mid to late 20th century. In the mid 1900s, large freeway networks such as the United States Interstate Highway System and the Trans-Canada Highway not only connected different cities, but brought together their respective metropolitan areas, eventually leading to the decentralization of the downtown core in favour of higher mobility and a stronger local economy in the suburbs (Brinkman, 2022; Handy, 1994). However, decentralization did not impact everyone equally. The freeway system created vast inequalities still experienced today. Well documented cases such as Robert Moses' Cross-Bronx Expressway led to urban decay in historically lower income, marginalized, and higher density residential neighbourhoods (Caro, 1975). As industries followed the displacement of people outwards, the urban cores were inhabited by those not wealthy enough to move to the developing urban periphery. These downtown populations suffered a poor quality of life marked by substandard services as well as low population and employment densities (Brinkman, 2022). Although the freeway system sealed the fate for many downtowns in North America, the 1960s also birthed a considerable critique of the freeway system. In a few North American cities, automobile-led decentralization and dependency was discouraged, instead favouring transit-oriented development (TOD), specifically high frequency public transportation along with high density, mixed land-use.

A notable example is Vancouver, Canada, which since the rise of automobile-led development, made key policy decisions to thwart attempts to construct freeways through its downtown core and instead prioritize transit and carefully planned peripheral town centres. Vancouver is widely commended as a model city for the successful implementation of the TOD model, with terms such as “Vancouverism” and the “Vancouver Model” emerging to describe its unique approach to effectively planned growth. Vancouver’s transit, namely the SkyTrain rapid transit system which opened in 1986, has proven to increase accessibility to the Metro Vancouver region through cost-efficient, long range, and high frequency service. However, the Metro Vancouver region benefits from mobility stemming from its existing freeway system, such as the Trans-Canadian Highway network, alongside provincial freeways built in the 1960s. Growth derived from rapid transit is widely studied, however its long-term effects on population and job growth targets alongside automobile-oriented infrastructure are noteworthy gaps in research. As rapid transit systems are relatively new, few studies have covered their longitudinal effect in proximity to freeways.

Using Vancouver as a case, we determine if major freeways inhibit the potential density gains in employment and population encouraged by transit. Examining the evolution of transit, specifically the bus and train services, and density growth between 2001 to 2021, we uncover the magnitude to which freeways impede population and employment density growth. Firstly, we conduct a correlation analysis to examine the relationship between the change of transit frequency, population and job density, and its proximity to planned urban centres and freeways throughout the study period. We follow this with a combined index derived from changes in density and transit service frequency to discover potential trends around stations located closer to freeways. Prior literature illustrates both freeways and transit as systems lead to population and employment growth (Lai et al., 2024). However, contemporary studies show proximity to freeways has reduced population numbers, but whether that is a result of transit service increasing is unknown (Brinkman, 2022). We hypothesize that proximity to freeways negatively affect the growth in population and employment encouraged in transit-oriented areas, particularly around SkyTrain stations. The findings serve as a useful tool for policymakers to determine regions of low service, and to facilitate the development of future transportation plans. For researchers, this correlation analysis and combined index using publicly available data to analyze transit frequency can guide future research aiming to measure past and future transit service and emphasize the role of service frequency in density-related studies.

2. Literature Review

This chapter discusses existing literature concerning (1) the interactions between transit frequency and density, (2) the impacts of freeways, (3) the Vancouver-specific context, and (4) the existing gaps of these studies in evaluating transit service quality alongside automobile infrastructure. This purpose of this literature review is to provide a strong foundation for a correlation analysis based on empirical data that elucidates density changes in transit and freeway corridors. Furthermore, we elaborate a need for an accessible index associating density changes with service frequency changes.

2.1 Interactions between Transit Frequency and Density

2.1.1 Definition of Transit Frequency

Prior research has attempted to define transit frequency across a spatial scale as well, examining frequency as one of the indicators of overall quality of service and accessibility. In Vancouver, transit frequency is specified as service across a specific route less than 15 minutes apart, equating to a minimum of 120 trips per day (Walker et al., 2009). Further literature emphasizes this measure, with research in Montreal deducing frequency in their study as the average time between the next bus or train at the same stop. Transit frequency is often tied into other measures of transit supply, which delineates the adequacy of service in an area regarding the demand for transit of its population (Jiao & Dillivan, 2013). Jiao & Dillivan (2013) measure transit supply as a mixed variable affected by the quantity of buses and rail stops, the frequency of these services measured daily, and the overall number of routes in the system. Areas of low service from both transit and the automobile are transit deserts, and scholars and policymakers aim to resolve deserts through the increase of density.

2.1.2 Transit Frequency and Population Density

Transit experts describe two key density metrics to consider when comparing the impact of transit and the automobile on an urban area. Firstly, population density, defined as the number of residents within a given area, is a critical factor for measuring the success of urban transportation. Ridership is an important variable when observing the relationship between population density and transit frequency. Transit agencies depend on ridership to contribute to an efficient system, and without ridership, budgetary issues arise. Examining this relationship, Mattson (2020) discovered that higher density, leads to higher frequency of transit to alleviate automobile traffic congestion. Whereas in less dense neighbourhoods, low frequency is common, as densities are insufficient to provide a reasonable investment in transit (Mattson, 2020). Similarly, transit frequency is an indicator of ridership rates, compared to the price of fares, proving that frequency is a make-or-break indicator for encouraging transit use (Taylor & Fink, 2013).

Many studies aim to determine the influence of increasing transit services on population density. Brooks & Denoeux (2022) compared transit ridership in Bogota, Columbia and Jakarta, Indonesia, exploring the impression of high frequency bus rapid transit (BRT) in both cities. Despite their construction around the same time, the BRT in Bogota had a seven-fold ridership rate compared to the similar frequency network in Jakarta, simply from pre-existing high residential densities, which were a result of historical transit-oriented development. In Jakarta, where zoning by-laws favoured growth around freeways, the implementation of rapid transit saw minimal results as ridership numbers dwindled far below expectations (Brooks & Denoeux, 2022). Cervero & Gorham (1995) reinforced these findings, as historically streetcar-served neighbourhoods harboured more accessible transit. In Los Angeles, accessibility had significant impact on commuting patterns, making it 1.4% more likely for people to use transit in transit-accessible neighbourhoods compared to automobile-dependant residential areas, when controlling for population density (Cervero & Gorham, 1995). Moreover, Beaudoin & Tyndall (2023) show that residential density amplified by six times around BRT routes and stations compared to the rest of an urban area—also proven temporally from the increase in housing demand over time (Beaudoin & Tyndall, 2023).

Transit frequency and population density thus have a mutualistic relationship, illustrated in *Figure 1*. As higher density provides sufficient ridership numbers for transit agencies to invest in frequent transit service to increase accessibility, density grows with the increase of transit service. This relationship reinforces the need to examining fringes between automobile and transit-led development to better address investments in densifying areas.

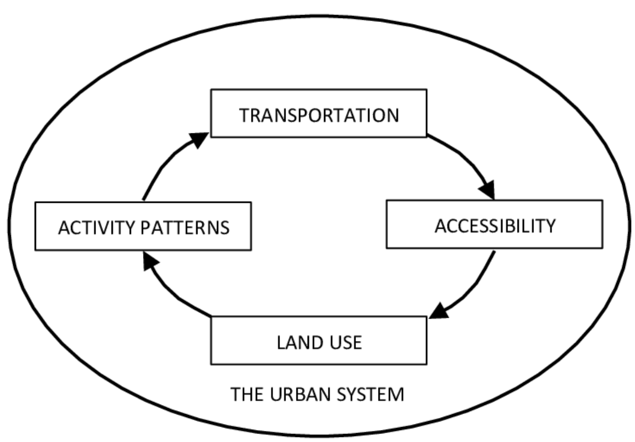

Figure 1: Mutualistic relationship between transportation and density (Higgins et al., 2014)

2.1.3 Transit Frequency and Employment Density

Employment density has a slightly different relationship with transit frequency. A sizable proportion of research shows employment density is dependent with the increase of transit and population densities; however, automobile-led development in US metropolitan regions has also led to employment density growth in the urban periphery. Whereas population density decreases with automobile use, employment density sometimes increases. Circella et al. (2014) point instead to existing residential densities and a job-housing balance as key drivers for employment density growth (Mattson, 2020). They also explain that Californian cities enacted policies to specifically increase employment density through the increasing of transit quantity and population density to combat office suburbs served only by the automobile. Although these policies seemed effective in theory, evaluating empirical evidence of employment density is convoluted, when paired with other factors such as the effects of zoning ordinances, parking restrictions, and infrastructure developments (Circella et al., 2014). However, previous studies demonstrate a clear relationship between employment and transit use, especially in the peak morning rush hour. Frank & Pivo's 1994 study discovered strong linear relationships between employment density and transit use, more than automobiles and even walking. Moreover, they discovered that increasing job density resulted in the reduction of total trips by personal vehicles compared to other areas. This link was even stronger than the relationship between transit use and population density, which in this study, the latter illustrated a non-linear relationship (Frank & Pivo, 1994).

Regarding transit frequency, a growing body of research points to frequency influencing employment density in both space and time. Comparing Boston and Toronto, cities of matching size and population, Schimek (1997) discovered that greater spatial distribution of high employment density census tracts led to better transit service, especially at the inner suburban core. Relating these discoveries back to Brooks & Denoeux's 2022 assessment of Bogota and Jakarta, they illustrate similar findings. As transit expands outwards from the Central Business District (CBD), transit frequency decreases, alongside employment density concentrated in the urban core. Boston, historically marked with automobile-led development, failed to gain the density required for transit investments at the urban periphery. Toronto, however, densified the inner suburbs, making them more attractive for transit investments in higher frequency networks, despite still being accessible by freeways. This study specifically highlights that job density can promote transit growth through higher frequency routes, which in return, amplifies density. Schimek notes that greater frequencies mean less overall transit time for commuters, creating an attractive alternative to automobile travel and the potential to shape housing and employment opportunities in the long term (Schimek, 1997). Yang et al. (2023), also underline high densities with equal accessibility by cars and by transit, generating less vehicle-miles-traveled (VMT) (Yang et al., 2023). These finding are echoed by Ewing & Cervero (2010), who conclude that accessibility to jobs by automobile are inversely related to VMT (Ewing & Cervero, 2010). Even in CBDs, employment density is considered a much larger predictor of transit mode share than regional populations, proving that higher densities run collinearly with higher transit use and lesser automobile use (Taylor & Fink, 2013). Mattson (2020) reiterates these findings, claiming that generally low density and low frequency areas are marked with higher levels of unemployment (Mattson, 2020). Just as density created incentives to increase transit frequency, current literature evaluates the effect of transit frequency on density. In Seoul, Korea, the implementation of a BRT system replacing a lower frequency network led to employment density increasing by 54% over just five years (Kang, 2010). Additionally, the number of bus routes are also explanatory variables for gauging employment density growth (Lai et al., 2024).

2.2 Understanding the Impacts of Freeways

Research on the interaction between freeways and densities in cities are studied more than transit use and density. Most research relates the debate of transit and freeways with that of accessibility and mobility. Sprawl led by automobile-oriented development prioritized mobility at the cost of high-density land uses and long-term accessibility. As cities scramble to remedy this archaic approach, metropolitan regions are still largely inaccessible for alternative modes of transportation such as walking, cycling, and transit. Handy (1994) argues that the prioritization of accessibility is inherently better than mobility for the future of our cities. She suggests that traditional quantitative measures of mobility used to guide transportation research such as freeway level of service, volume-to-capacity ratios, and even vehicle-miles-traveled, should be abandoned for measures that reflect accessibility (Handy, 1994). Some studies attempt to measure the effect of high-capacity roadways with density metrics. Brinkman (2022) illustrates the decline of population densities in proximity to freeways in US metropolitan areas, suggesting through simulated models that if freeways were buried, population densities would undoubtedly rise (Brinkman, 2022). Comparing Vancouver, Montreal, and Toronto, Filion et al. (2010) underscore Vancouver's decision to remove freeways from the downtown core as a pivotal cause for the 25% increase of population density in the urban core, inner city, inner suburb, and outer suburb compared to other Canadian metropolitan regions (Filion et al., 2010). Both studies suggest that the absence of freeway infrastructure contributes to lower population densities. The impact of freeways specifically on employment density is difficult to quantify but one study proposes that employment density increases near interchange ramps, however, it also increases with the implementation of a BRT system (Kang, 2010).

2.3 Context of Vancouver, Canada

In Vancouver, literature on density development from transit projects follows the construction and proliferation of the rail rapid SkyTrain network. Since its opening in 1986, the SkyTrain has resulted in the highest passengers-per-route-km and actual patronage in Canada within a decade after its construction. Due to a favourable geographical and political context, the SkyTrain proved to be very efficient, with its frequency credited for the densification of nearby town centres (Babalik-Sutcliffe, 2002). Moreover, the SkyTrain system increased residential and employment density in the region. Between 1986 to 2006, the number of high-density residential apartments around SkyTrain stations increased by 839.6% compared to a regional average of 121.6% (Foth, 2010). Martino et al. (2021) evaluate accessibility in Vancouver by comparing walking to work, biking to work, and transit frequency at a scale of trips every 10 minutes. They determined that transit frequency in Vancouver greatly contributed to accessibility and livability in Vancouver. Moreover, Martino et al. (2021), uncovered that Vancouver's accessibility rises as density increases with frequent and rapid transit, supporting the findings regarding other cities in earlier sections of this literature review (Martino et al., 2021). A recent study strengthened these outcomes with a twenty-year analysis between 1996-2016, demonstrating that census tracts in proximity to the 97 B-Line, 98 B-Line, and 99 B-Line BRT and Expo, Millennium, and Canada SkyTrain lines saw much higher gains in residential density compared to areas outside the transit corridor (Kapatsila et al., 2024). Lastly, perception towards transit outside of the area served by the SkyTrain and BRT systems are equally important to consider. One study discovers that lower residential density neighbourhoods in the Greater Vancouver region have a poorer perception of transit, deriving their opinion on the inadequate frequency and coverage of the network. Contrarily, the higher the density, the higher the number of people satisfied with transit services, contributing to higher ridership. Chaudhury et al. (2012) suggest that low density neighbourhoods are more comfortable with the mobility provided by the automobile, as their neighbourhoods are oriented towards its use (Chaudhury et al., 2012). Published by TransLink, Walker et al. (2009) determine that core indicators of the positive success of frequent transit are (1) the development of a more attractive system compared to the automobile, (2) increased employment density and major activity zones, (3) more growth around transit corridors, and (4) the future of land use and development. In 2007, TransLink and Metro Vancouver unveiled its plan for the Frequent Transit Network (FTN) in the metropolitan region. The goal of the FTN was to connect corridors between urban centres, such as Burnaby, New Westminster, Surrey, and Richmond, with service frequency of 15 minutes or less. The second goal of this program was to solely rely on rapid transit such as the SkyTrain for high frequency, but to increase bus service as well, providing a broader influence of transit on the region (Walker et al., 2009). Furthermore, the Metro Vancouver 2040 Regional Growth Strategy emphasized development around this network, especially within 800m of a SkyTrain station. The Growth Strategy particularly highlights growth targets at urban centres, with estimates of increasing the existing 26% proportion of Metro Vancouver's population to over 40% in thirty years. However, the estimates also keep growth at areas around SkyTrain stations relatively stable, with the existing percentage of residents and jobs within 800m of stations rising only 2% and 5%, respectively. (Greater Vancouver Regional District, 2013).

2.4 Addressing Gaps in the Literature

2.4.1 Gaps in Transit Frequency and Density Studies

Urban transportation is a complex organism, and thus, it is a challenge to confidently rely on just one variable to reach conclusions. Despite significant ridership rates between Bogota and Jakarta, Brooks & Donoeux (2022) indicate difficulty to evaluate the influence of transit service on an area when compounding variables such as neighbourhood type and transit usage intertwine with the results. Some scholars suggest that for analysis of densities in relation to better transit, there must be more quantitative data to examine external and internal factors that also have influence (Taylor & Fink, 2013). Transit frequency, in prior studies, lacked a comparable temporal scale. For example, one study only observed the morning rush hour between 5am to 9am, and disregards evening rush hour and weekend service which could prove density increases for other activities (Kaeoruean et al., 2020). The TransLink publication on frequent networks emphasized the importance of all-day and all-week assessment, suggesting that future implementations rely not just on peak frequency, but on off-peak and weekend ridership numbers (Walker et al., 2009).

Frank & Pivo (1994) reveal that increase in population and employment density is not necessarily the result of better accessibility or transit, but also due to implicit costs and demographics (Frank & Pivo, 1994). Populations are heterogeneous by nature, and despite making assumptions for transit-demand across an entire census tract, it is complex to find a single value that serves as the reason for an individual to choose transit over the automobile. Moreover, analysis of actual ridership rates do not account for the potential of ridership expressed by transit frequency, which greatly guides future density growth in an area (Jiao & Dillivan, 2013; Kaeoruean et al., 2020).

2.4.2 Gaps in Understanding the Impact of Freeways

Furthermore, an extensive gap pervades any understanding of the role of freeways as influencing density within a developed city. Historically, most literature focuses on the effects of freeways before transit implementation, or in the sprawl it causes when it is the only form of mobility. Mamun et al. (2013), endeavoured to measure transit service frequency between census tracts, tying frequency with accessibility to rail transit infrastructure. However, they fall short in uncovering the relationship of transit with the freeway dimension which is used by bus routes as well as personal vehicles (Mamun et al., 2013). Despite Brinkman (2022) bidding to highlight its effects in a city connected with transit, they only found declines of population density and not substantial evidence on the effect of employment density (Brinkman, 2022). Kang's (2010) article did not find employment density changes over time in cities with growth around both freeways and BRT systems in proximity to high-capacity roads (Kang, 2010).

2.4.3 Gaps in Understanding Growth in Vancouver

Lastly, there is a substantial lack of current research in the local context of Metro Vancouver. Studies infer the potential to study long-term impacts of the SkyTrain and BRT on the employment and residential densities in low-density, automobile-oriented neighbourhoods. At present, research on SkyTrains suggest marginal alleviation of traffic congestion as a result of its implementation (Babalik-Sutcliffe, 2002). The ability to measure replacement of vehicles with transit is a challenge faced in other studies as well (Verbich et al., 2017). Martino et al. (2021) examines a point-in-time livability index for Vancouver but overlooks their accessibility measure by not anticipating mobility by freeways in their calculations (Martino et al., 2021). The FTN revealed by TransLink did not mention the potential fragmentation and decreases in density growth caused by the Trans-Canada Highway and provincial freeway systems on Frequent Development Areas around SkyTrain stations.

2.5 Conclusion

The findings from the literature review underline key breakthroughs in transit research but point to an insufficient understanding of the fringe between freeways and transit service using population and employment as vectors for growth. In some cases, transit service is assumed to increase with population and employment density, outlined by a mutualistic relationship where both grow from the increase of each other. As the city expands from the CBD, density starts to diminish, with transit service diminishing in automobile-oriented neighbourhoods but higher in denser, accessible neighbourhoods. Understudied, freeways reduce population density but show mixed results when contrasted to adjacent rapid transit systems. Moreover, employment density is a less conclusive indicator in the comparison of free interchanges and bus rapid transit. Current research of Vancouver focuses on the density changes that follow the implementation of the SkyTrain as well as the political decisions to remove freeways from the downtown core. The influence of the existing freeways in the regional district remains unknown. The current gaps necessitate a longitudinal study to understand the impacts of transit service increases in areas closer and farther away from freeways. Finally, a quantitative metric derived from population and employment density growth, and transit service frequency in correlation with proximity to interchanges should reveal the underlying impact of freeways.

3. Methodology

3.1 Study Site

The Metro Vancouver Regional District is comprised of the City of Vancouver and several urban and municipal town centres that are connected through the TransLink transit network (SkyTrain and buses) and freeway system (Trans-Canada Highway; British Columbia Highway 91 and 99). The SkyTrain network, illustrated in *Figure 2*, is made up of three lines. In 2001, the SkyTrain consisted of 20 stations on the Expo Line which connected the City of Vancouver with Burnaby, New Westminster, and Surrey. Over the next decade, the SkyTrain network grew with the opening of the Canada Line which extends down to Vancouver International Airport and the City of Richmond, and the Millenium Line which runs parallel north to the Expo Line for a total of 49 stations. Finally, in late 2016, the Evergreen extension opened on the Millenium Line with 6 stations: from Burquitlam and to Lafarge Lake-Douglas College. Since our study examines transit frequency and urban density in TOD areas and their proximity to freeways, we examined these variables in an 800m buffer around each SkyTrain station.

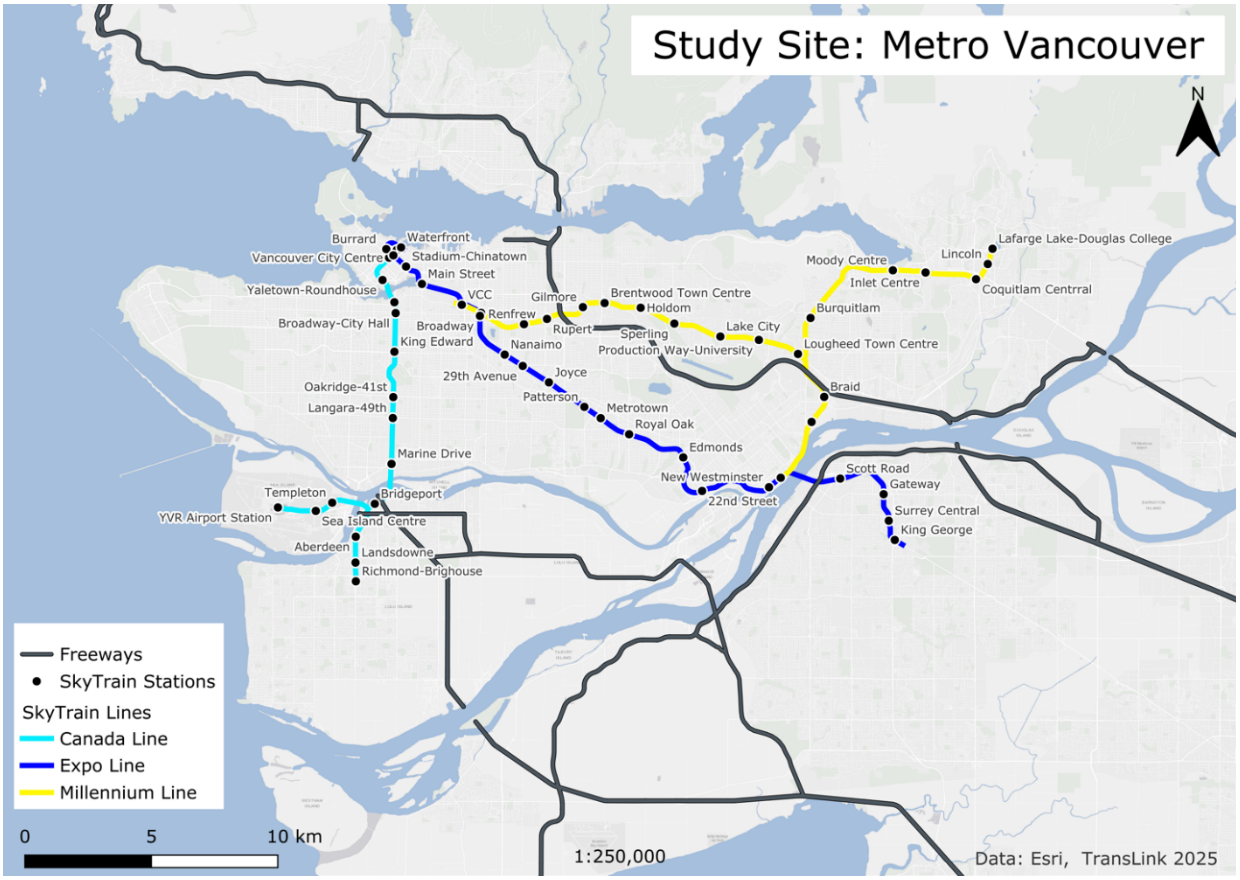

Figure 2: Metro Vancouver Study Site

3.2 Study Design

To assess the use of transportation infrastructure and the quantity of people and jobs concentrated in different neighbourhoods of Vancouver, we employed two quantitative approaches across a temporal scale: a correlation analysis and a combined index. We used Geographical Information Systems (GIS) to measure population and employment density around SkyTrain stations in 2001, 2011, and 2021. This study period was selected due to data availability from Statistics Canada's census and scanned transit timetables from TransLink.

Interchanges are chosen to represent entrances and exits into the controlled-access highway network and signify that automobile-led development would stem from these points.

Therefore, distances were measured from the centres of the 800m buffer of TOD SkyTrain stations to interchanges. Moreover, we marked the centroids of planned municipal and urban centres, to account for planned densities in Metro Vancouver. Since urban centres are pre-planned to concentrate population and employment, it is critical to consider their proximity to both SkyTrain stations and freeways to avoid conflating the impact of intentional land-use planning with automobile infrastructure. Consequently, we can clearly examine the potential correlation between TOD areas and freeways over the study period.

This following section will outline the collection of population, employment, and transit data, and the methods used to establish the variables used in the correlation analysis and the Combined Density-Transit frequency Index.

3.2.1 Population and Employment Density

We imported spatial data files for the Census Metropolitan Area (CMA) of Vancouver and downloaded census profiles for 2001, 2011, and 2021 from the Statistics Canada archives accessed through the Canadian Census Analyser (CHASS) (University of Toronto, 2025). We collected boundary spatial data for Metro Vancouver at the census tract (CT) level. Defined by Statistics Canada as geographic areas typically containing between 2500-7500 people, boundaries follow fixed physical features such as barriers, streets, and municipal limits for each of the study years. We determined CTs are the appropriate scale for this study, as populations share similar socio-economic conditions therefore maintaining reasonable homogeneity when generalizing their accessibility to transit and freeway systems (Statistics Canada, 2022). We downloaded CTs in shapefile format to manipulate using QGIS, an open-source GIS software. We obtained population counts from Statistics Canada and extracted in spreadsheet format using the Beyond 20/20 browser. Employment data fitted to the boundaries of respective study years was only available as fitted to 2021 boundaries. Afterwards, we used QGIS 'Join' function to join CT unique identifiers between employment and population with the CT spatial data.

Based on methods from Townsend & Ellis-Young (2018), we removed large non-urban areas such as bodies of water, large green spaces, agricultural land, and non-urban industrial zoned land to better represent populated areas. Moreover, we only considered areas with a density higher than 400 persons per square kilometre and removed parks and green spaces over 10ha, illustrated in *Figure 3* (Townsend & Ellis-Young, 2018). To calculate density, we divided population counts for each of the years by their respective spatially adjusted CT area and retained the same equation for job counts across years using the 2021 CT boundaries.

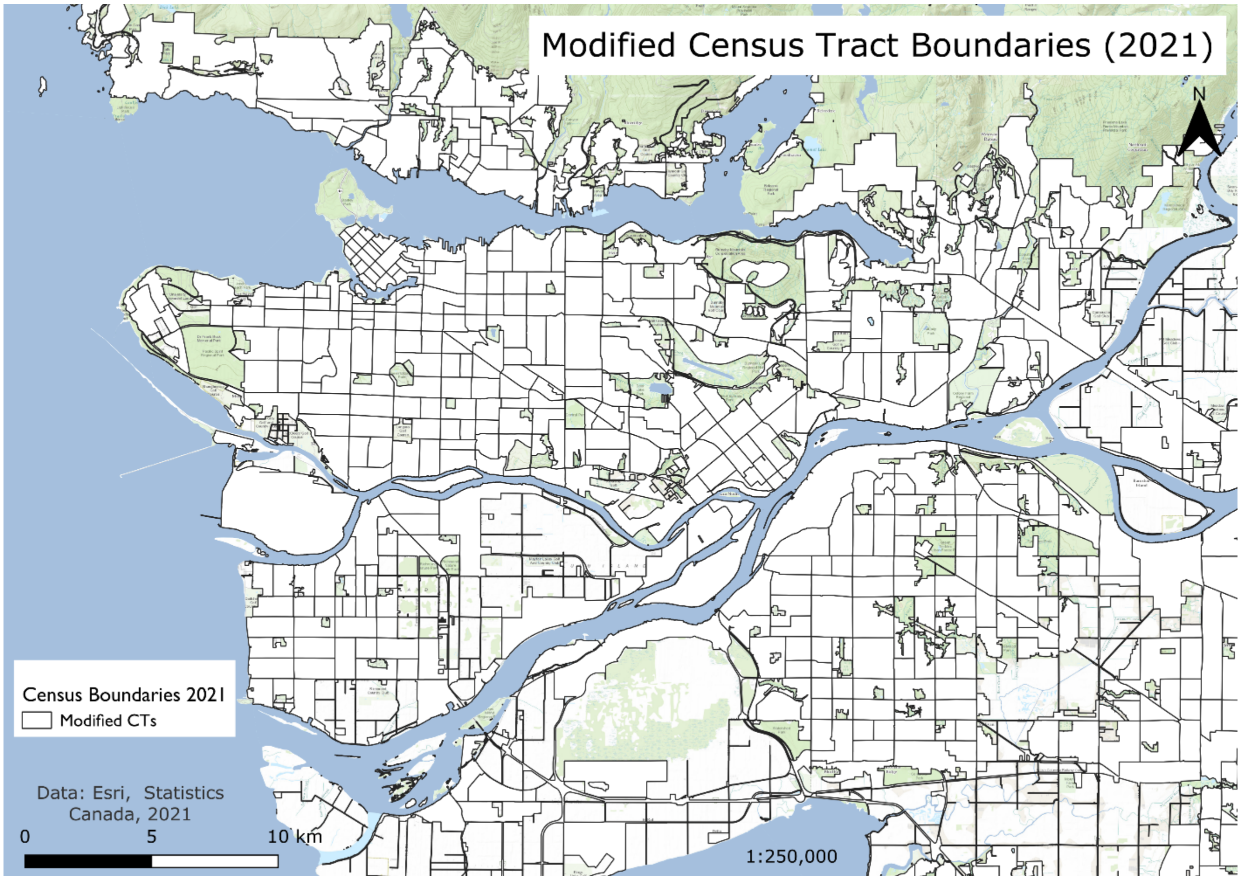

Figure 3: Census Tracts with Removed Non-Urban Areas (2021)

3.2.2 Transit Data

We collected transit frequency data from scanned and digitized SkyTrain schedules for each line for each of the study years. This data was collected for each stop during peak (6am-9am; 3pm-6pm) and off-peak hours (9am-3pm; 6pm-12am), and weekends (Saturday: 6am-12am; Sunday: 8am-12am) for a duration of a week in mid-September, summating to a weekly total. To spatially construct transit stops and lines, we downloaded publicly accessible General Transit Feed Specification (GTFS) from TransLink and Open Mobility Data for 2011 and 2021. We subsequently transformed GTFS data into spatial data using the 'Points to Paths' QGIS plugin. Spatial data for the 2001 study period existed from a prior research assistant's study and had transit frequency data attached. Transit frequency data for 2011 and 2021 had to be manually attached from scanned timetables to the lines deduced from the GTFS data.

To determine the transit-oriented development area around SkyTrain stations, we created a catchment area of 800m around each station using the 'Buffer' and 'Dissolve' tools in QGIS. In total, there are 51 SkyTrain stations considered in this study, with the three stations serving the Vancouver International Airport (Templeton, Sea Island Centre, and YVR Airport Station). These three stations were excluded, as their sole census tract yielded lower than 400 persons per square kilometre. We overlayed each SkyTrain catchment area on top of the CTs to measure which CTs were within the coverage area of the 800m buffer by using the 'Polygon centroid' function. We selected these census tracts to measure the average population and employment density of areas in proximity to the SkyTrain station.

Finally, we tied transit data into these TOD areas by using the 'Select by Radius' QGIS tool to determine which transit lines served the 800m buffer for each station. We extracted these lines and summed the frequencies of regular service bus, SkyTrain, and BRT lines. We specifically excluded community shuttles and night-time buses, as they do not serve Metro Vancouver with sufficient frequency to be influential on population and employment density. A detailed examination of the methodology for the 2001 study year is illustrated in *Figure 4*.

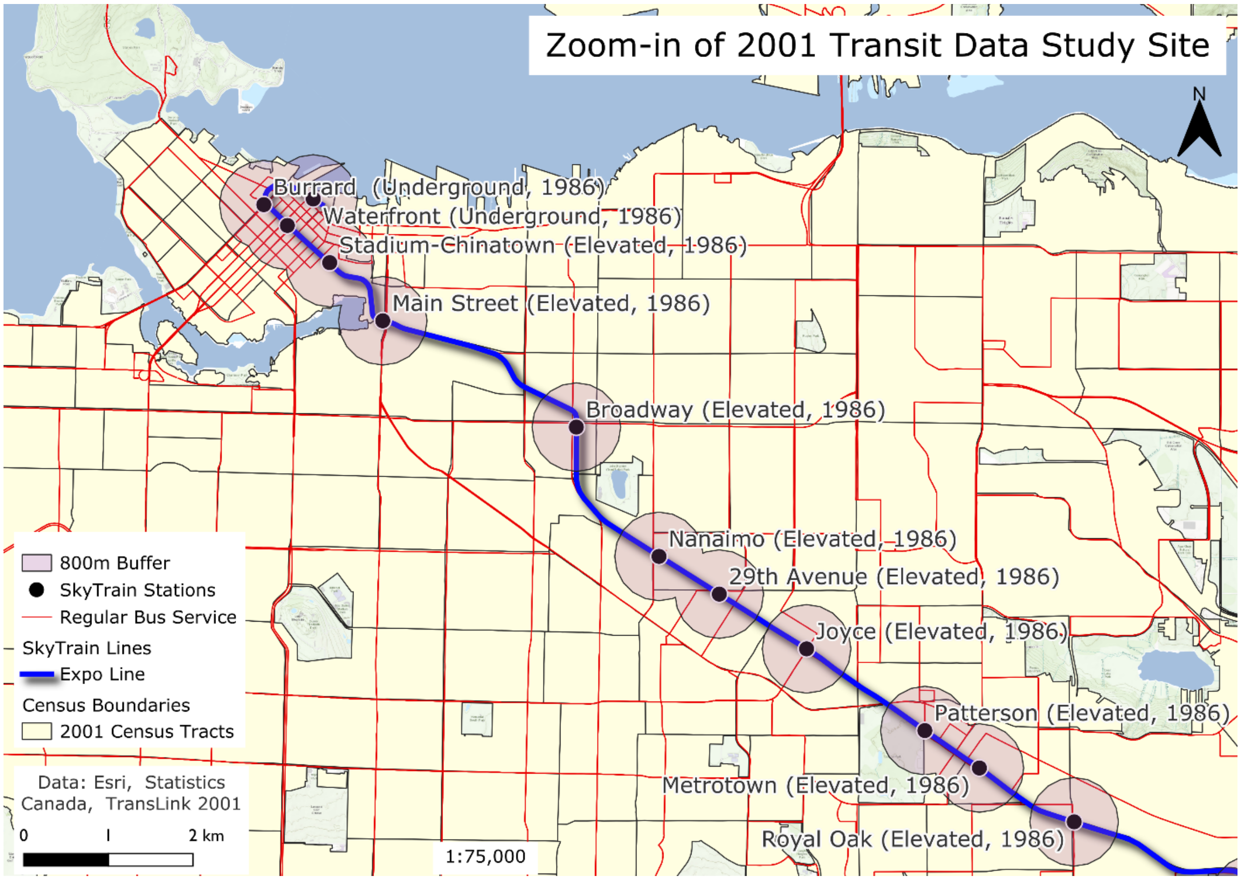

Figure 4: Closer Analysis of Study Design—TOD Buffers with CT Boundaries

3.2.3 Freeway and Urban Centres

To measure the impact of freeways, we identified major interchanges along the Trans-Canada Highway 1, Highway 91, and Highway 99, which make up the major high-capacity road network of Metro Vancouver (Townsend & Ellis-Young, 2018). On QGIS, we used the 'Nearest hub (point to point)' tool to calculate the nearest distance from a SkyTrain station (in km) to an interchange.

Urban centres outlined in the Metro Vancouver's strategic growth plans, play a significant role in population and employment density. Through policy, urban centres are specifically planned to intensify growth in the suburban regions of Metro Vancouver (Greater

Vancouver Regional District, 1975). As a result, these centres will drastically increase densities around SkyTrain stations and should be factored into the analysis. We created a point-layer representing the centroid of each urban centre in Metro Vancouver: Burnaby, New Westminster, Surrey, Coquitlam, Richmond, and North Vancouver City (Lonsdale). Moreover, we listed the centroid of the Vancouver CBD as an urban centre. We used the 'Nearest hub (point to point)' tool to find the nearest distance from each SkyTrain station to the nearest urban centre.

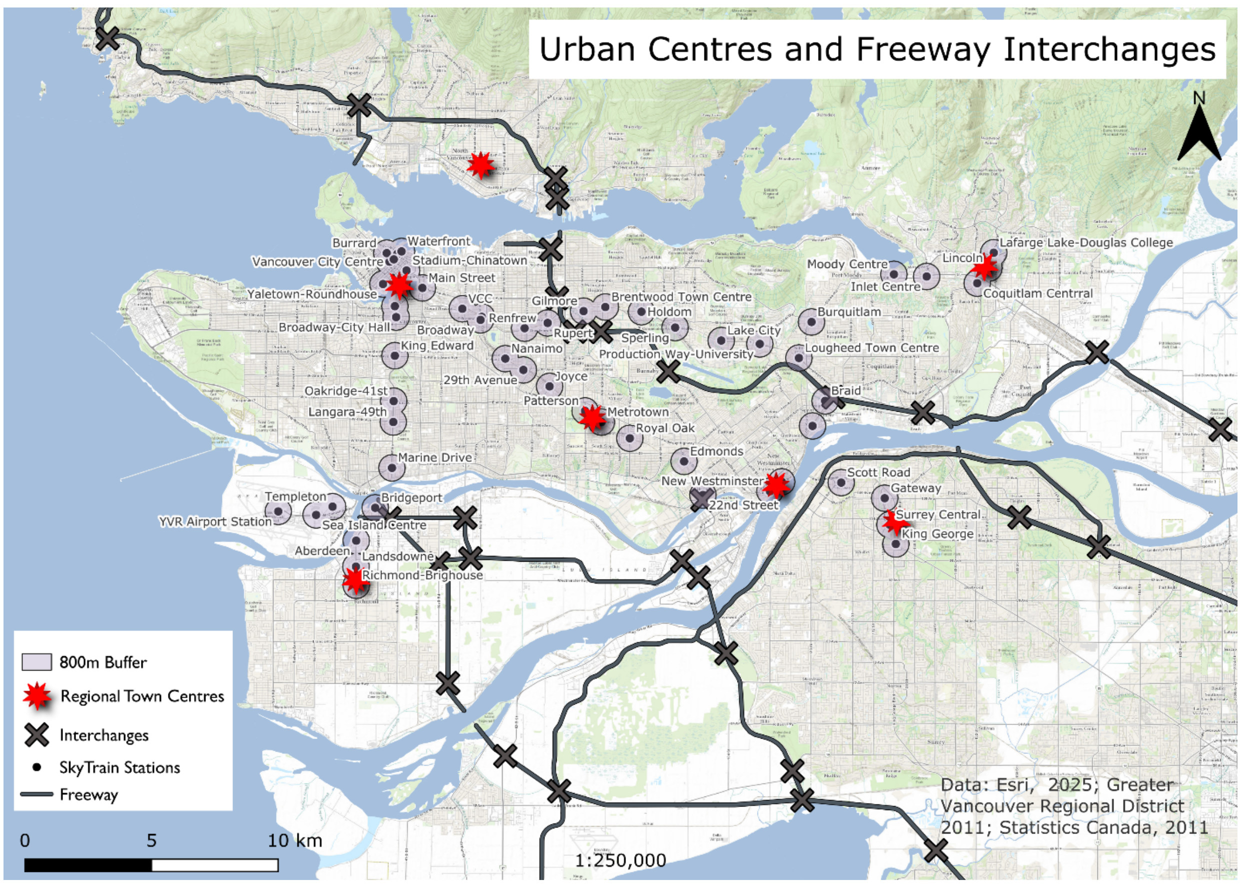

Figure 5: Urban Centres and Freeway Interchanges (2021 dataset)

3.3 Correlation Analysis

We analyzed the correlation between density, transit frequency, and distances to freeways and urban centres to uncover potential relationships between variables. To accomplish this, we manipulated data collected in Section 3.2. The compiled spreadsheet contained weekly transit frequency, population density (persons/km^2), employment density (jobs/km^2), distance to nearest urban centre (km), and distance to nearest interchange (km) for each of the SkyTrain stations in 2001, 2011, and 2021. We conducted all further analysis using R statistical software. We used the 'dplyr' package to create separate columns for measuring population, employment, and transit frequency change between 2001-2011, 2011-2021, and 2001-2021, by subtracting values from the later years by the earlier years. Afterwards, we used the 'corrplot' package to create a correlation matrix for each of the change variables and the distances. It calculated Pearson's R coefficients between each of the variables and plotted them onto a matrix for each study period range. Alongside the correlation coefficient, we joined the p-values in the matrix, highlighting which were statistically significant. This allowed us to visualize whether transit frequency or freeways were greater determinants and vectors of density change, regardless of their direction.

3.4 Combined Density-Transit Frequency Index (CDTFI)

The Combined Density-Transit Frequency Index (CDTFI) was measured to address the relationship between density and transit frequency that could not be answered by a correlation analysis alone. This index also serves as an accessible tool to visualize the combined effect of density growth and transit frequency changes across time. The CDTFI was derived from the same data as the correlation analysis, however, amalgamated population and employment density with transit frequency into a standardized metric. The first step involved calculating the Density to Service Ratio (DSR) for each station; a combined metric of densities around each SkyTrain station using the following equation:

$$DSR_i^t = \frac{Density_i^t}{Frequency_i^t}$$

where:

- DSR_i is the ratio of densities and transit frequency around station i for year t,
- $Density_i$ represent the sum of population and employment density around station i for year t,
- $Transit\ Frequency_i$ represents the sum of weekly frequencies of buses and SkyTrains inside the 800m buffer around SkyTrain station i for year t.

Since this metric is derived from two different scales, we standardized it to make it comparable to other stations and the same station across different years. The following equation was employed for standardization:

$$Z_{DSR_i^t} = \frac{DSR_i^t - \mu_{DSR^t}}{\sigma_{DSR^t}}$$

where:

- $Z_{DSR_i^t}$ is the z-score value at station i for year t,
- μ_{DSR^t} represents the mean of DSR values around each station for year t,
- σ_{DSR^t} being the standard deviation for all stations for year t.

The z-score centres the DSR around its mean, where values higher than zero are stations indicate that densities are higher than the supply (frequency) of transit service. Lower values indicated an over-supply of transit relative to density. Finally, to create the CDTFI, we measured the difference of z-scores of the Density to Service Ratio over time, using the following equation:

$$CDTFI_i^{(y-x)} = Z_{DSR,i}^{y} - Z_{DSR,i}^{x}$$

where:

- $CDTFI_i^{(y-x)}$ equals the difference of the DSR z-scores for station i between year x and year y,
- $Z_{DSR,i}^{y}$ and $Z_{DSR,i}^{x}$ represent the z-scores in the later and earlier years, respectively.

A positive CDTFI value means that as time progressed, density increased to a level where transit service frequency was not adequate to meet demand. A value of 0 would mean that density and transit service frequency are maintained, and a negative value illustrates an area that increased transit frequency, however, does not have the density to benefit from it.

4. Results

<u>4.1 Summary Statistics of Data Collected</u>

This section presents descriptive statistics of all collected data for variables in the 2001, 2011, and 2021, found respectively in *Appendix A – Table 1*, *Table 2*, and *Table 3*.

In 2001, the average transit frequency within 800m of the 20 stations analyzed was 11811 buses and trains/week. The average population density was 6266 persons/km^2 and employment density was 9083 jobs/ km^2. The average distance to interchanges was 3.69km and the average distance to the nearest urban centre was 1.64km.

The top weekly frequencies were at the Granville (31547 buses and trains/week), Burrard (29188 buses and trains/week), and Waterfront stations (27514 buses and trains/week), located in downtown Vancouver. The three least served stations by measure of transit frequency were King George (3234 buses and trains/week), Royal Oak (4401 buses and trains/week), and Gateway stations (4745 buses and trains/week). When we examined population density, the top cumulative CTs were found around Patterson station (14037 persons/km^2) in Burnaby, Burrard station (13286 persons/km^2), and Metrotown station (12809 persons/km^2) in its eponymous urban centre. The three least dense areas were around Scott Road station north of Surrey (411 persons/km^2), Gateway (4745 persons/km^2), and around 22nd Street station (3055 persons/km^2). Additionally, the sparsest census tracts with respect to employment density exist around Scott Road station and 22nd Street station (342 and 389 jobs/km^2, respectively) along with 29th Avenue station (524 jobs/km^2).

When examining stations in relation to distance from highways, 22nd Street station is the closest to an interchange, being 0.21km from Highway 91. Edmonds is also located closest to Highway 91 (1.69km) and lastly, Joyce-Collingwood station is located 2.37km from Trans-Canada 1. Eight of the stations in 2011 are located within 1km from a planned urban centre. However, Columbia (0.26km from New Westminster), Surrey Central (0.29km from Surrey), and New Westminster (0.33km from its eponymous urban centre) in the nearest proximity to an urban centre. Nanaimo station (4.15km), Edmonds (3.75km) and Commercial-Broadway (3.47km) are located the furthest away from a planned urban centre.

In 2011 (*Table 2*), the average transit frequency within 800m of the 35 stations analyzed was 9449 buses and trains/week. The average population density was 7198 persons/km^2 and employment density was 8167 jobs/ km^2. The average distance to interchanges was 3.30km the average distance to the nearest urban centre was 2.55km.

The three areas around SkyTrain stations with the largest weekly frequencies coincide with the greatest employment density: Burrard, Granville (tied with Vancouver City Centre), and Waterfront (30990, 30933, 30845 buses and trains/week; 51622, 46320, 44800 jobs/km^2, respectively). The least served stations were Sapperton (2877 buses and trains/week located north of New Westminster, Lake City Way station (3345 buses and trains/week) located in central Burnaby, and lastly, Holdom station (3584 buses and trains/week) in northwest Burnaby. Yaletown-Roundhouse (23350 persons/km^2) and Burrard (17611 persons/km^2) stations in downtown are the most densely populated, along with Joyce-Collingwood in Burnaby (18929 persons/km^2). Scott Road remained the least densely populated station with 436 persons/km^2, however, Production Way-University in eastern Burnaby (1326 persons/km^2) and Bridgeport north of Richmond (1382 persons/km^2) closely followed. Scott Road, 22nd Street, and 29th Avenue remain the least employment dense areas in the network (468, 367, 496 jobs/km^2, respectively).

The 22nd Street station remained the closest to a freeway interchange, with Braid (0.35km) and Bridgeport (0.71km) following. Considering Gilmore and Brentwood Town Centre stations, these are the five stations located within a kilometre of a freeway interchange. Yaletown-Roundhouse, Olympic Village, and King Edwards, all stations moving south of Downtown Vancouver, were the farthest away from an interchange. Twelve stations are located within a kilometre of an urban centre, with Richmond-Brighouse, Columbia, and Surrey Central being the closest (0.21, 0.26, 0.29km, respectively). The furthest were Lake City station

(5.91km), Production Way-University (5.60km) and Langara-49th station in South Vancouver (5.37km).

In 2021, an additional six stations were added through the Evergreen extension (*Table 3*). The average transit frequency within 800m of the 41 stations analyzed was 9676 buses and trains/week. The average population density was 8532 persons/km^2 and employment density was 5788 jobs/ km^2. The average distance to interchanges was 3.51km and the average distance to the nearest urban centre was 2.53km.

Granville and Burrard retained the highest transit frequency, however, Stadium-Chinatown, east of downtown Vancouver, was served by 27916 buses and trains/week. The least served stations remained Lake City Way and Sapperton, however they both gained roughly 500 additional transit services per week. Additionally, Aberdeen declined in transit frequency, to 3843 buses and trains/week. Yaletown-Roundhouse and Vancouver City Centre had the highest population densities (31213 and 22209 persons/km^2). Joyce-Collingwood retained the second highest population density in Vancouver for the study period, with over 23042 persons/km^2. The least dense areas persisted around Scott Road, Lake City Way, and Production Way-University, with a mere 510 persons/km^2 and tied at 1432 persons/km^2. The densest employment was located downtown at the same stations as a decade prior. Moreover, Scott Road, 22nd Street, and 29th Avenue station areas remained the sparsest in terms of employment count.

The same stations from the 2011 study period continued to be respectively closest and farthest to a freeway interchange. Burquitlam became the furthest station from a planned urban centre, being 6.57km away from Coquitlam. Conversely, but also found on the Evergreen extension, Lincoln station tied with Richmond-Brighouse to be the closest to an urban centre (0.21km).

<u>4.2 Correlation Analysis</u>

In the first half of the study period, all but one correlation was statistically insignificant (pictured in *Figure 6*). Distance between urban centres and highways had a R^2 of -0.51, illustrating a negative correlation in distance between each. This means that as stations were in proximity to urban centres, freeway interchanges had the moderate effect of being farther away. The sample size consisted of the 20 stations along the Expo Line.

The second half of the study period, between 2011-2021 showed many substantial correlations, as illustrated in *Figure 7*. Weekly transit frequency and change in employment density showed a positive, moderate correlation of $R^2 = 0.51$, denoting that as transit frequency increased, so did employment density in that decade. There was no significant correlation between transit frequency and population density, and no significant correlation in distances to urban centres nor in distances to interchanges. Population density and employment density had a weak-moderate negative relationship ($R^2 = -0.35$). Population density also had a negative relationship with distance to urban centres ($R^2 = -0.44$), implying that lower distances to urban centres yielded higher population densities, compared to CTs farther away. In relation to the distance to the nearest interchange, population density expressed a moderately positive relationship of $R^2 = 0.48$, which meant that areas near freeway on- and off-ramps had significantly lower population densities. Employment density returned a moderately negative correlation with distance to interchanges (R^2 = -0.48), suggesting higher employment counts in proximity to freeways. The sample size was comprised of 45 stations across the three SkyTrain lines.

Lastly, the correlation matrix of the change between the entire study period (2001-2021) is provided in *Figure 8*. Weekly transit frequency demonstrated a strong positive relationship with employment density (R^2 = 0.64). Moreover, transit frequency showed a nearly equally strong negative relationship (R^2 = -0.62) with distance to nearest interchange, implying that frequency increased around SkyTrain buffers closer to interchanges. Population density displayed a moderate, positive correlation (R^2 = 0.52) with the distance to interchange. Employment density produced a nearly opposite interaction with the distance to interchange variable (R^2 = -0.46), indicating that areas closer to freeways had higher employment densities.

Across all three study periods, the relationship between the distance to urban centres and the distance to freeway interchanges remained the same, with an R^2 of just over -0.5.

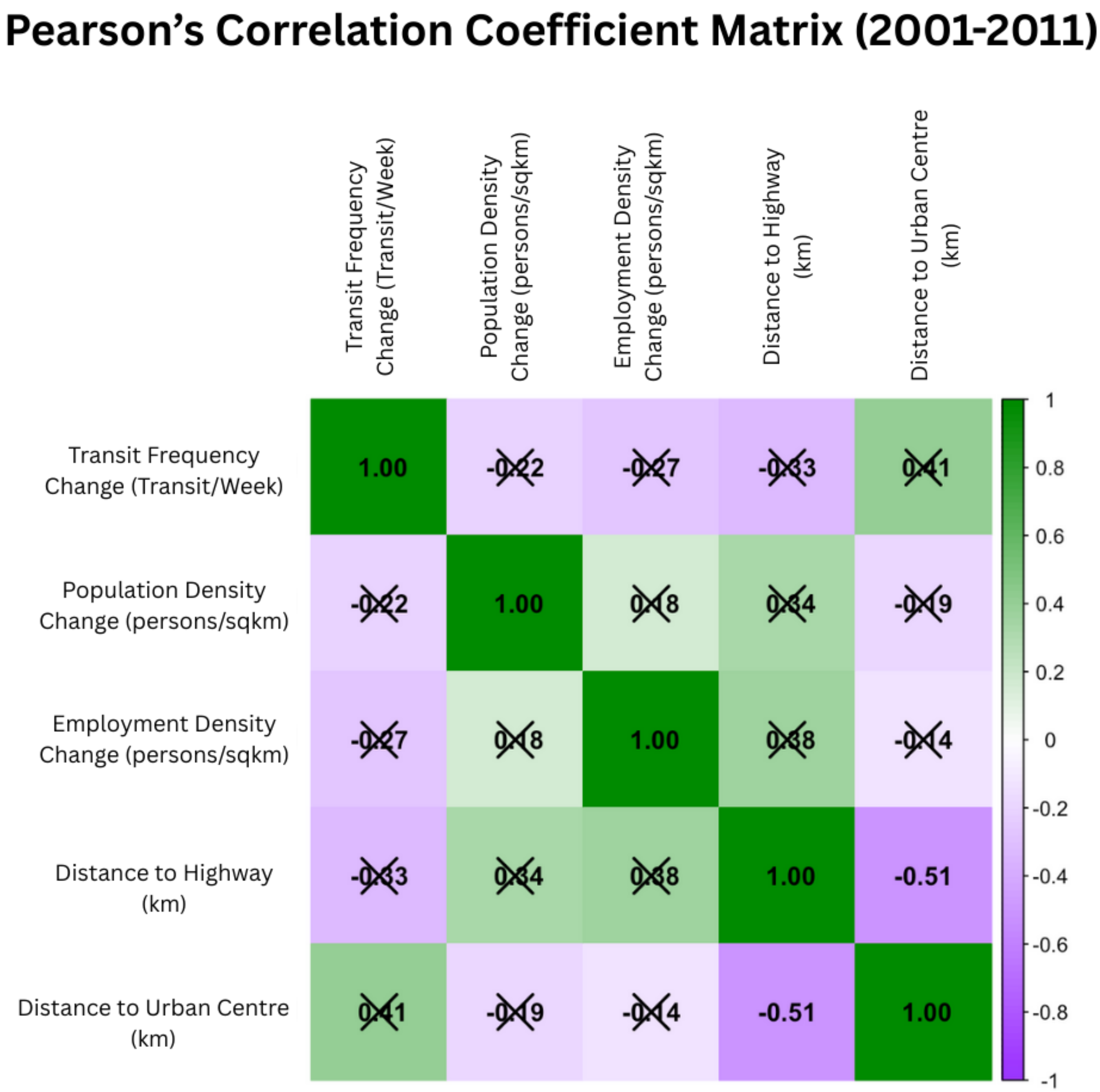

Figure 6: Correlation Matrix (2001-2011)

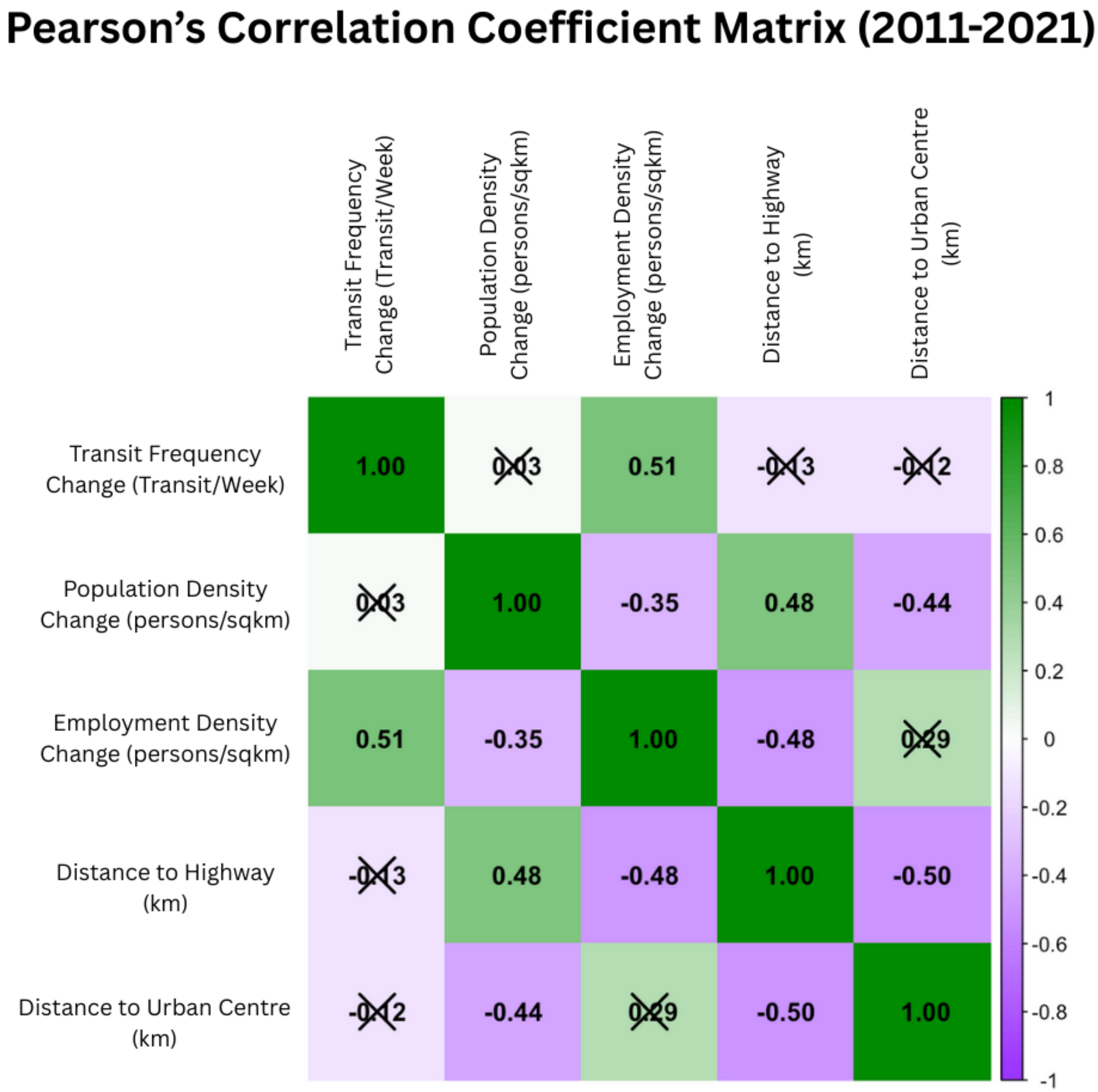

Figure 7: Correlation Matrix (2011-2021)

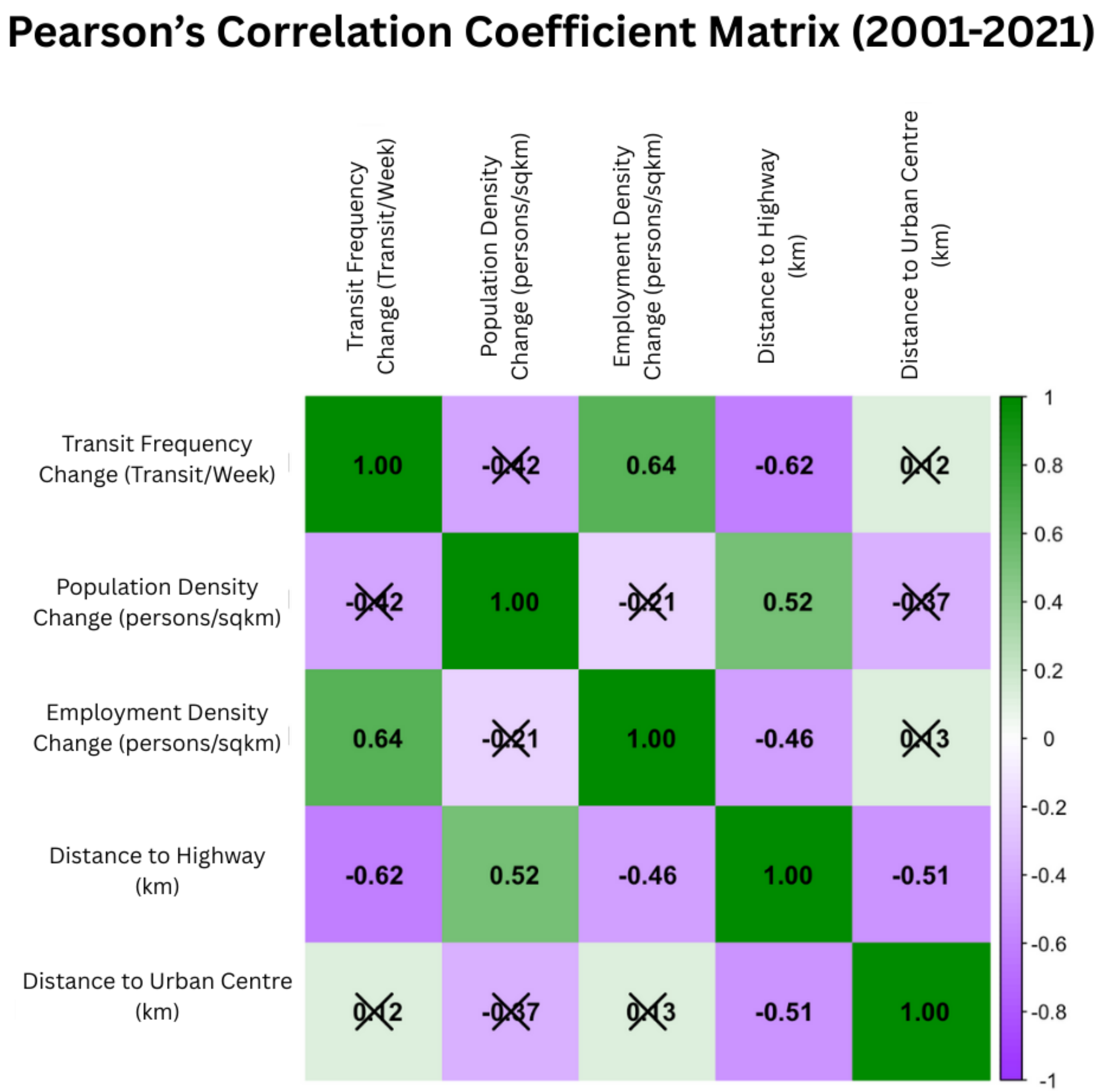

Figure 8: Correlation Matrix (2001-2021)

4.3 Combined Density-Transit Frequency Index (CDTFI)

This section highlights the results from the Combined Density-Transit Frequency Index (CDTFI) depicted in Appendix B (Tables 2, 3 and 4). The CDTFI, also known as the standardized change in the DSR over the different study years, aimed to evaluate whether densities and transit are well balanced, and note spatial inconsistencies. After calculating the difference for standardized DSRs at each station, the tables illustrate the differences between each year. In the study period between 2001-2011 and 2001-2021, only 20 stations as they appeared at both years.

Between 2001-2011, the average CDTFI was -0.07, with the largest CDTFI being 1.10 around Joyce-Collingwood Station. This result is derived from the standardized Density to Service Ratio being significantly greater in 2011 (1.45) than in 2001 (0.35). The actual DSR between the two years, listed in Appendix A Table 1 and Table 2, was 1.44 in 2001 and 2.61 in 2011. The lowest CDTFI was around Waterfront station (-1.33). The actual DSR was 2.30 in 2001 and 1.84 in 2011. The area around Patterson Station had a similar CDTFI of -1.32, with the actual DSR being 2.31 in 2001 and 1.86 in 2011. From the 20 stations analyzed, 7 yielded negative CDTFI values and 13 generated positive values. Scott Road and Burrard stations produced a value of 0.06, the closest to zero. The station with the highest CDTFI is located 2.57km (Joyce-Collingwood) from the nearest interchange whereas the two stations with the lowest CDTFI values are located over 3.14 km (Patterson) and 5.87 km (Waterfront) from the nearest interchange despite both being within a kilometre of an urban centre.

Between 2011-2021, the average CTDFI was 0.02, with the highest being 1.30 at Yaletown-Roundhouse and the lowest being -2.32 at Richmond-Brighouse. The actual DSR at Yaletown-Roundhouse was 3.10 in 2011 and 3.80 in 2021. The actual DSR at Richmond-Brighouse was 4.37 in 2011 and 2.44 in 2021. From the 45 stations examined, 22 stations produced a negative CDTFI, and 21 stations had a positive value. Two stations, Nanaimo and Royal Oak, had CDTFI values of zero. The station with the highest CDTFI is located 6.73km

(Yaletown-Roundhouse) from the nearest interchange whereas the station with the lowest CDTFI value is located 2.94km (Richmond-Brighouse) from the nearest interchange despite both being within a kilometre of an urban centre.

During the entire study period (2001-2021), the mean CDTFI was -0.19, with the largest value being 1.75 at Joyce-Collingwood and the lowest being -1.81 at Patterson. Main Street had the second highest value (1.26) and Waterfront had the second lowest value (-1.74). The actual DSR at Joyce-Collingwood was 1.44 in 2001 and 2.92 in 2021. At Patterson, the actual DSR was and 2.31 in 2001 and 1.44 in 2021. Around Main Street Station between 2001-2021, the actual DSR increased from 0.48 to 1.47. Lastly, at Waterfront, the actual DSR decreased from 2.30 to 1.48 over two decades. Main Street Station is located 5.27km from the nearest interchange and within a kilometre from an urban centre.

5. Discussion

5.1 Correlation Analysis

During the first half of the study period, the correlation matrix displayed no statistically significant differences other than the interaction (R^2= -0.50) between the distances between urban centres and freeways. This is explained through Metro Vancouver's controlled planning from the 1970s to ensure that urban centres are not situated by freeways and instead are developed through the transit corridor.

In *Figure 7*, a larger number of significant correlations are likely a result from the increased sample size, from 20 to 45 SkyTrain station catchment areas. Furthermore, the newly introduced lines extend to different areas, running towards Highway 91 and Highway 99, unlike those that only run parallel to Trans-Canada Highway, such as the Expo Line in 2001. The positive correlation between transit frequency change and employment density points to planned growth targets at urban centres, especially downtown. Since employment density generally decreased in the census tracts from 8167 to 5788 jobs/km^2 while transit frequency only slightly increased from 9449 to 9676 buses and trains per week in all census tracts near the SkyTrain network, the positive correlation may stem from the decrease of both transit frequency and the decentralization of employment from census tracts. This decentralization could be a result of the COVID-19 pandemic, as many workplaces shifted to remote work; this employment data was collected by Statistics Canada in the Fall 2020. Although a weaker correlation, population density and employment density have a negative relationship. Between 2011-2021, population density greatly increased from 7198 to 8532 persons/km^2 whereas employment density declined. Considering this trend, population density likely rose around SkyTrain stations as land values increased through the increased connectivity provided through transit. This corroborates findings from Foth (2010) which highlight, rising costs for housing around SkyTrain stations and follows the trend for employment to extend outwards from rapidly densifying TOD areas (Foth, 2010). Moreover, the positive correlation between population density and distance to highways validates the findings prior literature that suggest people do not want to live near freeways, despite being within 800m of a rapid transit station (Brinkman, 2022). Additionally, the negative correlation between population density and distance to urban centres is well-explained in policy, once again proving the effectiveness of planned urban centres for densifying population. However, across the study range, employment density has a moderate negative correlation with freeway interchanges, denoting that areas in proximity to freeways yield higher employment, while also failing to be correlated with proximity to urban centres. Employment densities, especially industrial parks and office suburbs, occur in clusters, away from the downtown urban core. If we removed the top five employment density areas, the next SkyTrain Stations are located closer to the Trans-Canada Highway (such as Joyce-Collingwood station) or near provincial highways (such as Richmond-Brighouse and New Westminster stations).

Similar correlations are found when we analyzed the entire study period. Depicted in *Figure 8*, transit frequency has a stronger relationship with employment density, although both decreased over the twenty-year period. Interestingly, a negative correlation between transit frequency and distance to interchanges emerged, indicating that transit frequency was higher around stations closer to freeway interchanges over two decades. However, an important distinction must be made for the 2001-2021 study period, as only the Expo Line was examined. Assumptions can be made for transit frequency near census tracts around the Millenium and Canada Line before they were built, seeing as they would lack a significant portion of rapid transit. Considering the oversight of adding more CTs, there lacks a comprehensive understanding of the correlation between transit frequency and distance to highways. Furthermore, the relationship between population density and distance to urban centres is insignificant in this plot, as in the analysis between 2001-2011. There are four urban centres served by the Expo Line—Downtown Vancouver, Burnaby, New Westminster, and Surrey—the lack of relationship is expected, as the majority of the SkyTrain route is served by the same frequencies (on the same rapid transit frequency line) and the relative distance to an urban centre along the route is consistently similar. Other than this metric, all correlations that existed between 2011-2021, also exist for the entire study period.

5.2 Making Sense of the CDTFI

The CDTFI values between 2001-2011 show a balance between transit service frequency and densities across the 20 stations. However, stations such as Joyce-Collingwood, Waterfront and Patterson stations strayed considerably from the mean DSR. A closer examination of Joyce-Collingwood station between 2001-2011 indicates a sharp rise of population density from 8846 to 18929 people/km^2 despite employment density only rising from 2607 to 2770 jobs/km^2. This increase is the result of a new census tract being created (CTUID 9330016.06) to reflect the changing population and socio-economic conditions around Joyce-Collingwood Station. Illustrated in *Figure 9*, the collection of these residential towers within two blocks significantly increased population density. Despite transit frequency increasing, it did not sufficiently meet the increase in population density required to reduce the station's DSR.

Figure 9: Residential Buildings in CT around Joyce-Collingwood Station (Google Maps, 2023)

Conversely, both Waterfront and Patterson stations yielded a significantly transit frequency-oriented value, with their respective DSRs being well below zero. While population density increased from 6421 to 11872, a 200% increase, this was diminished by the reduced employment density from 56822 to 44800, thus, reducing the overall numerator of the DSR. Moreover. transit frequency increased from 27514 to 30845, increasing the denominator and reducing the DSR. This decentralization of employment density, mentioned in the correlation analysis, is another example of employment clusters decentralizing from the downtown core towards urban centres at the periphery. The impact of decentralized employment clusters is also reflected in other Canadian cities (Schimek, 1997).

Between 2011-2021, the CDTFI remained near zero (0.02), demonstrating that most of the CTs around the 45 SkyTrain stations studied were adequately served by transit frequency despite their density growth. At the extreme over-supply of transit frequency, Richmond-Brighouse measured a value of -2.32. From 2011-2023, Richmond-Brighouse recorded a decrease in population density (16007 to 11962) and employment density (11822 to 9796). While transit frequency increasing from 6362 to 8909 times a week may have had an effect, the primary reason for this drastic reduction in density is the splitting of CTs from two large coverage areas over Richmond-Brighouse to four smaller coverage areas. Moreover, the denser CTs were located outside the 800m buffer of Richmond-Brighouse station. At the other end of the index, the extreme under-supply of transit was at Yaletown-Roundhouse, found in the south end of downtown Vancouver. In 2011, Yaletown-Roundhouse had a sharp population and employment density increase (158%), with a marginal increase (5%) in transit frequency downtown. Both Richmond-Brighouse and Yaletown-Roundhouse are located inside of their planned urban centres, thus, increasing population and employment densities are expected. Distance to highways do not appear to explain any trends between transit frequency and densities.

Lastly, between the entire study period of 2001-2021, the average CDTFI leaned towards over-supplied transit frequency. Joyce-Collingwood had a significant difference in DSR, as pictured in *Figure 9*. Main Street Station, located on the southeast edge of Downtown Vancouver, underwent rapid density increases through the introduction of another census tract (CTUID 9330049.06) within its 800m buffer. Neither Joyce-Collingwood nor Main Street Station are significantly close to freeway interchanges. Furthermore, Patterson and Waterfront continue to follow decentralization of their employment density despite increasing population density.

While the Combined Density-Transit Frequency Index proved to be an intuitive tool in measuring the impact of changing densities and frequency changes as a combined metric, understanding the impact of freeways and urban centres remains challenging. The CDTFI allows for long-term analysis of TOD areas, offering explanations for different variables swaying the index, while also allowing for a large-scale analysis of the system to see if the transit network is meeting density needs for the metropolitan region. However, we are strictly limited by the minimum number of stations.

5.3 Insights into Both Techniques

Both the correlation analysis and CDTFI examine the potential relationship between transit frequency, densities, and the proximity to highways. Both techniques harbour different strengths when understanding the complex relationship between transit frequency, density, and the built environment.

The correlation analysis provides a useful understanding how variables relate to one another over time. As expected, the correlation between population density and distances to highways was illustrated, however, inconsistencies persisted with regards to employment density. The lack of patterns between CDTFI and the distance to interchanges regardless challenges our hypothesis. While it may not be a reliable predictor of whether transit-oriented growth was stunted by freeways, the standardization of this metric allows for cross-station comparison across time, notwithstanding units for supply or demand. Moreover, the CDTFI evaluates the effectiveness of transit, which would direct policymakers and researchers to note underserved areas. Although not indicative of causation, the relatively strong and significant correlation between transit frequency and distance to highways points to an interesting result: Transit frequency increases closer to the highway, suggesting the opposite of the initial hypothesis. Additionally, transit frequency was strongly correlated with employment density, potentially implying that frequency may not be used to serve people as much as it is used to serve employment zones.

6. Conclusion

Initially, this thesis built upon existing literature on transit frequency and density. We used Vancouver, Canada as a case study for model urban transportation to better understand the historical impact freeways have had on rapidly evolving transit systems. We assessed transit data around SkyTrain stations between 2001 to 2021, and produced a correlation analysis to identify which variables are essential for understanding possible mitigation from freeways. Moreover, we created a combined index using density and transit frequency to evaluate each TOD area around SkyTrain station. The findings from this study illustrate a conflicting relationship between freeways and transit. While population densities increase with distance away from freeways, employment and transit frequency suggest an increase around freeways, despite a long-standing, well-served transit system. There are limitations, including that CDTFIs are sometimes inflated due to changes in CT boundaries. Moreover, future studies should include the CTs before they became SkyTrain stations to increase the sample size and better assess density metrics prior to development. Ultimately, the findings from the paper emphasize the importance of continuing this research in comparative studies across cities. Whereas Vancouver implemented their SkyTrain system in 1986, many North American cities are rushing to implement these technologies to this day, regardless of their existing, large-scale freeway networks. Tools such as the CDTFI will become critical to efficiently evaluate these systems from around the world.

7. References

Babalik-Sutcliffe, E. (2002). Urban rail systems: Analysis of the factors behind success. *Transport Reviews*, *22*(4), 415–447. https://doi.org/10.1080/01441640210124875

Beaudoin, J., & Tyndall, J. (2023). The effect of bus rapid transit on local home prices. *Research in Transportation Economics*, *102*, 101370. https://doi.org/10.1016/j.retrec.2023.101370

Brinkman, J. (2022). *The Costs and Benefits of Fixing Downtown Freeways*.

Brooks, L., & Denoeux, G. (2022). What if you build it and they don't come? How the ghost of transit past haunts transit present. *Regional Science and Urban Economics*, *94*, 103671. https://doi.org/10.1016/j.regsciurbeco.2021.103671

Caro, R. A. (1975). *The power broker: Robert Moses and the fall of New York*. Vintage Books.

Cervero, R., & Gorham, R. (1995). Commuting in Transit Versus Automobile Neighborhoods. *Journal of the American Planning Association*, *61*(2), 210–225. https://doi.org/10.1080/01944369508975634

Chaudhury, H., Mahmood, A., Michael, Y. L., Campo, M., & Hay, K. (2012). The influence of neighborhood residential density, physical and social environments on older adults' physical activity: An exploratory study in two metropolitan areas. *Journal of Aging Studies*, *26*(1), 35–43. https://doi.org/10.1016/j.jaging.2011.07.001

Circella, G., Handy, S., & Boarnet, M. (2014). *Impacts of Employment Density on Passenger Vehicle Use and Greenhouse Gas Emissions Policy Brief* [Policy Brief]. California Environmental Protection Agency.

Ewing, R., & Cervero, R. (2010). Travel and the Built Environment: A Meta-Analysis. *Journal of the American Planning Association*, *76*(3), 265–294. https://doi.org/10.1080/01944361003766766

Filion, P., Bunting, T., Pavlic, D., & Langlois, P. (2010). Intensification and Sprawl: Residential Density Trajectories in Canada's Largest Metropolitan Regions. *Urban Geography*, *31*(4), 541–569. https://doi.org/10.2747/0272-3638.31.4.541

Foth, N. M. (2010). Long-Term Change Around SkyTrain Stations in Vancouver, Canada: A Demographic Shift-Share Analysis. *The Geographical Bulletin*, *51*, 37–52.

Frank, L. D., & Pivo, G. (1994). Impacts of Mixed Use and Density on Utilization of Three Modes of Travel: Single-Occupant Vehicle, Transit, and Walking. *TRANSPORTATION RESEARCH RECORD*.

Greater Vancouver Regional District. (1975). *The Livable Region 1976/1986: Proposals to Manage the Growth of Greater Vancouver*. GVRD.

Greater Vancouver Regional District. (2013). *Regional Growth Strategy Implementation Guideline #4: Identifying Frequent Transit Development Areas*.

Handy, S. (1994). Highway blues: Nothing a little accessibility can't cure. *Access*, *1*(5). https://escholarship.org/uc/item/66k8b8bz

Higgins, C., Ferguson, M., & Kanaroglou, P. (2014). Light Rail and Land Use Change: Rail Transit's Role in Reshaping and Revitalizing Cities. *Journal of Public Transportation*, *17*(2), 93–112. https://doi.org/10.5038/2375-0901.17.2.5

Jiao, J., & Dillivan, M. (2013). Transit Deserts: The Gap between Demand and Supply. *Journal of Public Transportation*, *16*(3), 23–39. https://doi.org/10.5038/2375-0901.16.3.2

Kaeoruean, K., Phithakkitnukoon, S., Demissie, M. G., Kattan, L., & Ratti, C. (2020). Analysis of demand–supply gaps in public transit systems based on census and GTFS data: A case study of Calgary, Canada. *Public Transport*, *12*(3), 483–516. https://doi.org/10.1007/s12469-020-00252-y

Kang, C. D. (2010). The Impact of Bus Rapid Transit on Location Choice of Creative Industries and Employment Density in Seoul, Korea. *International Journal of Urban Sciences*, *14*(2), 123–151. https://doi.org/10.1080/12265934.2010.9693672

Kapatsila, B., Rea, J. D., & Grisé, E. (2024). If you build it, who will come? Exploring the effects of rapid transit on residential movements in Metro Vancouver. *Journal of Transport and Land Use*, *17*(1), 163–185. https://doi.org/10.5198/jtlu.2024.2364

Lai, Y., Zhou, J., & Xu, X. (2024). Spatial Relationships between Population, Employment Density, and Urban Metro Stations: A Case Study of Tianjin City, China. *Journal of Urban Planning and Development*, *150*(1), 05023048. https://doi.org/10.1061/JUPDDM.UPENG-4416

Mamun, S. A., Lownes, N. E., Osleeb, J. P., & Bertolaccini, K. (2013). A method to define public transit opportunity space. *Journal of Transport Geography*, *28*, 144–154. https://doi.org/10.1016/j.jtrangeo.2012.12.007

Martino, N., Girling, C., & Lu, Y. (2021). Urban form and livability: Socioeconomic and built environment indicators. *Buildings and Cities*, *2*(1), 220–243. https://doi.org/10.5334/bc.82

Mattson, J. (2020). Relationships between density, transit, and household expenditures in small urban areas. *Transportation Research Interdisciplinary Perspectives*, *8*, 100260. https://doi.org/10.1016/j.trip.2020.100260

Schimek, P. (1997). Understanding Differences in Public Transit: Comparison of Boston and Toronto. *Transportation Research Record: Journal of the Transportation Research Board*, *1604*(1), 9–17. https://doi.org/10.3141/1604-02

Statistics Canada. (2022, February 9). *Illustrated Glossary—Census tract (CT)*. https://www150.statcan.gc.ca/n1/pub/92-195-x/2021001/geo/ct-sr/ct-sr-eng.htm

Taylor, B. D., & Fink, C. N. Y. (2013). Explaining transit ridership: What has the evidence shown? *Transportation Letters*, *5*(1), 15–26. https://doi.org/10.1179/1942786712Z.0000000003

Townsend, C., & Ellis-Young, M. (2018). Urban population density and freeways in North America: A Re-assessment. *Journal of Transport Geography*, *73*, 75–83. https://doi.org/10.1016/j.jtrangeo.2018.10.008

University of Toronto. (2025). *CHASS Data Centre*. http://datacentre.chass.utoronto.ca.lib-ezproxy.concordia.ca/

Verbich, D., Badami, M. G., & El-Geneidy, A. M. (2017). Bang for the buck: Toward a rapid assessment of urban public transit from multiple perspectives in North America. *Transport Policy*, *55*, 51–61. https://doi.org/10.1016/j.tranpol.2016.12.002

Walker, L., Garnett, L.-A., Kan, R., & Klitz, P. (2009, July). *Integrating Frequent Transit Service & Corridor-based Transit Supportive Environments in the Metro Vancouver Region*. Annual Conference of the Transportation Association of Canada, Vancouver, British Columbia. https://www.tac-atc.ca/wp-content/uploads/Walker.pdf

Yang, W., Tian, G., & Ewing, R. (2023). Impact of corridor highway system on communities: Built environment and travel mode choices. *Cities*, *141*, 104467. https://doi.org/10.1016/j.cities.2023.104467

8. Appendices

Appendix A: Tabular Results

Table 1: All Variables, DSR, and Standardized DSR (2001)

Name	Weekly Transit Frequency	Population Density	Employment Density	Distance to Highway	Distance to Urban Centre	Density to Service Ratio (DSR)	Standardized DSR
22nd Street	7632	3055	342	0.21	2.91	0.44	-1.29
29th Avenue	6489	6622	524	2.53	3.31	1.10	-0.21
Broadway	8694	7934	1468	3.13	3.47	1.08	-0.24
Burrard	29188	13286	38324	5.90	1.36	1.77	0.90
Columbia	7812	5929	8279	3.20	0.26	1.82	0.98
Edmonds	6401	3793	1587	1.69	3.75	0.84	-0.64
Gateway	4745	3028	1357	3.68	1.01	0.92	-0.50
Granville	31547	6421	27583	6.18	1.04	1.08	-0.25
Joyce	7970	8846	2607	2.37	2.09	1.44	0.35
King George	3234	3618	2238	4.98	0.90	1.81	0.97
Main Street	14730	3604	3497	5.27	0.91	0.48	-1.23
Metrotown	10783	12809	6213	3.30	0.39	1.76	0.89
Nanaimo	5700	5490	732	2.94	4.15	1.09	-0.22
New Westminster	9517	5402	6234	2.68	0.33	1.22	-0.01
Patterson	7504	14037	3280	3.14	0.40	2.31	1.79
Royal Oak	4401	4767	1766	3.03	1.68	1.48	0.43

Scott Road	5851	411	389	3.37	2.57	0.14	-1.80
Stadium - Chinatown	26464	6421	15905	5.73	0.65	0.84	-0.63
Surrey Central	10052	3421	2515	4.59	0.29	0.59	-1.05
Waterfront	27514	6421	56822	5.87	1.33	2.30	1.78

Table 2: All Variables, DSR, and Standardized DSR (2011)

Name	**Weekly Transit Frequency**	**Population Density**	**Employment Density**	**Distance to Highway**	**Distance to Urban Centre**	**Density to Service Ratio (DSR)**	**Standardized DSR**
22nd Street	10399	3322	367	0.21	2.91	0.35	-1.48
29th Avenue	8291	7086	496	2.53	3.31	0.91	-0.76
Aberdeen	3789	2325	4376	1.59	1.54	1.77	0.36
Braid	6331	3065	1313	0.35	3.84	0.69	-1.05
Brentwood Town Centre	6541	3857	4051	0.99	4.39	1.21	-0.37
Bridgeport	8111	1382	4645	0.71	2.93	0.74	-0.98
Broadway	10390	7135	1709	3.13	3.47	0.85	-0.84
Broadway-City Hall	11916	7510	16718	6.38	1.25	2.03	0.70
Burrard	30990	17611	51622	5.90	1.36	2.23	0.96
Columbia	6560	7608	8578	3.20	0.26	2.47	1.26
Commercial	7578	7135	1913	3.06	3.47	1.19	-0.39
Edmonds	8148	6492	2461	1.69	3.75	1.10	-0.52
Gateway	4088	5027	1864	3.68	1.01	1.69	0.25
Gilmore	3984	3396	4028	0.87	4.21	1.86	0.48
Granville	30933	11133	46320	6.18	1.04	1.86	0.47
Holdom	3584	3246	1082	1.78	4.60	1.21	-0.37
Joyce	8314	18929	2770	2.37	2.09	2.61	1.45

King Edward	5630	5220	2447	6.39	2.77	1.36	-0.17
King George	3943	4511	2931	4.98	0.90	1.89	0.51
Lake City	3345	2270	1494	2.41	5.91	1.13	-0.48
Landsdowne	4660	5796	5834	2.32	0.52	2.50	1.30
Langara-49th	4520	4569	1288	3.79	5.37	1.30	-0.26
Lougheed Town Centre	5833	8141	3086	2.05	5.09	1.92	0.56
Main Street	10391	6613	4940	5.27	0.91	1.11	-0.50
Marine Drive	7352	4397	2030	1.99	4.62	0.87	-0.81
Metrotown	12739	11515	7005	3.30	0.39	1.45	-0.05
Nanaimo	7018	6010	642	2.94	4.15	0.95	-0.71
New Westminster	8326	8693	5095	2.68	0.33	1.66	0.21
Oakridge-41st	4980	3640	1367	4.61	4.55	1.01	-0.64
Olympic Village	10868	6855	12101	6.39	0.84	1.74	0.32
Patterson	10300	15466	3701	3.14	0.40	1.86	0.48
Production Way-University	5002	1326	1494	3.57	5.60	0.56	-1.21
Renfrew	7715	4555	2295	1.74	4.42	0.89	-0.79
Richmond-Brighouse	6362	16007	11822	2.94	0.21	4.37	3.75
Royal Oak	4834	5263	1626	3.03	1.68	1.43	-0.09
Rupert	7510	4403	2095	1.04	4.13	0.87	-0.82
Sapperton	2877	2559	1646	1.39	2.74	1.46	-0.04
Scott Road	5910	436	468	3.37	2.57	0.15	-1.75
Sperling	4148	2791	857	1.74	4.82	0.88	-0.80
Stadium-Chinatown	24843	12517	22950	5.73	0.65	1.43	-0.09
Surrey Central	9422	4532	3904	4.59	0.29	0.90	-0.78

Vancouver City Centre	25751	16751	46320	6.25	1.00	2.45	1.24
VCC	7529	7585	3172	3.76	2.64	1.43	-0.09
Waterfront	30845	11872	44800	5.87	1.33	1.84	0.45
Yaletown-Roundhouse	12625	23350	15811	6.73	0.65	3.10	2.09

Table 3: All Variables, DSR, and Standardized DSR (2021)

Name	Weekly Transit Frequency	Population Density	Employment Density	Distance to Highway	Distance to Urban Centre	Density to Service Ratio (DSR)	Standardized DSR
22nd Street	11212	3329	630	0.21	2.91	0.35	-1.59
29th Avenue	8130	7236	1113	2.53	3.31	1.03	-0.62
Aberdeen	3843	4491	4011	1.59	1.54	2.21	1.09
Braid	6467	3343	2261	0.35	3.84	0.87	-0.85
Brentwood Town Centre	7311	8417	4867	0.99	4.39	1.82	0.52
Bridgeport	7799	2939	3853	0.71	2.93	0.87	-0.85
Broadway	8486	7297	2916	3.13	3.47	1.20	-0.37
Broadway-City Hall	9563	8498	14803	6.38	1.25	2.44	1.42
Burquitlam	5549	5262	1448	3.08	6.57	1.21	-0.36
Burrard	27669	21069	28882	5.90	1.36	1.81	0.50
Columbia	8655	10973	5122	3.20	0.26	1.86	0.58
Commercial	6475	7297	2916	3.06	3.47	1.58	0.17
Coquitlam Central	13280	5898	3188	5.44	0.72	0.68	-1.12
Edmonds	10821	7087	1936	1.69	3.75	0.83	-0.90
Gateway	5022	5920	1645	3.68	1.01	1.51	0.07
Gilmore	4170	5441	4576	0.87	4.21	2.40	1.37
Granville	29147	18529	22152	6.18	1.04	1.40	-0.09
Holdom	4527	3033	1159	1.78	4.60	0.93	-0.77

Inlet Centre	5609	7823	3924	5.35	2.29	2.09	0.92
Joyce	9965	23042	6010	2.37	2.09	2.92	2.11
King Edward	6039	5781	3400	6.39	2.77	1.52	0.09
King George	6764	7924	3262	4.98	0.90	1.65	0.28
Lafarge-Lake Douglas College	4565	7091	4010	5.64	0.65	2.43	1.41
Lake City	3830	1432	1214	2.41	5.91	0.69	-1.11
Landsdowne	6575	8142	4985	2.32	0.52	2.00	0.78
Langara-49th	5592	4798	1129	3.79	5.37	1.06	-0.57
Lincoln	11746	8349	5400	5.39	0.21	1.17	-0.41
Lougheed Town Centre	7613	8220	3079	2.05	5.09	1.48	0.04
Main Street	11931	11014	6580	5.27	0.91	1.47	0.03
Marine Drive	8712	5151	2591	1.99	4.62	0.89	-0.82
Metrotown	14807	15798	6546	3.30	0.39	1.51	0.08
Moody Centre	6398	2382	1513	5.38	3.55	0.61	-1.23
Nanaimo	7752	6195	1252	2.94	4.15	0.96	-0.72
New Westminster	10046	10879	5820	2.68	0.33	1.66	0.30
Oakridge-41st	7010	4086	1235	4.61	4.55	0.76	-1.01
Olympic Village	10710	11611	11921	6.39	0.84	2.20	1.07
Patterson	11748	13482	3484	3.14	0.40	1.44	-0.02
Production Way-University	5658	1432	1434	3.57	5.60	0.51	-1.37
Renfrew	5345	4590	1906	1.74	4.42	1.22	-0.35
Richmond-Brighouse	8909	11962	9796	2.94	0.21	2.44	1.42
Royal Oak	6596	6886	2296	3.03	1.68	1.39	-0.09
Rupert	4378	4608	1792	1.04	4.13	1.46	0.01

Sapperton	3183	3119	3468	1.39	2.74	2.07	0.89
Scott Road	7065	510	561	3.37	2.57	0.15	-1.89
Sperling	4577	3609	1143	1.74	4.82	1.04	-0.60
Stadium-Chinatown	27916	18046	14070	5.73	0.65	1.15	-0.44
Surrey Central	13783	6243	2915	4.59	0.29	0.66	-1.14
Vancouver City Centre	26850	22209	27522	6.25	1.00	1.85	0.57
VCC	7934	8312	4066	3.76	2.64	1.56	0.15
Waterfront	22484	13129	20113	5.87	1.33	1.48	0.03
Yaletown-Roundhouse	13270	31213	19265	6.73	0.65	3.80	3.39

Appendix B: Combined Density-Transit Frequency Index Results

Table 4: CDTFI (Z-Score Differences) for 2001-2011

Station Name	**Z-Score Differences 2001-2011**
22nd Street	-0.19
29th Avenue	-0.55
Broadway	-0.60
Burrard	0.06
Columbia	0.28
Edmonds	0.12
Gateway	0.75
Granville	0.72
Joyce-Collingwood	1.10
King George	-0.46
Main Street	0.73
Metrotown	-0.94
Nanaimo	-0.49
New Westminster	0.22
Patterson	-1.32
Royal Oak	-0.52
Scott Road	0.06
Stadium-Chinatown	0.55
Surrey Central	0.27
Waterfront	-1.33

Table 5: CDTFI (Z-Score Differences) for 2011-2021

Station Name	Z-Score Differences 2011-2021
22nd Street	-0.11
29th Avenue	0.13
Aberdeen	0.74
Braid	0.19
Brentwood Town Centre	0.89
Bridgeport	0.13
Broadway	0.47
Broadway-City Hall	0.72
Burrard	-0.46
Columbia	-0.68
Commercial	0.57
Edmonds	-0.38
Gateway	-0.18
Gilmore	0.89
Granville	-0.56
Holdom	-0.39
Joyce-Collingwood	0.66
King Edward	0.27
King George	-0.23
Lake City Way	-0.63
Landsdowne	-0.52
Langara-49th	-0.31
Lougheed Town Centre	-0.52
Main Street	0.52
Marine Drive	-0.01
Metrotown	0.13
Nanaimo	0.00
New Westminster	0.09
Oakridge-41st	-0.37
Olympic Village	0.75
Patterson	-0.49
Production Way-University	-0.16
Renfrew	0.44

Richmond-Brighouse	-2.32
Royal Oak	0.00
Rupert	0.83
Sapperton	0.93
Scott Road	-0.14
Sperling	0.20
Stadium-Chinatown	-0.35
Surrey Central	-0.36
Vancouver City Centre	-0.67
VCC	0.24
Waterfront	-0.41
Yaletown-Roundhouse	1.30

Table 6: CDTFI (Z-Score Differences) for 2001-2021

Station Name	**Z-Score Differences 2001-2021**
22nd Street	-0.3005
29th Avenue	-0.41394
Broadway	-0.12592
Burrard	-0.39394
Columbia	-0.39918
Edmonds	-0.2609
Gateway	0.572263
Granville	0.157689
Joyce-Collingwood	1.758569
King George	-0.68344
Main Street	1.258725
Metrotown	-0.81528
Nanaimo	-0.49359
New Westminster	0.303122
Patterson	-1.80928
Royal Oak	-0.52076
Scott Road	-0.08102
Stadium-Chinatown	0.191277
Surrey Central	-0.09168
Waterfront	-1.74474