The value of dedicated right of way (ROW) to transit ridership and carbon emissions

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Table of Contents

List of figures

List of Tables

Executive summary

Transit systems are instrumental in reducing vehicle miles travelled and greenhouse gas (GHG) emissions. The transitway program in the Twin Cities, initially focused on dedicated right of way (ROW), has seen newer forms such as mixed traffic and managed lanes emerge. Understanding the impact of different ROWs on ridership and emissions is critical for future planning.

This research project examined the influence of dedicated ROW on transit ridership and GHG emissions reduction. With data from 78 US rail transit and BRT routes, we applied the gradient boosting decision tree method to assess the impact of four ROW types and other factors on ridership and GHG emissions.

Transit routes with less traffic interference attract substantially more passengers. An upgrade from mixed traffic to semi-exclusive ROW could see a yearly ridership increase of 70,000, while moving from semi-exclusive to exclusive could add 3.68 million passengers annually. Apart from ROW, number of stops, commence year of the route, population density, signal priority, and several other factors significantly influence ridership. Upgrading ROW has substantial GHG emission reduction benefits, especially with increased usage of electric BRT vehicles.

Improving ROWs can notably enhance transit route performance in terms of ridership and GHG reductions. Strategies like dedicated transit lanes, smart traffic management systems, and enhancing service frequency can boost the efficacy of transit routes. It's also pivotal to focus on areas with sufficient population and network density. Implementing a larger share of electric bus vehicles can further amplify emission reductions.

While increasing ridership and reducing carbon emissions through enhanced ROWs is beneficial, a comprehensive cost-benefit analysis involving all stakeholders is vital before allocating a dedicated ROW to any transit route.

1 Introduction

Transit systems play an important role in reducing vehicle miles travelled (VMT) and associated greenhouse gas (GHG) emissions as well as helping Minnesotans create a sustainable transportation system. The transitway program, envisioned by state, regional, and local stakeholders and deployed in the Twin Cities, used to adopt dedicated right of way (ROW) to enhance travel time savings and reliability. Recently, other types of ROWs (e.g., mixed traffic and managed lanes) have emerged and become popular in practice, including the A Line and Orange Line in the Twin Cities. However, there is little evidence on how different types of ROWs contribute to transit ridership and GHG emissions. Filling this gap will provide concrete evidence for planners and policymakers to quantify carbon emissions associated with different types of ROWs and decide how to make transitway investment.

This research project aims to examine the value of dedicated ROW in increasing transit ridership and reducing GHG emissions. We include four types of ROWs, which are mixed traffic, semi-exclusive ROW, exclusive ROW, and grade separation. We regard exclusive ROW and grade separation as dedicated ROW. Applying the gradient boosting decision tree method to the data collected from local transit agencies in the US, we evaluate the impact of different types of ROWs along with other factors on ridership of rail transit and BRT routes. In addition, we predict the ridership of transit routes with different types of ROWs and estimate the reduction in GHG emissions associated with enhanced ROW in various scenarios that involve different proportions of electric bus rapid transit (BRT) vehicles.

This research project has four contributions. First, we apply the data collected from the local transit agencies nationwide in the US. To our knowledge, this is the first research project that uses real-world data to specifically examine the influence of ROW on transit performance. Second, our results not only confirm the importance of ROW to transit routes but also estimate the ridership increase associated with the enhanced ROW. The results could help decision making when planning transit routes with different types of ROWs. Third, besides ROW, we find that other factors such as the number of stops, population density, and signal priority are important to transit ridership. The nonlinear relationships also reveal the ridership change related to these factors. These results could offer additional insights into how different factors affect transit ridership. Finally, we estimate the GHG emission reduction related to upgrading ROW in scenarios with different share of electric BRT vehicles.

The rest of this report is organized as follows. We review different types of ROWs and the benefits of dedicated ROW in Chapter 2. We introduce our data and method in Chapter 3. We present and discuss the results in Chapter 4. In Chapter 5, we conclude this research project and provide policy implications.

2 Literature review

2.1 Transit Operating Environments

Transit Capacity and Quality of Service Manual, 3rd Edition, defines four types of operating environments (TCRP 2013):

Mixed traffic: Transit vehicles use the same road facilities as other vehicles. They are subject to the same delays that other vehicles face, such as traffic volumes, turning vehicles, stopped and parked vehicles, interactions with pedestrians and bicyclists, and traffic controls. In North America, more than 98% of directional route miles are in the mixed-traffic environment.

Semi-exclusive ROW: A semi-exclusive facility may be dedicated to transit use for certain times of a day, such as during peak hours. It may also allow certain traffic (e.g., right-turning vehicles, pedestrians, and bicyclists) to use the facility. An example in the Twin Cities is the time-limited bus lane on Hennepin Ave. It is dedicated to shuttle buses and service vehicles of the University of Minnesota. High occupancy vehicle (HOV) or high occupancy toll (HOT) lanes used by buses can also be considered as semi-exclusive facilities.

Exclusive ROW: An exclusive facility is fully dedicated to transit use, but it allows at-grade crossings. Exclusive ROW eliminates the delays due to many external factors such as right turning vehicles and pedestrian crossing. However, it is subject to delays of traffic controls at intersections. Examples in the Twin Cities include the bus lanes on the Marquette and Second Avenues in downtown Minneapolis and light rail transit.

Grade separation: A grade separate facility has exclusive ROW and it does not allow at-grade crossings. All other traffic needs to cross under or over the facility. Therefore, transit operation on this type of facility receives the least interferences. Subway, Metro, and Elevated Lines are examples of grade-separated facilities. Portions of the Blue Line light rail in Minneapolis and at the MSP International Airport operate with grade separation.

Moreover, to offer buses preferential treatments, transportation planners have developed an innovative use of highways for transit vehicles: bus only shoulders. With certain restrictions, buses can use highway shoulders to bypass the traffic when general purpose lanes are congested. In the Twin Cities, there are more than 300 miles of bus only shoulders [1].

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[1] https://www.metrotransit.org/transit-advantages, accessed on October 7, 2022.

2.2 Benefits of Dedicated ROW

The facility with dedicated ROW offers many benefits to transit riders, transit agencies, residents, and businesses around the facility. It mainly enhances operating speed, service reliability, and facility capacity. It also improves the visibility of the upgraded facility and may stimulate economic activities and land development along the facility (Deng and Nelson 2011; Higgins, Ferguson, and Kanaroglou 2014).

2.2.1 Speed and travel time savings

Travel time is a key determinant of individuals' mode choice. A shorter travel time will attract additional passengers, increasing fare box revenue. Furthermore, it may reduce the number of transit vehicles and hence drivers needed to keep the same level of service, lowering both capital and operating costs of transit agencies.

Dedicated ROW can reduce running time loss due to traffic blockage and improve average operating speed. For example, in the central business district (CBD) area with typical traffic signals, bus lanes allowing right turning traffic (a semi-exclusive operating environment) have a shorter running time of 1 minute per mile than the mixed-traffic environment; bus lanes without right turning traffic (an exclusive operating environment) have an additional running time saving of 0.8 minutes per mile; grade separation can save 3 minutes per mile (TCRP 2013). In the areas outside the CBD, grade separation could save up to 1 minute per mile, compared to mixed traffic (TCRP 2013).

The facility with dedicated ROW is often associated with longer stop spacing (i.e., the distance between two consecutive stops), which may increase and decrease speed[2] simultaneously. However, its net outcome is often an improvement in the average speed (TCRP 2013). In particular, longer stop spacing reduces fixed delays (such as time required for acceleration/deceleration and door opening/closing) and hence increases speed. On the other hand, because longer stop spacing enlarges the catchment area of a stop, it increases the demand at the stop, which in turn leads to longer dwell time and hence reduces speed.

Other features accompanying dedicated ROW can also improve speed. Transit signal priority or grade separation can reduce or eliminate delays at the intersection. If buses can make full use of adjacent lanes at stops or online stops are adopted, buses will have shorter clearance time and hence higher average operating speed. Strategies that reduce dwell time at stops (such as level boarding, multi-door boarding/alighting, and proof of payment fare method) can reduce trip time and improve speed.

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[2] Longer stop spacing will increase the number of passengers per stop and hence increase dwell time and reduce the operating speed.

Moreover, high frequency services have the potential to reduce dwell time by reducing the number of passengers per transit vehicle.

2.2.2 Reliability

Together with speed and safety, service reliability is one of the most important attributes that affects transit quality of service (van Oort 2021). From the perspective of passengers, reliability means whether they can arrive at destinations on time (on time performance) and how long they need to wait for the next transit vehicle (related to regularity of headway). Unreliable transit service may lead to late arrivals for employment and appointments, jeopardizing passengers' well-being. They may have to plan extra time for on-time arrivals. Furthermore, unreliable service will increase average wait time. First, it makes passengers unable to plan for their wait time. Second, it may make timed transfers unachievable, further increasing wait time. Even worse, wait time is often perceived longer than in-vehicle travel time. It is evident that the perceived wait time ranges from 0.8 to 5.1 times of in-vehicle travel time, with an average of 2.1 times (TCRP 2013). Therefore, each additional minute of wait time tends to have a larger impact on passenger satisfaction than each minute of in-vehicle travel time.

Transit agencies anticipate some variability in cycle time (the time required to make a round trip). When preparing transit scheduling, they usually designate recovery time (e.g., 10% of the cycle time) to ensure on-time departure of the next trip. However, when delays exceed the designated recovery time, transit operators may have to dispatch extraboard personnel and additional vehicles to maintain a reliable service, increasing both capital and operating costs of transit agencies.

Dedicated ROW helps improve reliability (TCRP 2013). First, the facility with dedicated ROW is not vulnerable to the variability of traffic volume and traffic congestion that prevail in the mixed traffic environment. Second, it eliminates the delays caused by other traffic such as right turning vehicles, stopped/parked vehicles, and other unauthorized use of the facility. Grade separation further eliminates the interactions with other travel modes at the at-grade crossing. Third, other features accompanying dedicated ROW may also reduce the variation in travel time. For example, level boarding enables wheelchair users to board/alight transit vehicles independently, eliminating the needs for lift/ramp use and reducing dwell-time variability. Wheelchair lift/ramp is an important instrument to ensure equitable access to transit. However, it is sometimes complained about by inpatient passengers. Transit signal priority minimizes the delays due to traffic control and can also enhance service reliability.

2.2.3 Capacity

Dedicated ROW can improve the capacity of a transit facility. The fewer interactions with other traffic, the higher the capacity. In general, many factors that affect speed and reliability of transit service also influence facility capacity (TCRP 2013). For example, transit vehicles on a dedicated ROW will not be interfered by the general traffic and right turning vehicles, so the vehicle capacity of a facility does not need to be adjusted by the traffic blockage. Online stops with passing lanes or dedicated ROW with offline stops reduce clearance time (including re-entry time), increasing loading area capacity and hence facility capacity.

Although capacity is not a problem for most facilities, it may be a constraint on those in downtown areas or where routes merge. Insufficient capacity can lead to stop failure: when a vehicle arrives at a stop, other vehicles are occupying the loading areas. This will adversely affect speed and reliability of transit service. Therefore, dedicated ROW can be a solution to address the issue of vehicle capacity.

2.2.4 Visibility

Dedicated ROW means that a road segment or a corridor is reserved for transit use. The facility with dedicated ROW and the vehicles operating on the facility are visible to all road users. Awareness may stimulate the interest of riding the transit. By contrast, private vehicle users may not perceive an arterial BRT operating in the mixed traffic environment differently from regular buses, although the BRT has designed (such as proof-of-payment fare method and multi-door boarding and alighting) or branded (such as using the same color as light rail vehicles) differently (Benson and Cao 2020).

2.2.5 Economic development

Developers and individuals value the sense of permanency associated with dedicated ROW, particularly rail tracks (Dittmar and Ohland 2004). Transit infrastructure enhances accessibility. The sense of permanency reduces individuals' and firms' concerns about investment risk (Currie 2006). Therefore, dedicated ROW helps improve the values of properties around station areas, stimulating further investment. By contrast, regular buses are flexible. Transit agencies may adjust their routes based on the changing passenger demand. Because accessibility improvement of transit infrastructure is often at the immediate proximity of stop areas, the adjustment is likely to redistribute accessibility by transit substantially and increase the risk of investing in transit-oriented development.

The literature shows that permanency could be a reason to explain the different premiums associated with light rail transit (LRT) and arterial BRT lines. For example, the commencement of the Green Line LRT in the Twin Cities increased the values of housing around LRT station areas (Cao and Lou 2018), but the A-Line BRT had no effects on housing values (Benson and Cao 2020). The A-Line BRT operates in the mixed traffic environment. The main goals of the BRT line are to improve operating speed and promote bus ridership.

2.3 Drawbacks of Dedicated ROW

The facilities with dedicated ROW are associated with high capital costs, particularly elevated facilities and underground ones. If the facility is at grade, it may take road spaces used for other traffic. On-street parking spaces are often reduced to accommodate the facilities (e.g., the Green Line LRT in the Twin Cities). Business and residents worry about the loss of parking spaces and may push back against the development of dedicated ROW. Sometimes, trees and other vegetation (e.g., Zhongshan Avenue BRT in Guangzhou, China) may have to be removed to make room for the facilities.

Auto drivers may have a negative perception of dedicated ROW. The main goal of transit facilities is to move people instead of moving vehicles. With the same person throughput, there will be many fewer transit vehicles on the facilities than private vehicles. This will give auto drivers an impression that the facilities are underused. When general purpose lanes are congested and there are only a few transit vehicles on the facilities with dedicated ROW, auto drivers may challenge the legal basis and feasibility of the facilities. For example, transit agencies in Dehli, India, lost the legal battle and had to open the dedicated ROW to other vehicles [3].

2.4 Dedicated ROW and Ridership

In-vehicle travel time elasticities of ridership range from -0.3 to -0.5 (TCRP 2007). The default elasticity is -0.4. In other words, if travel time reduces by 10%, ridership will increase by 4%. If commuting trips are affected by dedicated exclusive bus lanes, the travel time elasticity ranges from -0.5 and -0.7 (TCRP 2007).

Few studies have explored passengers' response to changes in service reliability. Anecdotal evidence suggests that unreliable service reduces ridership because of additional wait time and associated uncertainty, anxiety, and annoyance (TCRP 2013). Using automatic vehicle location and automated passenger counter data of several radial and cross-town bus routes in Portland, Oregon, Kimpel, Strathman, and Dueker (2000) modeled the impacts of service reliability on passenger demand. They found that headway delay variability (the difference between the actual and scheduled headway) and departure delay variability since the previous time point have significantly negative associations with passenger demand. The size of the associations varies among route types, operation periods, and reliability measures. They showed that "a 10% reduction in headway delay variation at the previous timepoint on radial routes in the a.m. peak leads to an increase in 0.17 passengers per trip per time point" (p. 24). However, the relationship between service reliability and ridership can be complex because of the influences of confounding factors. We could also use travel time elasticity to estimate wait time

[3] https://systemicfailure.wordpress.com/2012/07/13/delhi-car-owners-prevail-in-lawsuit-against-brt/, accessed on October 7, 2022.

elasticity. Because wait time is on average 2.1 times as valuable as travel time (TCRP 2013) and travel time elasticity is -0.4, wait time elasticity can be estimated at about -0.8.

The literature also has some evidence on the bundled effects of transit advantage features on ridership. Berrebi et al. (2022) showed that the A-Line BRT and the Green Line light rail in the Twin Cities generated 12% and 86%, respectively, more ridership than the local bus routes they replaced. By summarizing Bus Rapid Transit Practitioners' Guide (TCRP 2007), TCRP (2013) concluded that "Studies of corridor ridership before and after the implementation of BRT service have found up to a 25% increase in ridership in the corridor beyond what would be expected simply from frequency and travel time improvements. It is hypothesized that other elements of BRT - exclusive running ways, branding, enhanced stops and stations, etc. contribute to a "premium service" image that is attractive to passengers." (p. 4-39). The ridership increase represents new trips resulting from the BRT application. Among BRT elements, grade-separated ROW could contribute to up to 20% of the 25% increment (TCRP 2007) (Table 1). That is, it could account for a 5% increase in the ridership in the corridor. Moreover, at-grade busways, median arterial busways, and all-day bus lanes (specially delineated) could contribute to 15%, 10%, and 5%, respectively (Table 1). The Guide also estimated that stations, vehicles, service patterns, ITS applications, and branding could contribute to up to 15%, 15%, 15%, 10%, and 10% of the 25% increment, respectively (Table 1). Furthermore, the synergy of BRT elements could contribute to another 15% if the subtotal of the elements is more than 60% (TCRP 2007).

Table 1. Percentage of improvement among the 25% increment by BRT elements

BRT elements	Percentage of the 25% increment
Grade-separated ROW	20%
At-grade busways	15%
Median arterial busways	10%
All-day bus lanes	5%
Stations	15%
Vehicles	15%
Service patterns	15%
ITS applications	10%
Branding	10%

Furthermore, rail transit services can have a modal bias of up to 12 minutes of in-vehicle travel time beyond what would be expected simply from improvements in travel time, service frequency, and cost (TCRP 2007). That is, in mode choice models, travel time of rail transit services could be reduced by 12 minutes. A critical feature of rail transit services is dedicated ROW, although streetcars and some LRT lines have semi-exclusive ROW. The Guide recommended a modal bias of 10 minutes for full-featured BRT (TCRP 2007).

3 Data and methods

In this section, we introduce the data and methods that are used to identify influencing factors of transit ridership and estimate the reduction in greenhouse gas emissions associated with upgrading the operating environment of transit routes in the Twin Cities area.

3.1 Data

As shown in Table 2, we assembled six types of variables related to transit routes, including general information, route characteristics, service attributes, built environment characteristics, socio-demographics, and regional characteristics.

We collected the first three types of variables according to the answers of local transit agencies to our online questionnaires and interviews. General information includes the name of a transit route, its operating agency, yearly ridership in a year before 2020, and the corresponding year of the ridership. Route characteristics include the variables describing physical features, locations, and facilities of the transit route. Service attributes contain operation characteristics of the transit route. The procedure of collecting these data includes three steps. First, we identified around 100 rail transit routes (light rail and streetcar) and 130 bus rapid transit (BRT or bus transit sharing same features with BRT) routes in the US. These routes are operated by more than 70 transit agencies. Second, we emailed the transit agencies to request them to fill in a questionnaire, which includes questions related to the general information, route characteristics, and service attributes of transit routes (see Appendix). Third, after transit agencies confirmed their willingness to take part in the survey, we emailed them the link to the online questionnaire. We also provided the option of virtual interviews. We asked transit agencies to complete the questionnaire by August 31st, 2022. Most of the transit agencies chose to complete the questionnaire online, while three provided their answers through virtual interviews. We obtained the information on 58 BRT routes and 20 rail transit routes from 31 transit agencies (Figure 1). These routes account for approximately 30% of the BRT and rail transit routes in the US.

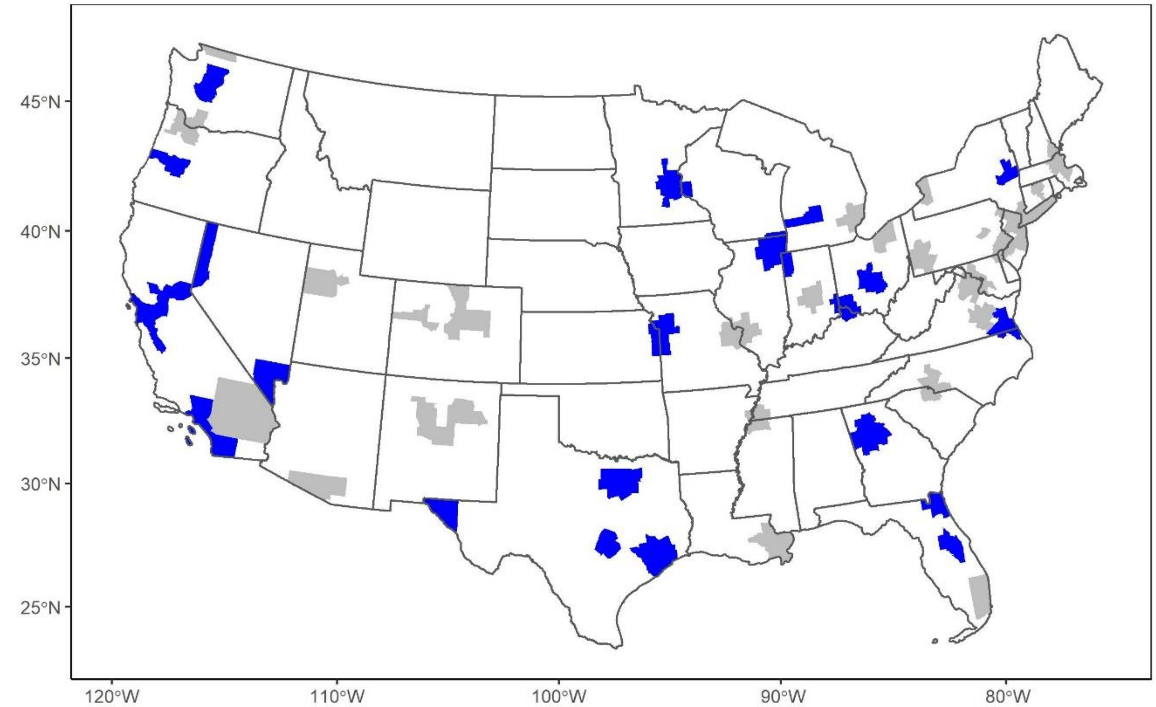

Figure 1. CBSAs (Core-based Statistical Areas) where the transit routes in the data are located, highlighted in bule (transit agencies in the CBSAs highlighted in grey were non-responsive.)

We computed built environment characteristics, socio-demographics, and regional characteristics using third-party data sources, based on the locations of the transit routes. Built environment characteristics and socio-demographics were calculated using the information within half-mile buffers along the transit route. That is, the variables were measured at the route level. Regional characteristics include several variables measured at the regional level (e.g., state, core-based statistical area, and urbanized area where the data are available) that might influence the ridership. Table 2 lists the data sources of these variables. We selected the sources because they contained the variables we need in this project.

Table 2. Variable description and data source

Variable	Definition	Data source
Transit route	The name of the transit route	This study
Transit agency	The operating agency	This study
Ridership	Yearly total ridership of the route (before 2020)	Local transit agency
Ridership year	Year when the ridership was measured	
Route characteristics		
Transit type	The type of the transit route, including rail transit (LRT and streetcar) and BRT (BRT or bus transit with some BRT features)	Local transit agency
Route length	Length of the route in miles	
Number of stops	(Average) number of stops in one direction	
Number of park and ride	Number of park-and-ride facilities	
Shared micro-mobility	Whether there are bike sharing and/or e-scooter systems in the CBSA (Core based Statistical Area) where the route is located	
Integration with other transitways	Whether the route is connected with other transitways	
Downtown	Whether the route is connected to a downtown	
Airport	Whether the route is connected to an airport	
Enhanced stations	Whether stops are enhanced to be distinct from those of traditional transit routes	
Enhanced vehicles	Whether vehicles are enhanced to be distinct from those of traditional transit routes	
Brand identity	Whether the route is branded differently from traditional transit routes	
Center lane	Whether the lane is in center lanes or medians (vs. curbside)	
Physical separation	Whether the lane is physically separated from other lanes (vs. painted lines)	
Freeway managed lane	Whether the route is operated on a managed lane (for HOV, HOT, Buses, Trucks, etc.)	
Shoulder lane	Whether the route is operated on a shoulder lane	
Ramp queue jump	Whether highway ramp queue jumps are provided for the route	
Service attributes		
Commence year	Year when the route started operation	Local transit agency
Fare	Fare before any discount for the general public during peak hours	
Headway	The shortest headway during peak hours	
Operating speed	Operating (commercial) speed during peak hours	
Operating environments	The operating environment of the route, including mixed traffic, semi-exclusive, exclusive, grade separation • Mixed traffic: other traffic modes are allowed to share the lane with the route during all time • Semi-exclusive: certain traffic modes are allowed at certain locations and/or during certain time, e.g., vehicles on freeway managed lanes, cyclists and pedestrians on transitway, turning vehicles, parking lanes during non-peak hours • Exclusive: other traffic modes are allowed only at grade crossing • Grade separation: transit routes are operated underground or on elevated lanes and other traffic modes are completely excluded	
Off-board fare collection	Whether tickets are purchased before boarding	
Level boarding	Whether the platform enables level boarding	
Signal priority	Whether there is transit signal priority	

Variable	Definition	Data source
Intersection treatment	Whether there are preferential treatments at intersections such as turning prohibition and queue jump	
Information system	Whether there are high-quality information systems (smartphone application, traveler information, etc.) for the route	
Multi-door	Whether multi-door boarding and alighting are allowed	
Built environment characteristics (weighted by the size of the CBGs within the half-mile buffer along the route)		
Population density	Gross population density (people/acre) on unprotected land	EPA[4]
Land use entropy	A diversity index for 8-tier employments (Retail, office, industrial, service, entertainment, education, health, public administration)	
Network density	Total road network density (road mile/square mile)	
Socio-demographics (weighted by the size of the CBGs within the half-mile buffer along the route)		
Zero-car households	Percentage of households with zero vehicles	EPA
Average car ownership	Average number of vehicles available to households	NHGIS [5]
Median household income	Average median household income	
Share of white people	Average share of white population	
Percent of population in poverty	Average percentage of population with income below the poverty threshold	
Regional characteristics		
Regional ridership	Yearly total ridership of the urbanized area (UZA) where the route is located	NTD [6]
Population	Population in the CBSA where the route is located	Census [7]
Sprawling index	Sprawling index in the CBSA where the route is located	MRC [8]
Temperature (January)	Average temperature in January in the location where the route is located	Weather Underground [9]
Temperature (July)	Average temperature in July in the city where most of the route is located	Weather Underground
Congestion level	Travel time index in the UZA where the route is located	TTI [10]
Fuel price	Average fuel price in the state where the route is located	EIA [11]

[4] Environmental Protection Agency Smart Location Mapping: https://www.epa.gov/smartgrowth/smart-location-mapping
[5] National Historical GIS: https://www.nhgis.org/
[6] National Transit Database: https://www.transit.dot.gov/ntd
[7] https://www.census.gov/data/tables/time-series/demo/popest/2010s-total-metro-and-micro-statistical-areas.html
[8] Metropolitan Research Center: https://gis.cancer.gov/tools/urban-sprawl/
[9] Weather Underground: https://www.wunderground.com/
[10] Texas A&M Transportation Institute: https://mobility.tamu.edu/umr/
[11] US Energy Information Administration: https://www.eia.gov/dnav/pet/pet_pri_gnd_a_epm0_pte_dpgal_a.htm

Table 3 describes potential predictors of yearly ridership considered in this research project. In the data, 26% of transit routes are served by rail transit and the remaining are served by BRT. Most transit routes operate in mixed traffic and semi-exclusive environments and dedicated ROW (i.e., exclusive ROW and grade separation) accounts for 12%. Among the routes with dedicated ROW, eight are served by rail transit and one is served by BRT.

Table 3. Descriptive statistics of variables

Variables		**Mean**	**Standard deviation**
	Ridership (million passengers)	2.16	3.2
Route characteristics	**Route type (rail transit, dummy)**	0.26	0.44
	Route length (mile)	15.15	12.26
	Number of stops	19.38	13.94
	Number of park and ride	2.45	3.41
	Shared micro-mobility (dummy)	0.66	0.48
	Integration with other transitways (dummy)	0.69	0.46
	Downtown (dummy)	0.78	0.42
	Airport (dummy)	0.13	0.34
	Enhanced stations (dummy)	0.82	0.39
	Enhanced vehicles (dummy)	0.81	0.4
	Brand identity (dummy)	0.82	0.39
	Center lane (dummy)	0.26	0.44
	Physical separation (dummy)	0.26	0.44
	Freeway managed lane (dummy)	0.38	0.49
	Shoulder lane (dummy)	0.18	0.39
	Ramp queue jump (dummy)	0.25	0.43
Service attributes	**Commence year**	2012	5.77
	Fare (US dollar)	2.17	1.38
	Headway (minute)	14.55	9.03
	Operating speed (mile per hour)	21.35	10.79
	Operating environments	Mixed traffic: 46% Semi-exclusive: 42% Exclusive: 5% Grade separation: 7%	
	Off-board fare collection (dummy)	0.58	0.5
	Level boarding (dummy)	0.55	0.5
	Signal priority (dummy)	0.58	0.5
	Intersection treatment (dummy)	0.39	0.49
	Information system (dummy)	0.99	0.11
	Multi-door (dummy)	0.78	0.42
Built environment characteristics	**Population density (person per acre)**	13.79	20.89
	Network density (road mile per square mile)	24.01	6.2
	Land use entropy	0.67	0.05
Socio-demographics	**Zero-car households**	0.15	0.08
	Average car ownership	1.5	0.29

Variables		Mean	Standard deviation
	Median household income (US dollar)	69273	26273
	Share of white people	0.62	0.13
	Percent of population in poverty	0.19	0.09
Regional characteristics	**Regional ridership (million passengers)**	180.33	207.50
	Population (million people)	4.29	3.31
	Sprawling index	108.43	26.13
	Temperature (January, Fahrenheit)	40.95	14.34
	Temperature (July, Fahrenheit)	77.19	7.41
	Congestion level	1.25	0.1
	Fuel price (US dollar per gallon)	2.99	0.5

3.2 Method

We developed a gradient boosting decision trees (GBDT) model to estimate the relationships between the ridership of transit routes and several types of independent variables, including route characteristics, service attributes, built environment characteristics, socio-demographics, and regional characteristics (Table 2). Based on the works of Friedman (2001, 2002), GBDT is a combination of two methods: decision tree and gradient boosting. The decision tree method divides the sample into several subsamples (also known as terminal leaves) based on certain rules and uses the average value of the observations in each subsample to predict ridership. However, single decision tree has a weak capability of prediction. Gradient boosting improves the model prediction performance by sequentially combining simple decision trees into one large, complex model. In this research project, we used the generalized boosting method (GBM) package in R (Ridgeway 2020) to estimate the GBDT model.

Selecting suitable input parameters is an essential step in GBDT implementation. We focused on four main parameters: tree depth, shrinkage, the number of observations in each leaf, and the quantity of trees. Tree depth defines the number of levels in a tree, and thus, it significantly influences the tree's complexity. Typically, tree depth values range from 1 to 10. Shrinkage determines the proportion of each simple tree that is amalgamated into a more complex structure. While smaller shrinkage values typically enhance model performance, they also escalate computational costs. The number of observations in each leaf defines at most how many observations will be included in each terminal leaf. For a small sample size like this research project, each leaf will have less than 10 observations. The number of trees governs the number of trees to be combined. While a greater number of trees can enhance model performance, it may also induce overfitting—a situation where the model fits the training data exceptionally well but poorly predicts other data sets (e.g., test data). To mitigate overfitting, we utilized cross-validation. Specifically, for this research project, we employed five-fold cross-validation. This technique divides the sample into five subsamples, with four serving as training data sets and one as a test data set.

We set tree depth as 1, 3, 5, or 7, number of observations in each subsample as 3, 5, or 7, and shrinkage as 0.01, 0.05, 0.001. We used root mean squared errors to assess the model performance with different combination of parameters. We applied the five-fold cross validation to seek the optimal number of trees for the model with the best performance. The best model has its tree depth as 7, number of observations in each leaf as 3, and shrinkage as 0.01. The corresponding number of trees is 1,409. The pseudo-R squared for the model is 0.986.

We used relative importance and partial dependence plot to interpret model results. Simply put, adding an independent variable in the model may improve the prediction of the dependent variable and hence reduce the prediction error. The relative importance of an independent variable measures its contribution to the reduced error generated by all the independent variables in the model. The combined relative importance of all predictors equates to 100%. A partial dependence plot for an independent variable showcases the average influence of that variable on predicting the dependent variable, taking into account its interactions with all other variables present in the model. Since the partial dependence plots are vulnerable to multicollinearity, we removed several variables with correlation larger than 0.6 before estimating the GBDT model. We included 33 predicators in the final model (see Table 4 for a complete list of these variables).

We applied the results of the GBDT model to estimate greenhouse gas (GHG) emission reduction related to upgrading operating environments of the BRT and rail transit routes in the Twin Cities. GHG emissions in this research project refer to carbon dioxide equivalent (CO_2e) emissions generated from carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) related to vehicle travel. Specifically, we focused on the reduced emissions caused by switching vehicle drivers to BRT or rail transit riders. We used Equation (1) to compute the reduction.

$$\begin{aligned} &Changes\ in\ CO_2e\ emissions = Ridership\ increase \times \\ &Percentage\ of\ previous\ drivers\ among\ the\ new\ riders \times Average\ transit\ trip\ distance \times \\ &The\ difference\ in\ CO_2e\ emission\ rates\ between\ driving\ and\ transit \end{aligned} \tag{1}$$

In the Twin Cities, there are two LRT routes and five BRT routes operated by the Metro Transit. In addition, there are two LRT extension routes and six BRT routes under construction or planning. With the GBDT model trained with the data from BRT and LRT routes nationwide, we predicted the annual ridership in different operating environments for the transit routes in the Twin Cities. Then, we calculated the ridership change associated with upgrading the operating environment.

To compute the reduction in CO_2e emissions, we made the following assumptions. First, we assumed that 40% of new rail transit riders are used to be drivers. According to Light Rail Now (2005), 40% of Blue Line LRT riders in the Twin Cities were new to transit. Second, we assumed that 25% of new BRT riders are used to be drivers. According to a report by the Federal Transit Administration (FTA

2011), approximately 25% of BRT riders would have driven for the trip if BRT were not available. According to the 2016 Transit on Board Survey[12], the average BRT trip distance was 4.14 mile, and the average LRT trip distance was 5.56 mile.

Table 4 presents CO_2e emission rates by mode and fuel type. The CO_2e emission rates include the emission during the life cycle of the fuel, which includes direct emissions of the vehicle, indirect emissions from power plants, and upstream emission from fuel production and distribution. More information about the methodology can be found in McGraw et al. (2021).

Note that we did not find the emission rate of BRT from a reliable resource. In this project, we used the emission rate of bus transit as a proxy for BRT. For bus transit, Table 4 provides two types of fuels: biodiesel and electric battery. Biodiesel is the main fuel for bus vehicles operated by Metro transit. In this research project, the emission by biodiesel includes biogenetic CO_2. Electric bus vehicles only account for a very small portion of all bus vehicles by Metro Transit (only eight by December 2021). However, based on the Zero-Emission Bus Transition Plan by the Metro Transit (Metro Transit 2022), the goal is to replace 20% of the 40-foot bus vehicles with electric ones during 2022 to 2027.

Table 4. Estimated CO_2e emissions for different travel modes

Mode	Rate (pound per passenger mile)
Private vehicle (gasoline)	1.12
Bus transit (biodiesel, including biogenetic CO_2)	0.78
Bus transit (electric battery)	0.23
LRT (electric propulsion)	0.53

Source: McGraw et al. (2021)

This estimation has two limitations mainly because of data availability. First, we focused on transit riders switching from driving but ignored other travel modes. This is because the proportion of riders switching from other travel modes such as walking, biking, and regular bus were not available. Switching from active travel to transit will increase CO_2e emissions. On the other hand, the enhanced transit improves active travelers' options. Second, the CO_2e emission rate and average trip distance of bus transit were used for BRT because of the lack of related information of BRT.

4 Results

4.1 Descriptive analysis results

For rail transit and BRT, we summarized the ridership, several route characteristics, and several service attributes, differentiated by their operating environment (Table 5). We observed a few patterns. Note that BRT operating in the exclusive environment was removed from the following discussion because only

[12] https://gisdata.mn.gov/dataset/us-mn-state-metc-society-tbi-transit-onboard2016

one route (i.e., the LYMMO line operated by Central Florida Regional Transportation Authority) fell into this category. Similarly, we did not discuss rail transit operating in the semi-exclusive environment.

The transit routes operating in the environment with fewer influences from other traffic have larger ridership. For BRT, the routes operating in the semi-exclusive environment have higher ridership than those in the mixed-traffic environment. For rail transit, grade separation has the highest ridership, followed by exclusive ROW, semi-exclusive ROW, and then mixed traffic. It is worth noting that there are large differences in the ridership between different operating environments. For example, the ridership of BRT routes in the semi-exclusive environment is more than twice as large as those in the mixed-traffic environment. This implies that changing to an operating environment with fewer influences from other traffic is associated with larger ridership.

The transit routes operating in the environment with fewer influences from other traffic generally have more park-and-ride facilities. One exemption is that grade-separated rail transit routes have fewer park-and-ride facilities than routes operating in the exclusive environment. This is likely because grade-separated rail transit often operates in the urban core whereas park-and-ride facilities are located in suburban areas.

More than 80% of the BRT routes operating in the semi-exclusive environment are integrated with other transitways, which is higher than those in the mixed-traffic environment. This is plausible because BRT routes with greater separation from other traffic are an important component of transitway networks. Collectively, they are the backbone of the transit system. The pattern for rail transit routes is not clear.

The transit routes operating in the environment with fewer influences from other traffic are more likely to be operated in the center lane or shoulder lane. For example, 75% of rail transit routes operating in grade-separated or exclusive environments are in the center lane, while the percentage of those in the mixed-traffic environment is 17%. Similarly, the transit routes operating in the environment with fewer influences from other traffic are more likely to be physically separated from other traffic. For instance, 16% of the BRT routes operating in semi-exclusive environments are separated with physical barriers. However, the same value is only 4% for BRT routes in mixed traffic.

The BRT routes operating in the semi-exclusive environment have a higher operating speed than those in the mixed-traffic environment. The pattern for rail transit routes is not clear.

Additionally, we can observe several other patterns from Table 5. The rail transit routes in the mixed-traffic environment tend to have lower shares of off-board fare collection, level-boarding, and intersection treatments than those in other types of operating environments. BRT routes operating in the mixed-traffic environment tend to have a higher share of off-board fare collection, level-boarding, multi-door boarding, signal priority, and information system than those in the semi-exclusive environment. The former finding makes sense, but the latter is counterintuitive. Presumably, although semi-exclusive ROW is unavailable, the BRT routes in the mixed-traffic environment need other BRT features to signify their BRT status. The patterns for other variables are not clear.

Table 5. Right of way attributes [13]

Type of transit routes	BRT (N=58)			Rail transit (N=16 [14])			
Operating environments	**Exclusive (N=1)**	**Semi-exclusive (N=32)**	**Mixed traffic (N=25)**	**Grade separation (N=4)**	**Exclusive (N=4)**	**Semi-exclusive (N=2)**	**Mixed traffic (N=6)**
Ridership (passengers)	534,828	1,797,727	799,684	10,499,693	4,085,068	931,700	568,784
Route characteristics							
Number of park and ride	0	2.0	1.1	2.8	7.3	0	0.6
Shared micro-mobility	100%	59%	60%	100%	100%	100%	100%
Integration with other transitways	100%	84%	56%	50%	50%	100%	83%
Downtown	100%	69%	76%	100%	100%	100%	83%
Airport	0	22%	0	25%	0	0	17%
Enhanced stations	100%	59%	96%	100%	100%	100%	100%
Enhanced vehicles	100%	75%	76%	100%	100%	100%	100%
Brand identity	100%	77%	92%	100%	100%	100%	67%
Center lane	0	34%	4%	75%	75%		17%
Physical separation	100%	16%	4%	100%	100%		17%
Freeway managed lane	0	66%	20%	0	25%		20%
Shoulder lane	0	25%	4%	50%	25%		17%
Ramp queue jump	0	28%	28%	0	25%		17%
Service attributes							
Fare (US dollar)	0	2.3	1.8	1.9	2.1	2.8	0.6
Headway (minutes)	7.0	15.6	14.7	9.5	16.8	11.0	13.0
Operating speed (miles per hour)	8.0	23.3	17.9		25.7		25.8
Off-board fare collection	0	29%	72%	100%	100%	100%	67%
Level boarding	100%	31%	52%	100%	100%	100%	83%
Signal priority	0	44%	72%	100%	33%	100%	100%
Intersection treatment	0	29%	32%	100%	67%	100%	50%
Information system	100%	100%	96%	100%	100%	100%	100%
Multi-door	100%	66%	76%	100%	100%	100%	100%

[13] Except for ridership, number of park and ride, fare, headway, and operating speed, all cells indicate the percentage of the routes with the corresponding feature. The blank cells mean that data are insufficient for computation.
[14] The operating environments of four rail transit routes are missing.

4.2 Relative importance of predictors

Table 6 presents the relative importance of independent variables to predicting yearly ridership of transit routes, which is generated by the GBDT model. Collectively, transit route characteristics and service attributes contribute about 74% of the predictive power. Built environment characteristics also play a role in predicting ridership, with a relative importance of approximately 16%.

Table 6. Results of relative importance

Variable		**Relative importance**	**Ranking**	**Sum**
Route characteristics	**Number of stops**	12.1	2	28.2
	Number of park and ride	5.4	6	
	Route length	3.4	9	
	Center lane	2.3	12	
	Rail transit	1.7	14	
	Freeway managed lane	1.3	18	
	Shoulder lane	0.9	21	
	Ramp queue jump	0.6	25	
	Integration with other transitways	0.3	26	
	Enhanced vehicles	0.0	28	
	Airport	0.0	30	
	Downtown	0.0	31	
	Enhanced stations	0.0	32	
Service attributes	**Operating environments**	18.1	1	46.0
	Commence year	11.3	3	
	Signal priority	7.9	5	
	Headway	4.0	7	
	Operating speed	2.7	10	
	Intersection treatment	0.9	20	
	Fare	0.7	23	
	Off-board fare collection	0.3	27	
	Level boarding	0.0	29	
	Multi-door	0.0	33	
Built environment characteristics	**Population density**	10.7	4	16.1
	Network density	3.8	8	
	Land use entropy	1.6	15	
Socio-demographics	**Zero-car households**	1.4	16	3.1
	Share of white people	1.0	19	
	Median household income	0.6	24	
Regional characteristics	**Sprawling index**	2.5	11	6.6
	Temperature (January)	2.0	13	
	Congestion level	1.3	17	
	Population	0.8	22	
Sample size		78		
Pseudo R^2		0.986		

The single most influential variable in predicting ridership is the operating environment of the transit route (Figure 2). This variable contributes more than one sixth of the predictive power. That is, it has a substantial relationship with transit ridership. Number of stops is the second important predictor. Commence year ranks third, followed by population density, signal priority, number of park-and-ride facilities, headway, network density, and route length. All other variables contribute less than 3% of the predictive power.

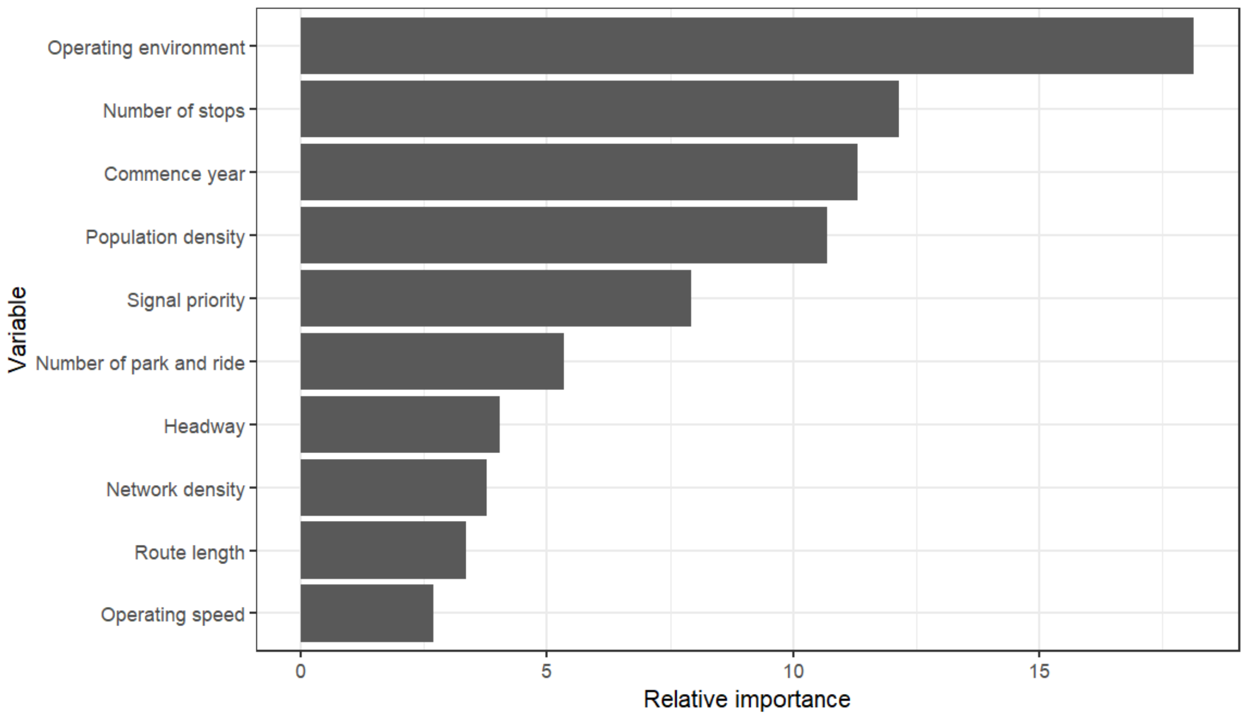

Figure 2. The ten most important variables

4.3 The relationships between predictors and transit ridership

We used partial dependent plots to illustrate the associations of independent variables with predicted ridership. We applied the same scale of y axis for most of the plots (except for signal priority) to facilitate comparison across plots. We also presented the distribution of the predictor on the x axis with rugs, which are small vertical lines indicating the data points of the sample.

Figure 3 shows that the predicted yearly ridership associated with dedicated ROW (exclusive and grade separation) is 5.25 million, and the corresponding statistics associated with semi-exclusive ROW and mixed traffic environments are 1.57 million and 1.5 million, respectively. Therefore, transit routes with dedicated ROW serve about 3.3 times as many passengers as those without dedicated ROW. This suggests that transit riders value the benefits associated with dedicated ROW. Semi-exclusive transit routes serve 4.6% more passengers (about 70,000) than the routes operating in mixed traffic. The ridership bonus is relatively small but non-trivial. On the other hand, if transit routes with semi-exclusive

ROW are equipped with additional features (such as signal priority and high service frequency), their cumulative ridership benefits could be substantial.

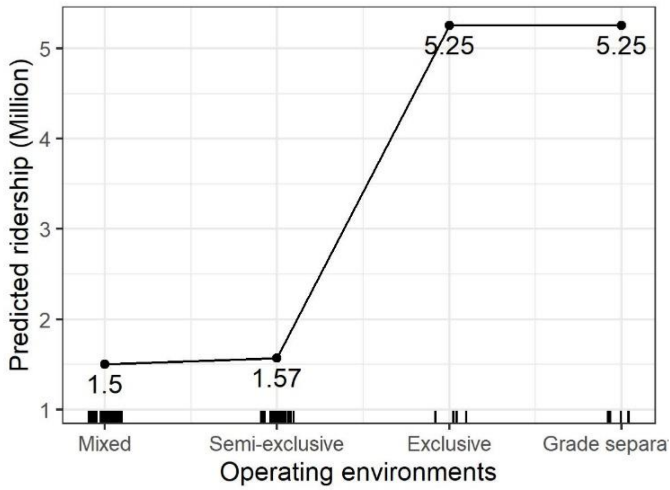

Figure 3. The relationship between operating environment and ridership

Figure 4 illustrates that the number of stops, measuring the number of opportunities to board and alight the service, is positively associated with transit ridership, which is consistent with our expectation. The nonlinear relationship suggests that the number of stops becomes effective in the range from about 10 stops to 25 stops. Out of this range, its impact is trivial.

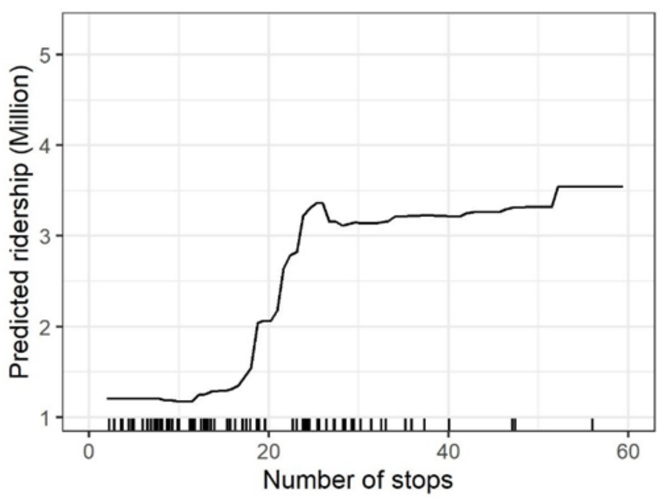

Figure 4. The relationship between number of stops and ridership

The relationship between commence year and transit ridership is shown in Figure 5. Generally, they are negatively associated. Over time, transit-supportive land uses are likely to be developed along transit routes and those who prefer transit may be able to sort themselves into the neighborhoods around transit stations. Accordingly, transit ridership grows. The plot shows that the transit routes commencing before 2010 have higher ridership than those starting revenue service after 2010.

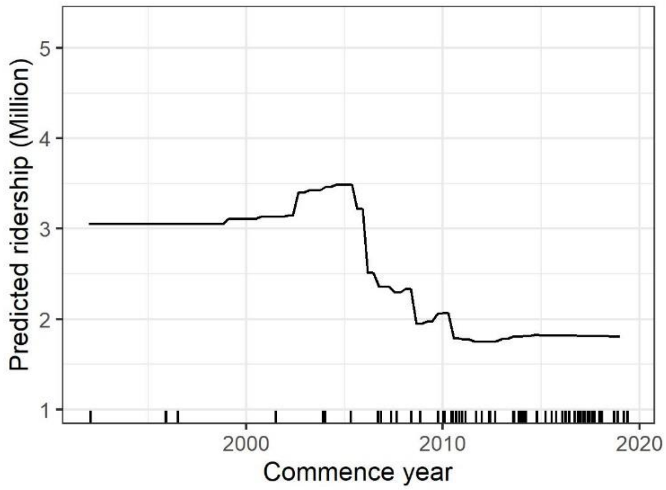

Figure 5. The relationship between commence year and ridership

Figure 6 shows the relationship between population density and transit ridership. When exceeding eight persons per acre, population density starts to show a positive relationship with transit ridership. That is, population density needs to be large enough to be an effective contributor to transit ridership.

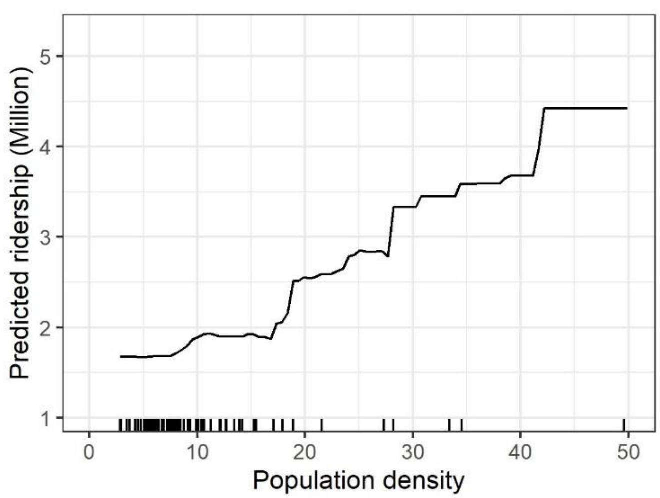

Figure 6. The relationship between number of population density and ridership

Figure 7 illustrates that signal priority is associated with higher ridership. It confirms the important role of signal priority in improving the performance of transit routes. According to the difference between predicted ridership, transit routes with signal priority serve 149,000 more passengers yearly.

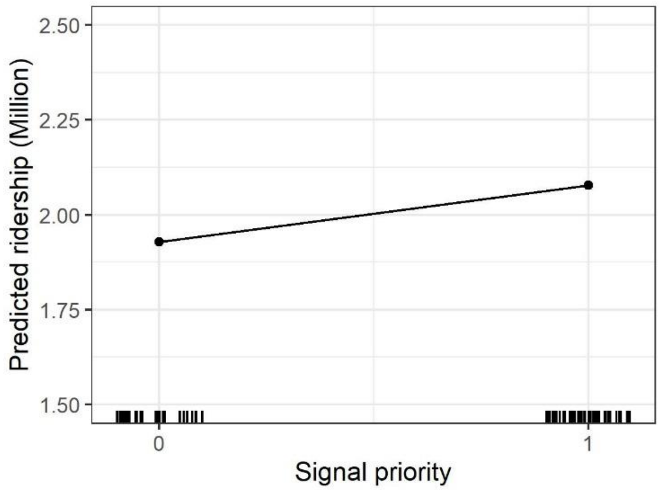

Figure 7. The relationship between signal priority and ridership

Figure 8 to Figure 11 show the effects of the number of park-and-ride facilities, headway, network density, and route length. The number of park-and-ride facilities is positively correlated with ridership, which is consistent with our expectation. Headway has a negative association with transit ridership. The ridership increases by about 1 million passengers when the headway reduces from 8 minutes to five minutes. When it increases from 8 minutes to 15 minutes, the ridership reduces by about 64,000 passengers. The areas with a denser road network tend to have more passengers. Route length has a positive relationship with transit ridership. Once the length reaches about 5 miles, its marginal effect is diminishing greatly.

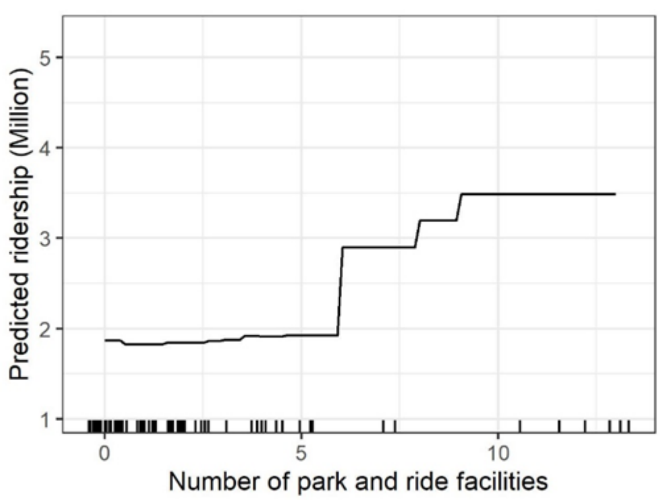

Figure 8. The relationship between number of park-and-ride facilities and ridership

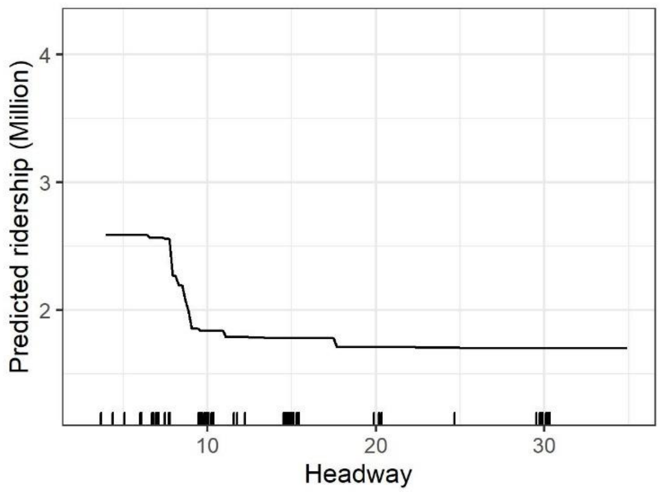

Figure 9. The relationship between headway and ridership

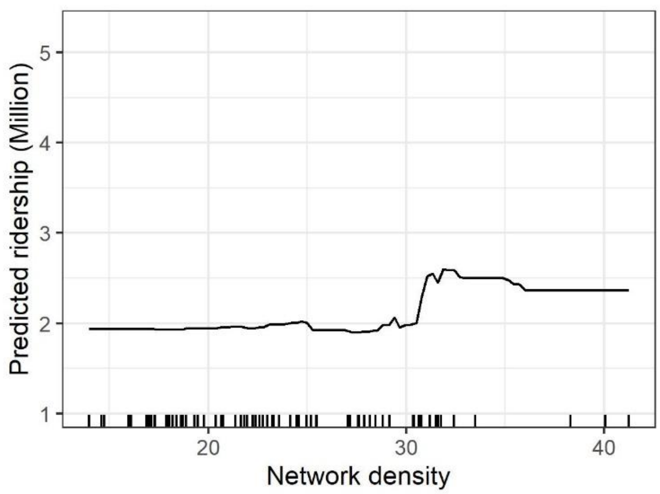

Figure 10. The relationship between network density and ridership

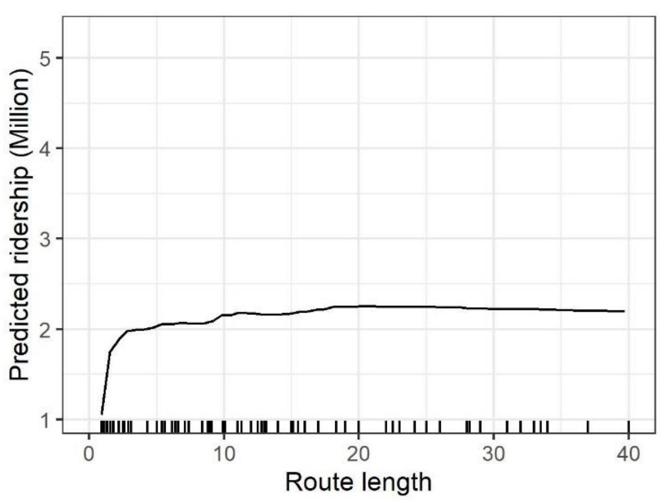

Figure 11. The relationship between route length and ridership

4.4 GHG reduction estimation

In this section, we estimated changes in GHG emissions associated with upgrading the operating environment of transit routes.

Based on Equation (1), we first calculated the transit ridership increase related to the operating environment upgrading (Table 7). Although some of the transit routes in operation cannot change their operating environments anymore (e.g., Blue Line and Green Line), we included them in our estimation because we hope that the results may help inform future decisions on transitway planning.

Table 7. Predicted yearly ridership (million passengers) in different operating environments for LRT and BRT routes in the Twin Cities

Name	**Type**	**Mixed Traffic**	**Semi-exclusive**	**Exclusive**
Transit routes in operation				
Blue Line	LRT	6.51	6.58	11.26
Green Line	LRT	8.55	8.64	13.47
Red Line	BRT	0.28	0.33	3.81
Orange Line	BRT	1.73	1.82	5.32
A Line	BRT	1.66	1.75	6.46
C Line	BRT	1.23	1.36	5.75
D Line	BRT	2.39	2.55	6.99
Transit routes under construction or planning				
Blue Line extension	LRT	0.95	1.00	4.59
Green Line extension	LRT	2.41	2.46	6.10
Purple Line	BRT	1.22	1.34	4.94
E Line	BRT	5.25	5.30	9.77
Gold Line	BRT	1.43	1.51	5.16
B Line	BRT	2.62	2.75	6.86
F Line	BRT	2.60	2.71	7.25
H Line	BRT	4.73	4.84	9.28
G Line	BRT	3.48	3.65	8.11

We, then, plugged the statistics of ridership change, percentage of previous drivers among the new riders, average transit trip distance, the difference in CO2e emission rates between driving and transit into Equation (1) to calculate the reduced CO_2e emissions in three scenarios for all BRT and LRT routes in the Twin Cities area (Table 8). These three scenarios include all transit routes with no electric BRT trips, all transit routes with 20% electric BRT trips, all transit routes with 100% electric BRT trips.

Table 8. CO_2e emissions (million pounds) reduction associated with upgrading operating environment

Transit routes	All transit routes with no electric trips		All transit routes with 20% electric BRT trips (2022-2027 goal)		All transit routes with 100% electric BRT trips	
	Mixed traffic -> Semi-exclusive	Semi-exclusive -> exclusive	Mixed traffic -> Semi-exclusive	Semi-exclusive -> exclusive	Mixed traffic -> Semi-exclusive	Semi-exclusive -> exclusive
Blue Line	0.10	6.19	0.10	6.19	0.10	6.19
Green Line	0.12	6.39	0.12	6.39	0.12	6.39
Red Line	0.02	1.26	0.02	1.65	0.04	3.22
Orange Line	0.03	1.26	0.04	1.65	0.08	3.23
A Line	0.03	1.70	0.04	2.23	0.08	4.35
C Line	0.05	1.58	0.06	2.08	0.12	4.06
D Line	0.06	1.60	0.08	2.10	0.15	4.10
Blue Line extension	0.07	4.75	0.07	4.75	0.07	4.75
Green Line extension	0.06	4.83	0.06	4.83	0.06	4.83
Purple Line	0.04	1.30	0.05	1.70	0.11	3.33
E Line	0.02	1.61	0.02	2.11	0.04	4.13
Gold Line	0.03	1.32	0.04	1.73	0.07	3.37
B Line	0.05	1.48	0.06	1.94	0.12	3.80
F Line	0.04	1.63	0.06	2.15	0.11	4.19
H Line	0.04	1.60	0.05	2.10	0.10	4.11
G Line	0.06	1.61	0.08	2.11	0.16	4.12

5 Conclusions

In this research project, we explored the impact of different ROWs (i.e., the operating environment) on the performance of rail transit and BRT routes with the data collected from 78 rail transit and BRT routes in the US. Specifically, we applied the GBDT method to estimate the nonlinear relationships between transit ridership and five types of independent variables, including route characteristics, service attributes, built environment characteristics, socio-demographics, and regional characteristics, with the focus on ROW. In addition, we used the GBDT model to predict the ridership in different operating environments for the BRT and LRT routes in the Twin Cities and estimated the GHG emission reduction associated with upgrading the operating environment.

The ROW operating environment had the most significant impact on the ridership of the transit routes we investigated. The descriptive analysis revealed that transit routes operating in the environment with less interference from other traffic attract a higher number of passengers and the difference in the ridership between different operating environments was substantial. Furthermore, the GBDT model showed that the operating environment had the most contribution in terms of relative importance (18%) to predicting transit ridership among all 33 variables present in the model. On average, upgrading from mixed traffic to the semi-exclusive operating environment could lead to a 70,000 increase in yearly ridership. Upgrading from the semi-exclusive to exclusive operating environment could add 3.68 million passengers to yearly ridership.

In addition to the operating environment, several factors had important contributions to transit ridership. The results of the GDBT model showed that, following the operating environment, the number of stops, transit route commence year, population density, signal priority, number of park-and-ride facilities, headway, network density, and route length all had large contributions (with the relative importance >3%) to predicting ridership. Specifically, transit routes opened after 2010 were associated with a smaller ridership than those opened before, the application of signal priority could increase yearly ridership by 149,000 passengers, and reducing headway from 15 to 10 minutes could add 64,000 additional passengers to yearly ridership. In addition, the nonlinear relationship of population density showed that population density should be large enough to be effective in influencing transit ridership and the threshold was eight people per acre. Similarly, network density should be larger than 30 miles per square mile to become an effective factor.

Upgrading the operating environment has a substantial influence on the GHG emission reduction by transit. In the scenario with no electric BRT vehicles, upgrading from mixed traffic to the semi-exclusive operating environment could cut CO_2e emissions by 20,000 to 60,000 pounds for BRT transit routes and 60,000 to 120,000 pounds for LRT routes in the Twin Cities. A further upgrade from the semi-exclusive to exclusive operating environment could reduce CO_2e emissions by 1.3 million to 1.7 million pounds for BRT routes and 4.75 million to 6.39 million pounds for LRT routes. Moreover, more electric BRT trips operating on the road are associated with larger CO_2e emission reductions. For example, when the bus vehicles are all electric, upgrading from mixed traffic to the semi-exclusive operating environment could reduce CO_2e emissions by 40,000 to 160,000 pounds and upgrading from the semi-exclusive to exclusive operating environment could reduce CO_2e emissions by 3.22 million to 4.35 million pounds for BRT routes in the Twin Cities.

This research project offers several policy implications for transit planning and sustainability. **First, upgrading to an operating environment with a higher level of ROW could substantially improve the performance of transit routes in terms of ridership and related reductions in GHG emissions**. Policies such as dedicated transit lanes during all time or only rush hours could help reduce influence from other traffic and enhance service reliability and efficiency. Furthermore, implementing smart traffic management systems to provide priority to transit vehicles at intersections could increase the attractiveness of these services to potential riders. Signal priority helps reduce delays of transit vehicles at intersections and improve service quality. **Second, enhancing the frequency of transit service could boost ridership.** Specially, reducing headway from 8 to 5 minutes has a much larger impact than that from 15 to 8 minutes on transit ridership. **Third, locating transit routes in the areas with enough population density and network density could improve their performance**. The corresponding thresholds are eight people per acre for population density and 30 miles per square mile for network density, according to our data. It's important to acknowledge that these thresholds could vary for different regions as they are influenced by the specific contextual factors of each area. **Finally, increasing the share of electric bus vehicles could further decrease GHG emissions**. A case in point is Metro Transit's Zero-Emission Bus Transition Plan, which establishes the goal of replacing 20% of the 40-foot bus vehicles with electric ones during 2022 to 2027. Similar policies could assist regional transportation agencies to achieve their emission reduction objectives, thereby fostering a more sustainable transportation system.

It is worth noting that this project primarily aimed to examine the advantages related to increased ridership and the reduction of carbon emissions resulting from upgrading the operating environment of transit routes. Given the substantial capital and societal expenses associated with constructing a dedicated ROW, a cost-benefit analysis and deliberation among various stakeholders would be crucial before deciding to allocate a dedicated ROW for any transit route.

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Appendix A

Transit route information form

Start of Block: Route and ridership information

Thank you for taking the time to provide the information on the transit routes. It will be used to study the influence of dedicated right of way (ROW) on transit ridership. Specifically, the research team will summarize transit preferential practices commonly associated with dedicated ROW and develop statistical models to examine the correlation between dedicated ROW and transit ridership. The results will be used to inform the decision making on the planning and investment of dedicated ROW for future transit routes.

Please fill out a survey form for each transit route. The questions with * are required. The deadline for this survey is August 31st, 2022.

If you have any questions, please contact the research team.

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* What is the name of the transit route?

____

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* What is the route type?

○ BRT or bus transit sharing some features with BRT

○ LRT or streetcar

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* Which transit agency operates this route?

____

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* Please provide the annual ridership in the most recent year before 2020 and indicate the corresponding year.

○ Ridership ____

○ Year of the ridership ____

End of Block: Route and ridership information

Start of Block: Route characteristics

In what year did the route commence operation?

○ Commence year ____

Hong long is the route in miles?

○ Length ____

How many stops does the route serve? If the numbers of stops differ between two directions, please take the average.

○ Number of stops ____

How many park-and-ride facilities serve the route?

○ Number of P&R facilities ____

Are there any bike sharing or e-scooter systems along the route?

- ◯ Yes
- ◯ No

Is the route connected to a downtown?

- ◯ Yes
- ◯ No

Is the route connected to an airport?

- ◯ Yes
- ◯ No

Is the route connected with other transitways?

- ◯ Yes
- ◯ No

Are stops enhanced to be distinct from those of traditional transit routes?

- ◯ Yes
- ◯ No
- ◯ I don't know.

Are vehicles enhanced to be distinct from those of traditional transit routes?

- ○ Yes
- ○ No

Is the route branded differently from traditional transit routes?

- ○ Yes
- ○ No

Is the majority of the route operated on center lanes or medians (vs. curbside)?

- ○ Yes
- ○ No

Is the lane physically separated from other lanes (vs. painted lines)?

- ○ Yes
- ○ No

Is the route or part of the route operated on a managed lane (for HOV, HOT, Buses, Trucks, etc.)?

- ○ Yes
- ○ No

Is the route or part of the route operated on a shoulder lane?

- ○ Yes
- ○ No

Are ramp queue jumps provided for the route?

- ○ Yes
- ○ No

End of Block: Route characteristics

Start of Block: Service attributes

How much is the fare before any discount for the general public during the peak hour?

- ○ Price ____

What is the shortest headway in minutes during the peak hour?

- ○ Headway ____

What is the operating (commercial) speed in miles per hour during the peak hour?

- ○ Speed ____

Please indicate the operating environment of the route.

○ Mixed traffic: other traffic modes are allowed to share the lane with the transit route during all time

○ Semi-exclusive: certain traffic modes are allowed at certain locations and/or during certain time, e.g., vehicles on freeway managed lanes, cyclists and pedestrians on transitway, turning vehicles, parking lanes during non-peak hours

○ Exclusive: other traffic modes are allowed only at grade crossing

○ Grade separation: transit routes are operated on underground or elevated lanes and other traffic modes are completed excluded

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Are tickets purchased before boarding?

○ Yes

○ No

Does the platform enable level boarding?

○ Yes

○ No

Is there transit signal priority?

○ Yes

○ No

Are there preferential treatments at intersections such as turning prohibition and queue jump?

○ Yes

○ No

Are there high-quality information systems (smartphone application, traveler information, etc.) for the route?

○ Yes

○ No

Can passengers get on and off vehicles through multiple doors?

○ Yes

○ No

Display This Question:
*If * What is the route type? = BRT or bus transit sharing some features with BRT*

What is the bus type (or length)?

____

Display This Question:
*If * What is the route type? = LRT or streetcar*

What is the number of cars for LRT and streetcar?

____

End of Block: Service attributes

Start of Block: Comment

Do you any additional comments?

____

End of Block: Comment