MEMO

SAFE STREETS Research + Consulting

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FROM: Jessica Schoner PhD, Rebecca Sanders PhD RSP_{2B}, Brian Almdale, and Emira Rista PhD
DATE: 2024-10-21
RE: Partial Working Draft White Paper for Task 4 System Safety Analysis
PROJECT: P029 BART Vision Zero Action Plan

Abstract

Robust transit service is a key component of a healthy transportation system. An understudied aspect of transit service is its role in creating a safer transportation system overall (Litman, 2014). This white paper explores whether improving transit levels of service and reliability of the San Francisco Bay Area Rapid Transit District (BART) can improve traffic safety outcomes (i.e., decrease injury and fatality rates). Two theoretical pathways are explored: (1) the Travel Behavior pathway, where a shift from driving to transit decreases driving-related injuries and fatalities (riding BART is 18 times safer than traveling by passenger vehicle[1]); and (2) the Roadway Facility pathway, where changes in roadway facilities (e.g. reduced parking, reduced roadway capacity, and/or slower speeds) reduce driver convenience and therefore decrease driving (and shift trips to transit, walking, and biking) and driving-related injuries and fatalities. These two pathways are related and can create a positive feedback loop: the more travel is shifted from passenger vehicles to transit, the more roadways can be retrofitted to prioritize safety. This white paper uses transit network and ridership data from the BART system to investigate these two pathways, the relationship between them, and to test how big of an impact they might have. In short, roadway changes that reduce driver speeds, volumes, and the number of travel lanes are necessary to reduce and ultimately eliminate traffic deaths and serious injuries. Transit alone cannot reverse the roadway safety crisis, but BART and other transit providers still have an important role to play in roadway safety in shaping the travel demand landscape and opening up opportunities for aggressive roadway safety countermeasures.

This white paper conducted three separate analyses: (1) a comparative analysis of safety outcomes on roads that serve the same origins and destinations of BART (referred to generally as the Parallel Systems) versus the safety outcomes on the rest of the roads in the study area (the five-county BART region); (2) an analysis of the traffic safety outcomes on the Parallel Systems

[1] Safe Trips to BART: An Action Plan for Safer Roadways. https://www.bart.gov/about/planning/station-access/safe-trips#:~:text=Overview,plan%20to%20improve%20roadway%20safety.

with and without BART, which was tested using two case studies: a comparative analysis of baseline safety data versus safety outcomes during a BART operators strike and a comparative analysis of traffic safety outcomes as BART expanded service between 2016-2023. The third analysis (3) quantifies potential future effects on traffic safety outcomes by implementing road diets (roadway reallocations) and increased BART ridership.

The first of the three analyses found that roads on the Parallel Systems have two to six times more severe crashes per 100 miles than the rest of the roads in the region (the range in crash density differ by sub-categories in the Parallel Systems). This means that people who drive or ride in passenger vehicles in routes served by BART are at higher risk of severe injury. Further, Parallel System streets saw a disproportionately higher concentration of severe crashes during late-night hours when BART is not operating (12AM to 6AM), when streets designed for peak-hour congestion operate at higher free-flow speeds. However, the Parallel Systems have a higher percentage of freeways than the roadways in the rest of the region. Parallel System roadways also have more lanes, higher speed limits, and higher traffic volumes, which likely partially account for the increased likelihood of severe injury. It is important to note that BART's High Injury Network, a network of roadways with a higher concentration of injuries and fatalities, is also over-represented on the Parallel Systems. Taken all together, the first analysis indicates that the roadways proximate to BART that serve the same origins and destinations are more dangerous in terms of crash frequency and injury severity than the rest of the roadways in the region. This analysis is not able to precisely quantify how much BART influences traffic safety, but BART remains significantly safer than driving along the Parallel Systems.

The second analysis was inconclusive due to sample size (BART strikes in 2013 were too small to find discernable patterns) and lack of normalization (service expansion scenario).

The third analysis identified about 729 miles of streets in BART's Parallel Systems that are potential candidates for road diets and estimated potential KSI crash reductions of 20-30% depending on the BART ridership scenario. Service improvements, such as increased frequency and reliability, of BART system could strategically reduce peak hour driving demand for these streets and improve the suitability of roadway reallocations ("road diets"). Applying this countermeasure could prevent approximately 127-155 severe crashes per year (out of 2,608 on the entire parallel system), depending on the various BART ridership and mode shift scenarios tested.

These findings begin to explore BART's role in traffic safety for the region. The evidence indicates that BART can alleviate peak-hour pressure on the freeway and arterial system. Designed for peak-hour congestion, these facilities see proportionately more late-night crashes than streets outside the parallel system, when the excessively wide right-of-way paired with low traffic volumes lead to higher operating speeds. By alleviating this pressure, BART service can enable roadway reallocations (e.g., road diets) that make driving conditions safer by reclaiming this excess capacity and encouraging safer speeds at all times of day. BART also provides safer ways to travel at off-peak operating times that may reduce risky driving behaviors higher speed or driving under the influence. This study has some notable limitations and opportunities for future research, explained further in Section 5.2.

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1 Introduction and Background

Robust transit service is widely recognized as a key component of a healthy transportation system. An understudied aspect of transit service is the role it plays in creating a safer transportation system overall (Litman, 2014). While transit trips are safer on a per-passenger-per-mile basis than all other modes of transportation,[2,3] few studies have examined how transit may act as a countermeasure to improve safety within the larger transportation network system. This white paper seeks to address the research question: would improving transit levels of service and reliability of the San Francisco Bay Area Rapid Transit District (BART) improve roadway safety?

This white paper studies transit as a transportation safety countermeasure by exploring two theoretical pathways and the synergy between the two pathways. The two theoretical pathways are: (1) the Travel Behavior pathway, where a shift from driving to transit directly decreases driving-related injuries and fatalities; and (2) the Roadway Facility pathway, where changes in roadway facilities – reduced parking, reduced roadway capacity (e.g. number of lanes), and/or slower speeds – reduce driver convenience, increase biking and walking, creating a sense of "safety in numbers" that reinforces a safer biking and walking experience, and ultimately reduces the number of injuries and fatalities in the overall transportation system. Each pathway can operate separately from the other but together can create a positive feedback loop that results in mode shift from driving to transit, walking, and biking and an overall transportation system with less injuries and fatalities.

Section 2 describes existing literature about the relationship between transit and traffic safety and details a theoretical model connecting transit and traffic safety. Section 3 describes the overall approach and methodology used in this analysis. Section 4 describes the results of the analysis. Section 5 summarizes key findings and documents limitations and opportunities for future research.

2 Background and Theoretical Model

2.1 Background Literature

The project team identified and reviewed relevant literature that addresses the research question of whether improving transit levels of service and reliability of BART would improve roadway safety.

Although VMT is widely recognized as a predictor of traffic fatalities (Litman, 2024), there is limited research to quantify the impact of improved transit service on VMT reduction, and

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[2] National Safety Council. (2025). Deaths by Transportation Mode. https://injuryfacts.nsc.org/home-and-community/safety-topics/deaths-by-transportation-mode/

[3] Centers for Disease Control and Prevention. (2024). Public Transportation System: Introduction or Expansion. Interventions Addressing the Social Determinants of Health. https://archive.cdc.gov/www_cdc_gov/policy/hi5/publictransportation/index.html

therefore improved roadway safety. A review of the literature found the following patterns related to transit, traffic safety, and mode shift/VMT reduction:

1) **The presence of transit can be connected to improved roadway safety outcomes, but more direct research is needed to understand this relationship.**

There is limited research evaluating the direct relationship between frequency improvements on existing U.S. heavy rail with roadway safety outcomes. Research does show, however, that transit-rich cities have better safety outcomes and transit-supportive land uses that positively impact roadway safety by reducing the need for vehicle ownership and vehicle travel[4]. Additionally, high-frequency transit investments that are coupled with user safety and traffic calming capital investments, as seen in most bus rapid transit (BRT) projects, positively impact roadway safety.

2) **Increased transit mode share has direct safety benefits.**

Rail transit is over 18 times safer than driving or riding in passenger vehicles when comparing fatalities per passenger-mile (National Safety Council, 2024). Although transit trips are often paired with trips that use less safe modes such as walking, biking, or driving, the magnitude of difference in safety outcomes indicates that there is still a safety benefit in increasing transit mode share alone. When paired with reduced vehicle speeds that cultivate a low-stress walking and biking environment, the safety benefits of increased transit mode share would be even greater.

3) **Safe roads enable safe first/last mile transit access.**

Improved first/last mile access to transit is a critical tool for generating ridership and inducing mode shift. Elements of high quality transportation networks, such as traffic calming measures and other roadway design interventions that reduce vehicle speed, generate both safety and ridership gains by easing the risks of accessing transit via active transportation.

4) **The COVID-19 pandemic impacted travel behavior, but more research is needed to understand long-term impacts on roadway safety.**

Finally, the impact of the COVID-19 pandemic on roadway safety is complex and varied based on the time period and environment studied and continues to be a research gap. The long-term impact of the COVID-19 pandemic on transit ridership, travel behavior, and roadway safety remains unknown, and it is therefore hard to predict what impact transit service improvements will have.

2.2 Theoretical Model of Transit as a Safety Countermeasure

As described in the literature review, transit service can influence traffic safety in multifaceted and primarily indirect ways. These influences can be described via two main pathways:

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[444] Litman, Todd. (2025) “A new Traffic Safety Paradigm.”Victoria Transport Policy Institute. https://www.vtpi.org/ntsp.pdf?trk=public_post-text

1. **Travel Behavior Pathway:** Increasing transit service and quality reduces driving, risky driving behaviors, and elevated rates of injuries and outcomes
2. **Roadway Infrastructure Pathway:** Providing more and better transit service helps cities justify retrofitting higher-risk roadway designs due to reduced demand for driving.

These pathways are depicted in Figure 1 and described below. Increases in transit service and changes in roadway design and operations are both listed as independent inputs at the top of the flowchart. While there are direct connections between roadway changes and outcome variables, most of the pathways between the independent variables and outcome variables flow through changes in travel behavior for all road users.

The Travel Behavior Pathway starts with the green box on the right, "Increases in Transit Service." Shifting behavior from driving to riding transit reduces the risk of traffic crashes for people who are driving less. There are other implications of this pathway as well. For example, the lowest purple box, "Safety in numbers[5] for VRUs," speaks to a pattern in the literature where higher rates of walking and bicycling tend to lead to better safety outcomes for vulnerable road users (VRU) due to increased driver expectancy. Through this lens, changes in travel behavior may have secondary effects that promote safety for all road users beyond the immediate benefit to people who are no longer driving or riding in a vehicle.

The Roadway Infrastructure Pathway primarily starts with the green box on the left, but as will be argued in the next section, it depends on elements of the Travel Behavior Pathway as well. This is illustrated by the plus symbol with circular arrows around it. In theory, roadway changes could occur independently, but significant roadway reconfigurations (e.g., removing vehicle travel lanes) are unlikely to be implemented without corresponding reductions in driving. In other words, transit's potential to reduce demand for driving is the "key" that "unlocks" the opportunity to retrofit roads at a much larger scale than would be feasible based on existing demand for driving.

[5] "Safety in Numbers" refers to research that has found in areas where there are more people walking and bicyclists, the likelihood for a motorist to collide with a pedestrian or bicyclists is reduced. To learn more about the safety in number effect, please see: Jacobsen, P L. "Safety in numbers: more walkers and bicyclists, safer walking and bicycling." Injury prevention : journal of the International Society for Child and Adolescent Injury Prevention vol. 9,3 (2003): 205-9. doi:10.1136/ip.9.3.205

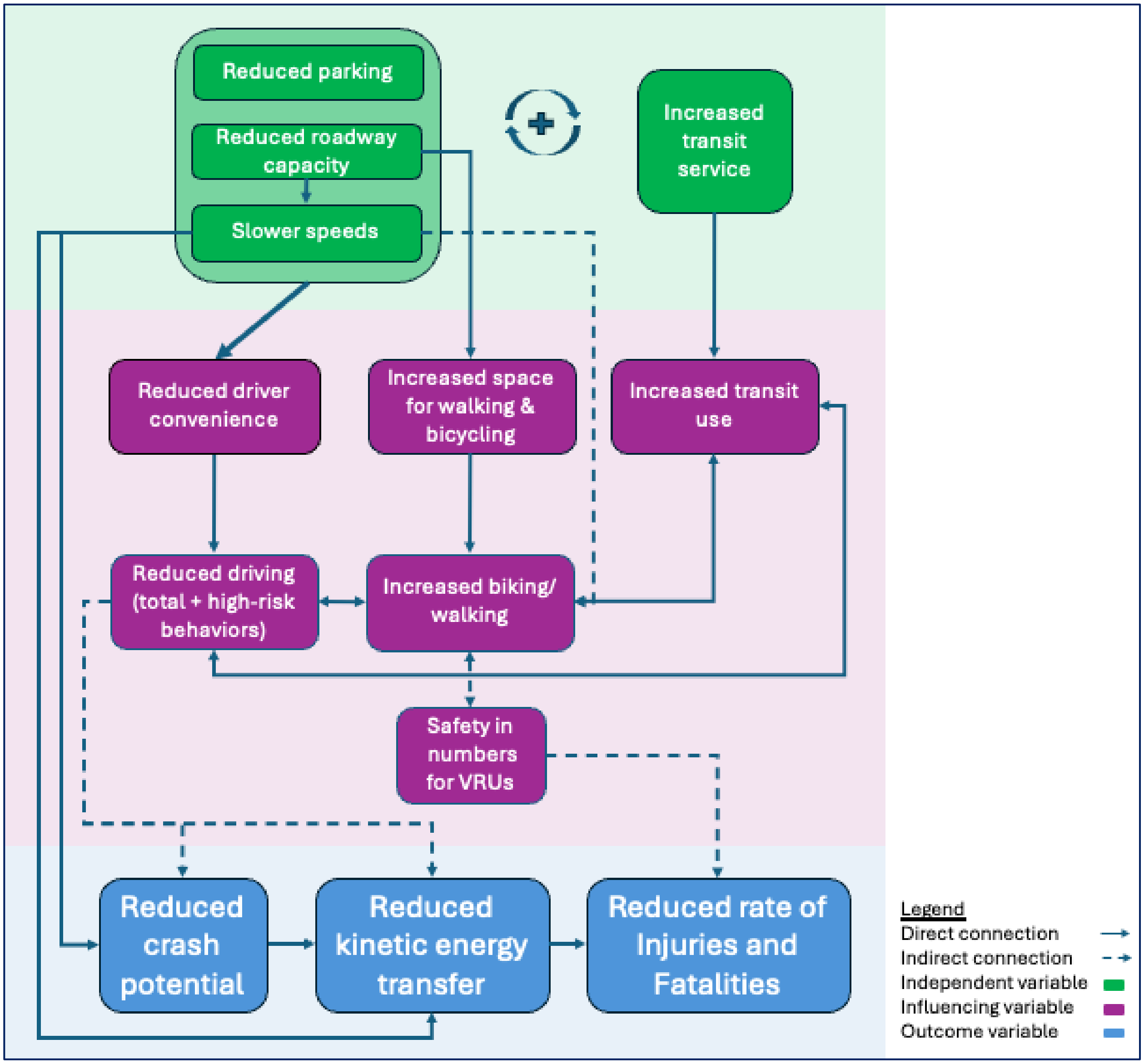

Figure 1. Theoretical Model of Transit as a Safety Countermeasure with Direct and Indirect Connections

2.3 Pathway 1: Travel Behavior Pathway

Figure 2 shows the Travel Behavior Pathway within the theoretical model. In this pathway, increased transit use is connected to both reductions in driving and increases in walking and bicycling. The connections in the diagram flow in both directions, meaning that increases in transit use can both cause and be caused by changes in walking, bicycling, and driving. Reduced driving overall tends to lead to safer roadways via reduced crash potential.

However, as evidenced by the COVID-19 pandemic, drastic removal of nearly all driving under traumatic circumstances may lead to wide open roads, excessive driver speeds, reckless driving, and ultimately increases in deaths and serious injuries. Under normal circumstances (as assumed in this white paper), both higher VMT and annual average daily traffic (AADT) are typically associated with more crashes; gradual reductions in driving do not cause the same drastic increases in speed and risk. The types of modest reductions in VMT and AADT that might occur when some percentage of travelers shift modes from driving alone to using transit, walking, or biking are expected to function more like normal conditions than the pandemic crisis conditions.

2.4 Pathway 2: Roadway Facility Pathway

Figure 3 shows the Roadway Facility Pathway within the theoretical model. While Figure 3 does not show the impact of transit service on this pathway, the research team argues that this pathway is only feasible in the context of reduced driving demand, which may arise from increases in transit service. In this pathway, reducing parking, reducing the number of travel lanes, and creating a slower-speed environment leads to improved transportation safety outcomes for all road users. Reduced roadway capacity and slower speeds reduce driver convenience, which reduces driving thus increasing traffic safety. Reduced roadway capacity and slower speeds also have individual and direct safety effects. Slower speeds directly decrease the potential for injury in a crash.[6],[7] Slower speeds also lead to a more comfortable environment for walking and bicycling, which tends to lead to both increased rates of walking and bicycling and increased safety for people walking and bicycling. Reduced driving and increased walking and bicycling has been shown to create a feeling of “safety in numbers” (Jacobsen, 2015), where drivers become habituated to people walking and biking and drive in a safer manner. Similarly, reducing roadway capacity, when it is reallocated to increased space for people walking and bicycling, contributes to the virtuous cycle of increased walking and bicycling, which in turn contributes to increased safety while walking and bicycling, and vice versa. Together, these factors lead to reduced injury and fatality rates, making the overall transportation system safer.

As seen in Figure 3, transit is not *strictly* necessary for the Roadway Facility Pathway, but implementing these changes in the absence of transit or another mechanism to reduce demand for driving is unlikely. A robust transit network (or another demand reduction mechanism) can reduce driving to a degree that measurable excess capacity could be identified and removed from roadways. This critical relationship is explored more deeply in the next section.

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[6] Tefft, B. C. (2013). Impact speed and a pedestrian’s risk of severe injury or death. *Accident Analysis & Prevention*, 50, 871–878. https://doi.org/10.1016/j.aap.2012.07.022

[7] Aarts, L., & Van Schagen, I. (2006). Driving speed and the risk of road crashes: A review. *Accident Analysis & Prevention*, 38(2), 215–224. https://doi.org/10.1016/j.aap.2005.07.004

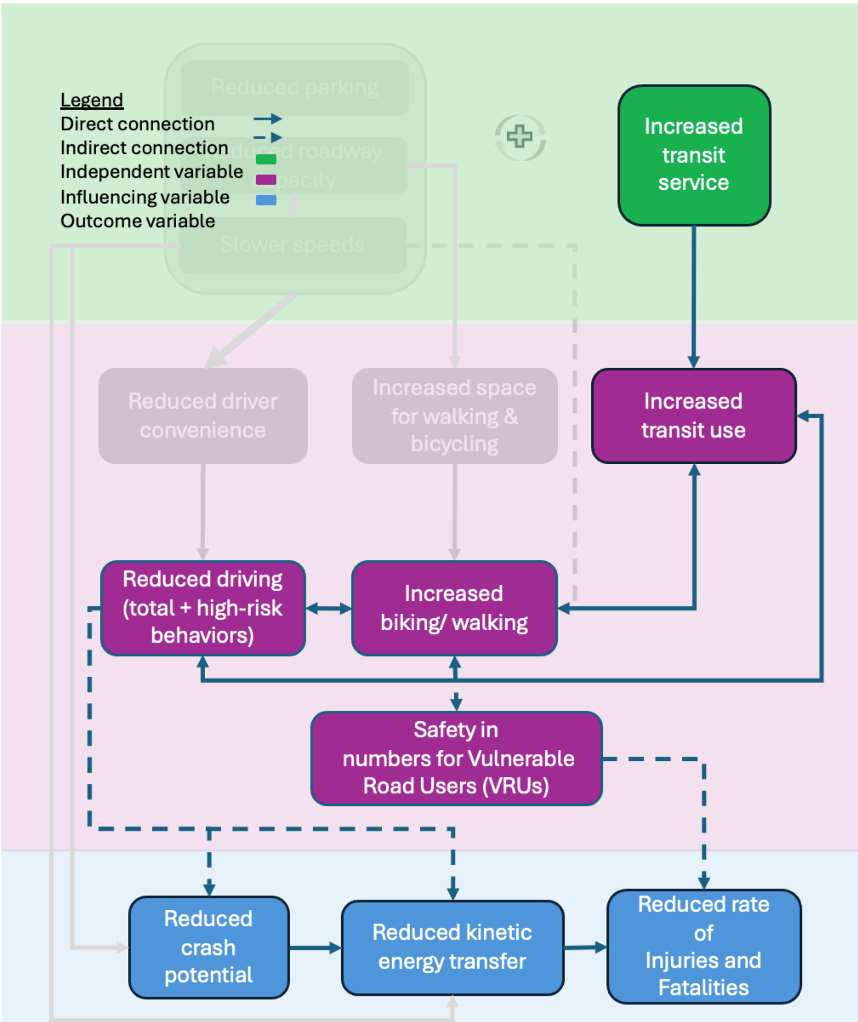

Figure 2. **Pathway 1: Travel Behavior Pathway**

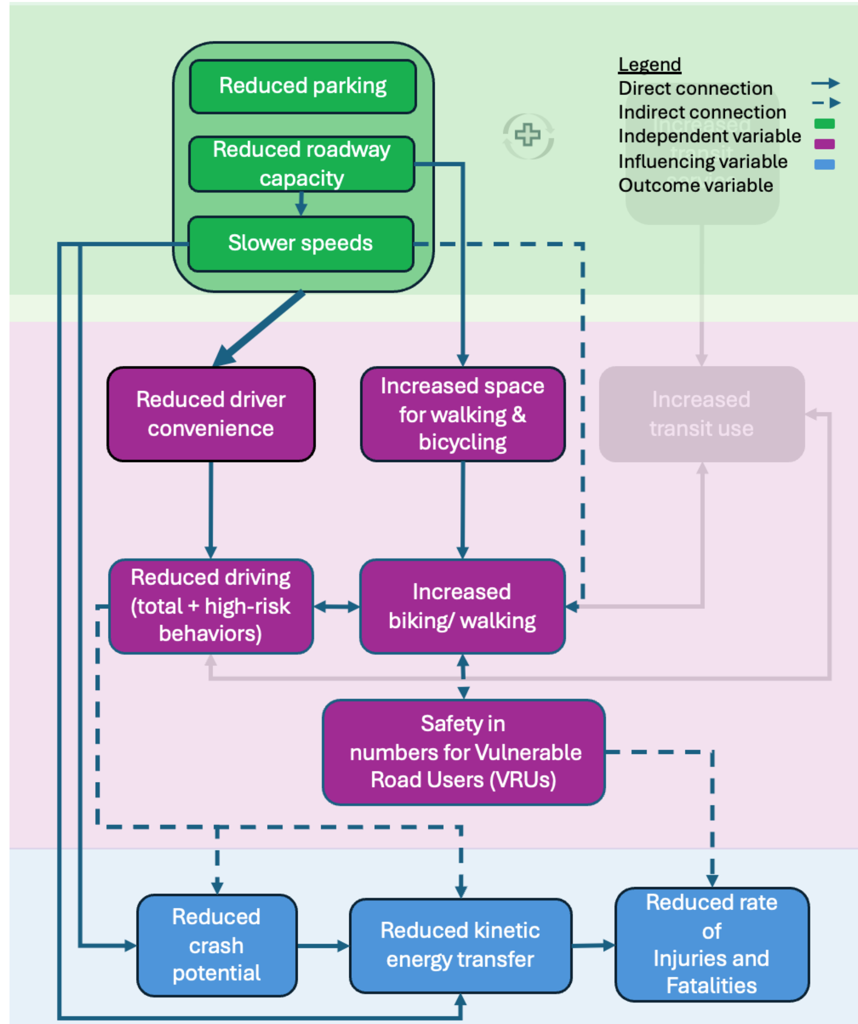

Figure 3. **Pathway 2: Roadway Facility Pathway**

2.5 Travel Behavior Pathway as a Necessary Precursor to Roadway Facility Pathway

Each pathway could, in theory, operate independently from the other. However, the pathways have an amplified effect together (Figure 1) and can create a positive feedback loop: the more mode shift from driving to transit, biking, and walking, the safer the overall transportation system. Further, as previously noted, the Roadway Facility Pathway may be limited by existing roadway usage; engineering warrants and guidelines do not typically recommend lane removal and other significant roadway reconfigurations on very high-volume roads.

Strengthening transit as the core or backbone of the transportation system offers people additional travel options when driving becomes less convenient. Investing in transit and other non-driving modes also provides reliable alternatives for conditions when people should not drive (such as when they are intoxicated, tired, or sick) and makes the system more equitable for people who do not drive due to cost, ability, age, or other barriers.

Transit supports and accommodates potential safety countermeasures that reduce speed, capacity, and driver convenience, which otherwise might be politically infeasible. Roadways are designed for peak hour capacity, but they operate at higher speeds at less congested times of the day. Overbuilding for peak hour needs has led to the system of higher capacity, higher speed arterials that contribute to traffic deaths and injuries. Because robust transit can be particularly helpful in reducing peak hour demand for driving, this potential helps practitioners justify reallocating and repurposing motor vehicle lanes for other modes – a proven safety countermeasure that would not otherwise be available in many cases.

The analyses presented in this white paper provide supporting evidence for various steps along both pathways in the theoretical model using both an analysis of crash history and a scenario planning analysis using BART ridership data. The following sections describe the methodology, results, and implications from the findings.

3 Approach and Methodology

This study used a range of descriptive and geospatial analyses to examine the relationship between transit and traffic safety illustrated in Figure 1.

3.1 Study Area Boundaries and System Definitions

The BART system operates in five counties within the San Francisco Bay Area, California: Alameda, Contra Costa, San Francisco, San Jose, and Santa Clara. These five counties comprise part of the Bay Area's nine-county Metropolitan Planning Organization (MPO), the Metropolitan Transportation Commission. Since this study is focused exclusively on BART, the study area includes only the five counties in which BART operates. Throughout this white paper, references to the region or study area mean these five counties, not the larger MPO nine-county area.

The BART system serves travel between 50 stations across this five-county region. The same origins and destinations are also served by a system of freeways, arterial and collector roadways, and local streets. To understand the effect of the BART system on regional safety, the research team identified a portion of the roadway network that operates in parallel to BART; in other words, portions of the region's roads that serve the same 50 station areas (origins and destinations) as BART. The rest of this methodology section is built around drawing comparisons between the roadway network that operates in parallel to BART and the rest of the roads in the region. The definition of the parallel network is explained in Section 3.4.

3.2 General Approach

To explore whether improving transit levels of service and reliability of the BART improve roadway safety via the two theoretical pathways (Travel Behavior and Roadway Facility), this white paper utilizes three analyses:

1. **Are roads serving the same BART trips less safe?: a comparative analysis of crash patterns and systemic risk factors between the Parallel System and the rest of the roadways in the study area.** This analysis explores crash frequency, severity, and roadway facility characteristics to understand whether the roadway network serving the same trips as BART has more or fewer severe crashes. If the Parallel System is comparatively more dangerous than the rest of the roadway system in the study area, improving transit levels of service and reliability on BART could offer a proven safer option for travel. The analysis also explores whether streets on the parallel network are qualitatively different than streets in the rest of the region, based on the roadways' operational, geometric, and land use characteristics.
2. **Have changes in BART services affected roadway safety?: an assessment of the effects of two BART system closures and an expansion scenario.** This analysis explores whether changes in BART service were correlated with changes in traffic safety outcomes on the roadways that also serve BART trips. The first part of this analysis examines the roadway safety impact of two BART closures for worker strikes in 2013. The second part of this analysis investigates whether the expansion of BART service – such as the 2014 Oakland Airport Connector or the 2020 Silicon Valley Phase I extension - changed traffic safety outcomes on the roadways parallel to BART.
3. **What could the impact on traffic safety be if road diets and increased BART service were implemented in tandem?: an evaluation of road diet opportunities based on potential BART service increases and ridership growth.** This analysis focuses on the potential for a single proven safety countermeasure (road diets) ability, when paired with growth in BART ridership, to change traffic safety outcomes. This analysis identifies candidate facilities in the region that appear eligible for a roadway reallocation from 4 or more through lanes to 2 through lanes and estimates potential traffic safety impacts based on BART ridership growth and mode shift scenarios. Freeways were excluded in these scenarios because roadway reallocation research and guidance focus on non-freeway facilities.

3.3 Data Sources

Traffic safety data were retrieved from UC Berkeley's Transportation Injury Mapping System (TIMS). The TIMS database does not include crashes in which no one was hurt (i.e., property damage only crashes). Data were retrieved for the years 2012 to 2023, spanning the range of

BART service changes being investigated through this research. At the time of retrieval, in May 2024, data for 2022 and 2023 were still considered provisional.

Roadway network data came from a mix of OpenStreetMap[8] (exported in May 2024) and the Highway Performance Monitoring System (data year 2022). Roadway volume data came from a mix of the Highway Performance Monitoring System (data year 2022) and segment-level trip count data from Replica (Wednesday trips from Fall 2023). Roadway data were combined using OpenStreetMap linking IDs and geospatial conflation. Geospatial processing was used to handle divided roads represented by two parallel features (called “dual carriageways”).

The research team and BART staff considered multiple scenarios for the various analyses described in Section 3.2. Upon finalization of the scenarios, BART staff provided ridership data from their ridership model and historic datasets for three years: 2023, 2019, and 2013.The years 2023 and 2019 were selected because they were the bookend years for the five most recent years of crash data available in the region. 2023 represented a new post-pandemic baseline year given the ridership and operational trends observed. Likewise, 2019 represented a typical pre-pandemic year. 2013 was the year of the BART strikes that were evaluated later in the analysis. The analyses used average midweek total daily travel (Tuesday, Wednesday, and Thursday) for all origin-destination pairs from 2019 and 2023.

Analyses were completed using a mix of Python, PostgreSQL/PostGIS (with pgRouting library), and R/RStudio.

3.4 Definition of BART’s Parallel Network and System

Between 1957 and 1962, engineering plans were developed for the BART system that would usher in a new era in rapid transit and reduce congestion in several high speed/high volume routes parallel to the proposed system. Fast forwarding to the present, many of the trips that people in the study area make can be made by two “parallel” systems. On one hand, BART connects origins and destinations near 50 BART stations to each other. On the other hand, a portion of the roadway network *also* serves trips that start and end near BART stations. Some of these roads and freeways run immediately parallel to the BART track alignments, such as portions of the Yellow Line that run along the median of California State Route 24 in Contra Costa County. The rest of these roads can also be thought of as serving “parallel” trips because the desire lines of the trips are the same, even if the alignments are not physically parallel, such as driving across the San Mateo-Hayward Bridge instead of taking BART to access the San Francisco International Airport. For this reason, this paper describe the collection of roads that

[8] OSM ways and nodes were extracted for the five counties in the region using the OSMnx Python package. OSMnx provides OSM data in routable data structure. For more information, please see Geoff Boeing’s white paper “Modeling and Analyzing Urban Networks and Amenities with OSMnx” https://geoffboeing.com/publications/osmnx-paper/. Tool documentation can be viewed here: https://osmnx.readthedocs.io/en/stable/

serve the same trips as BART as the "Parallel System" whether they are physically parallel or not.[9] The BART system map, with additional details for connecting rail, is shown in Figure 4.

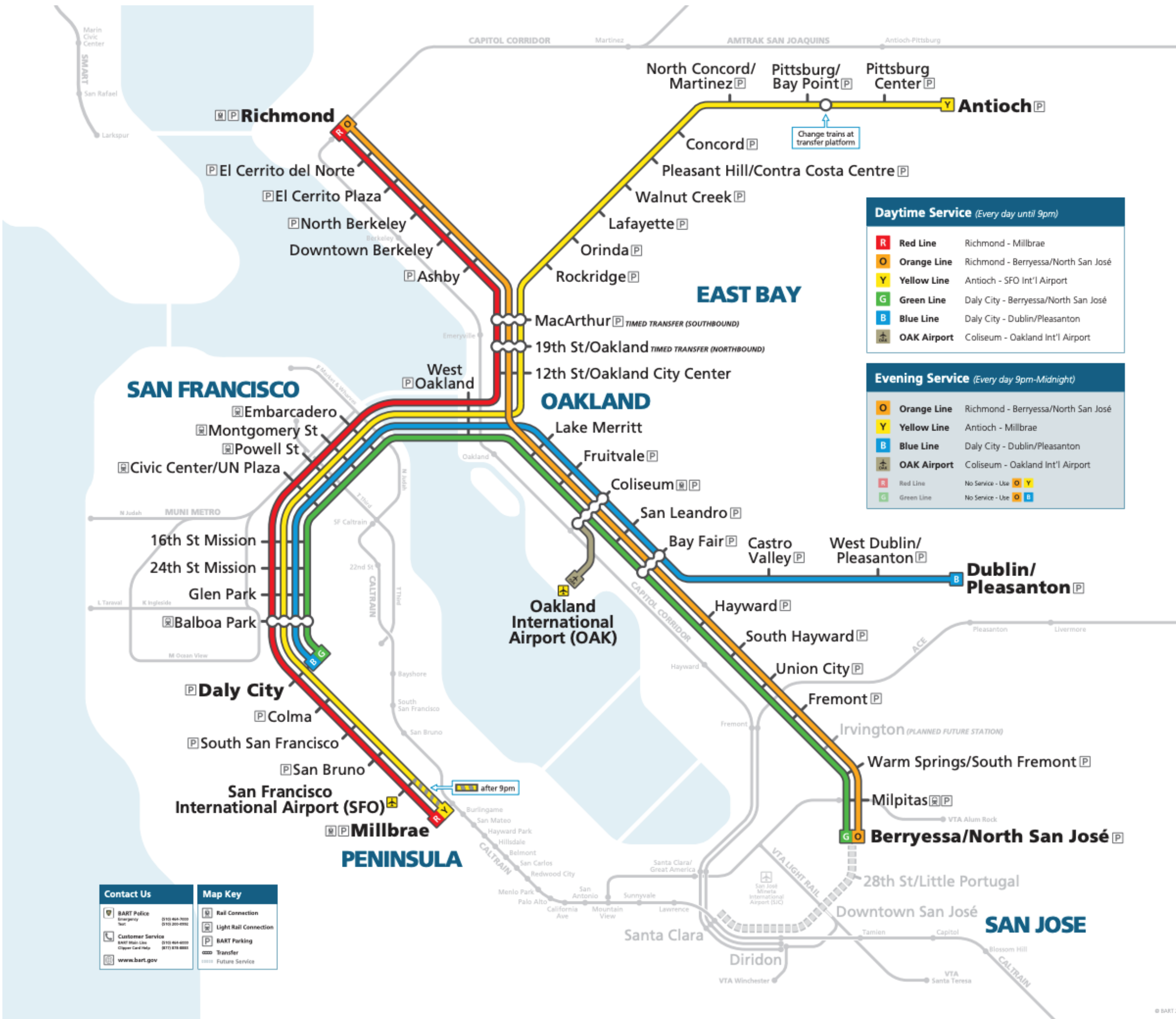

Figure 4. A detailed version of the BART system map showing connecting rail[10].

The first analysis aims to understand if and how crashes along the Parallel System network differ from crashes along the remainder of the regional roadway system to determine if improvements in BART transit system service could result in improving the Parallel System roadway safety. The third analysis delves more deeply into how changes in BART ridership and motorist traffic

[9] Although we describe this collection of roads as the "BART Parallel System", BART has no ownership over the facilities included in this system. The name refers to the fact that the system serves parallel trips to those that BART serves.

[10] https://www.bart.gov/system-map

volume along the Parallel System can shape the range of safety countermeasure opportunities available.

To define the parallel BART roadway network, the research team used geospatial analysis and BART's origin-destination data. BART's 50 stations serve 2,450 unique origin-destination pairs (excluding pairs that start and end at the same station and including both forward and reverse journeys for each station-pair). The analysis focused exclusively on BART trips starting and ending at or near BART stations and did not consider the broader impact of transfers between BART and other transit providers to expand the Parallel System.

A routing analysis was completed using an open-source network routing function based on Dijkstra's algorithm[11] to measure a set of six potential candidate routes that one might drive for each origin-destination pair under varying travel speed scenarios that approximate congested and uncongested conditions. The set of 14,700 routes included 15,288 unique network segments. The routes were visually reviewed for reasonableness (i.e., travel time, toll prices, etc.). Ninety-four routes (about 0.6% of the dataset) were removed due to being unreasonable (for example, detouring through the small island city of Alameda with very slow streets to travel from the Oakland Airport to the West Oakland BART station).

This routing analysis resulted in the identification of a "Primary Parallel (Roadway) Network" that serves the same origins and destinations as BART. BART ridership data were allocated among these routes based on the origin-destination pairs served. For each origin-destination pair, the average midweek daily ridership was allocated equally across all five or six routes that were generated to serve that pair. This allocation allowed the research team to make direct comparisons between traffic volumes using those streets and the number of BART riders who might be using those streets if they were driving instead.

Route choice is complex, and people use the BART system to travel to many locations near but not precisely at each of the 50 BART stations. To account for this unmeasured variation in travel behavior, a second version of the Parallel System (Secondary Parallel Network) was generated by buffering all the segments in the Primary Parallel Network by ¼ mile. Network-based Station Study Areas around each BART station were also included in this second version of the Parallel System. The size of these Station Study Areas was estimated using data from BART's Station Access Typology and Station Profile Study, reflecting the typical distances that people travel to access the various BART stations. This expanded version is described as the "Secondary Parallel Route Network." When the more general phase "Parallel System" is used without specifying whether Routed or Buffered, the text is referring to the general concept of a Parallel Roadway System serving trips that could also be made by BART or to analyses that are repeated for both the Primary Parallel Network and the Secondary Parallel Route Network.

These two versions of the Parallel System led to a set of three spatial units for analysis, as listed in Table 1. The rest of the five-county study area that is not part of the Primary or Secondary Parallel Route Network is described as the "Rest of Region" or "Non-Parallel System".

[11] pgRouting https://pgrouting.org/, pgr_dijkstra.

Table 1. Spatial Units of Analysis Based on Road Network that Operates Parallel to BART's Stations.

Geography Name	Definition	Analysis Purpose
Primary Parallel Route Network	Set of 5 to 6 routes people might take to travel between each origin-destination pair on the BART system	Any analysis that depends on comparing the roadway attributes and/or ridership data associated with the segments most likely driven when people do not use BART.
Secondary Parallel Route Network	Quarter-mile buffer around all of the origin-destination routes in the Primary Parallel Network plus Station Study Areas. *Primary Parallel Route Network is* also *contained within the Secondary Parallel Route Network*.	Any analysis comparing the segments potentially driven when people do not use BART; may rely on roadway attributes but not ridership data.
Rest of Region or Non-Parallel System	All streets within the five-county study area that have not been identified as part of the Primary Parallel Network or the Secondary Parallel Route Network.	Comparison group for analyses that use the Primary Parallel Network or Secondary Parallel Route Network.

The Primary Parallel Network and Secondary Parallel Route Network are shown in the maps in Figure 5 (whole region) and Figure 6 (zoomed view), respectively. All segments of the Primary Parallel Network are *also* part of the Secondary Parallel Route Network. Additional segments in the Secondary Parallel Route Network are represented in blue. Due to data restrictions, some of the analyses performed in this study only had data available for the Primary Network, whereas some could be completed for the entire Secondary Network including Station Study Areas.

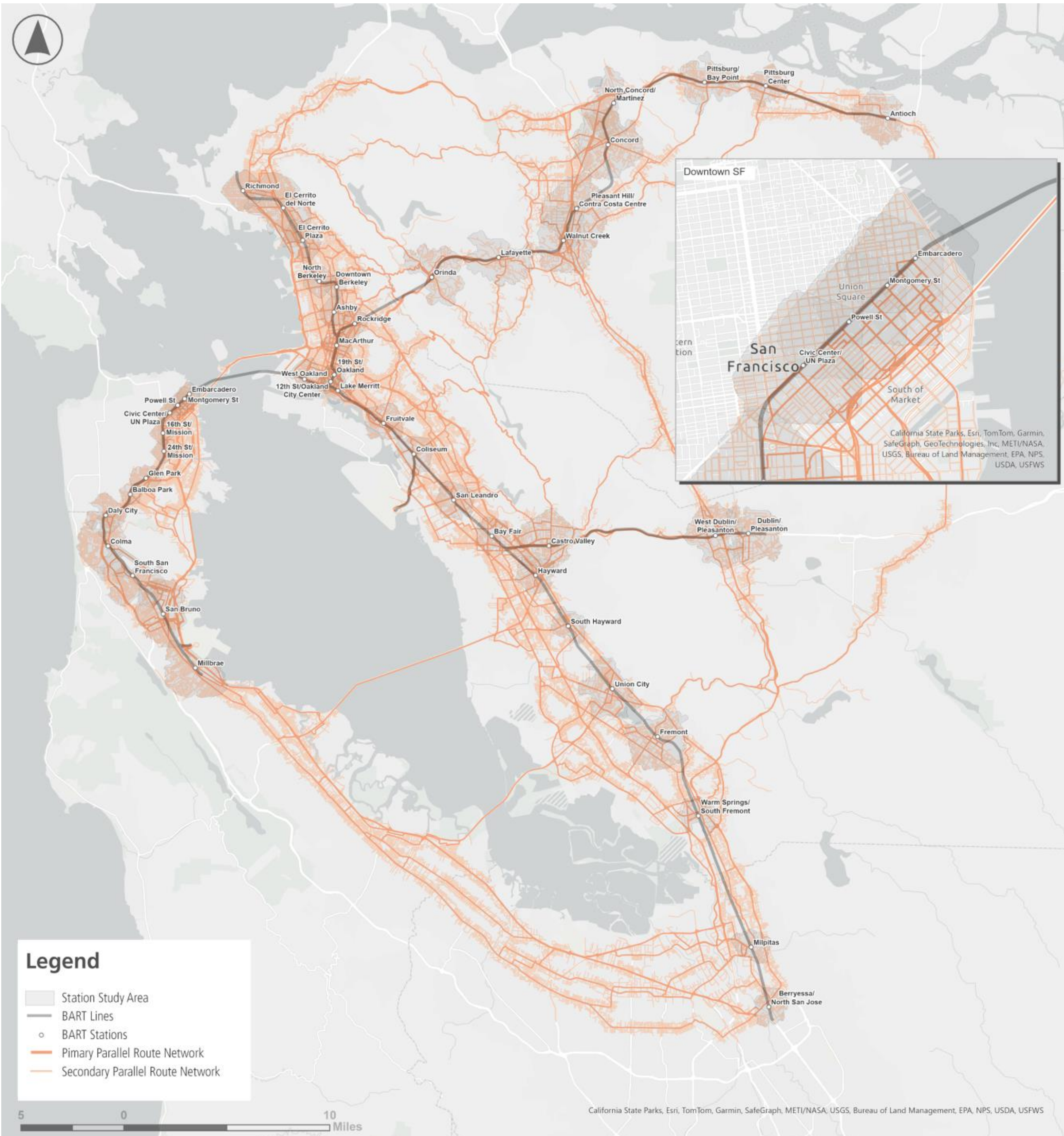

Figure 5. Map of the Primary Parallel Network Serving Trips Parallel to the BART System.

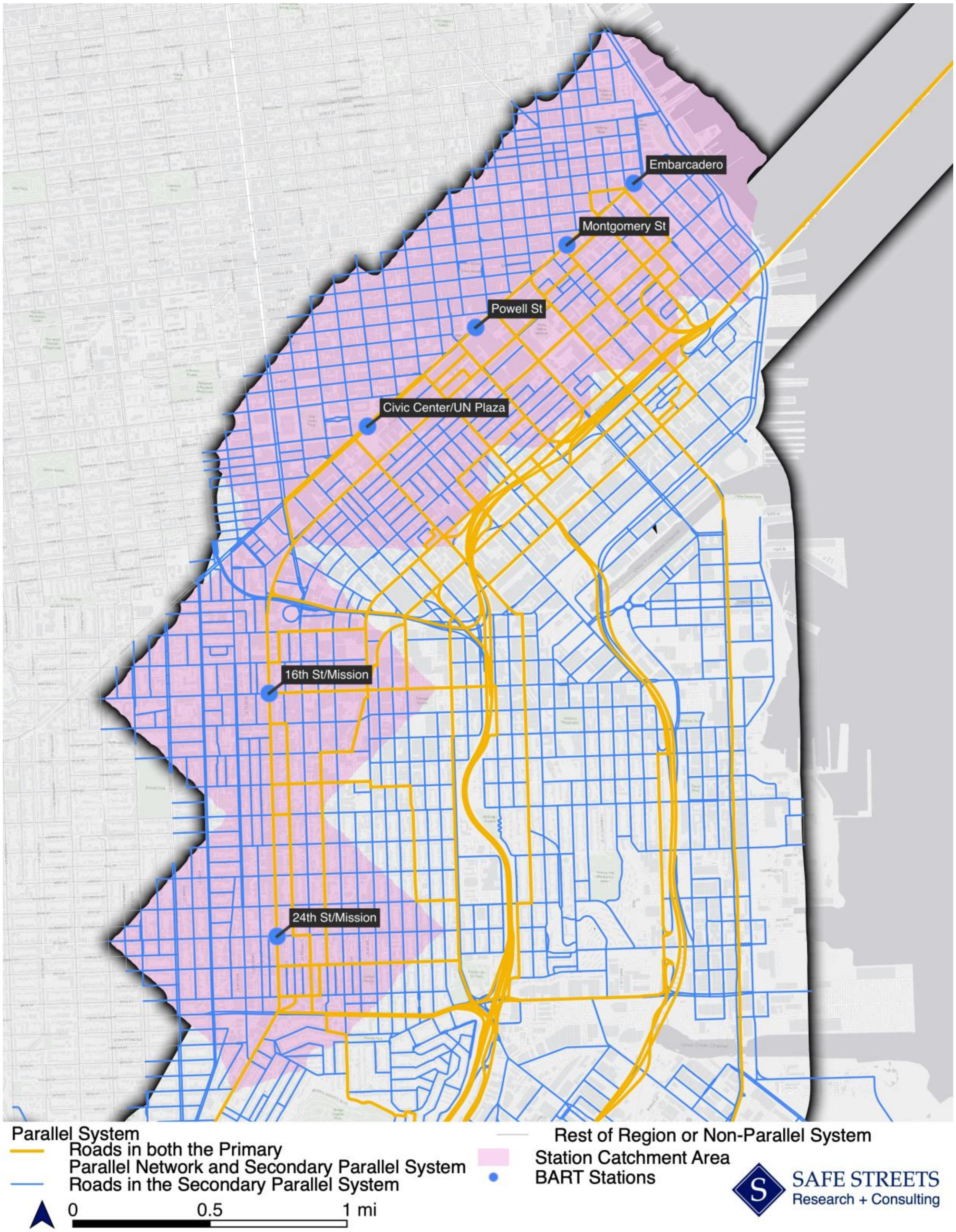

Figure 6. Area Map of the Primary and Secondary Parallel Route Network Serving Trips Parallel to the BART System for Selected San Francisco BART stations.

Primary and Secondary Parallel Route Networks were created for three different versions of the BART network: (1) the present-day 2023 BART system with 50 stations, (2) the system as it existed in 2019 with 48 stations, and (3) the system as it existed in 2013 with 44 stations. These three snapshots represent different stages in the BART system's growth. Most of the analysis used the present-day 2023 versions of the Primary and Secondary Parallel Route Networks. The 2019 and 2013 versions were used to evaluate changes in safety conditions as the BART network evolved over time and analyze historic scenarios.

We tested using Primary and Secondary Parallel Route Networks that included the whole system (all 2,450 origin-destination pairs) as well as a "top 50th percentile" system that included the top 50th percentile OD pairs (covering about 93% of all BART trips) and the top 50th percentile of segments by routed ridership. The analysis results for the whole system and for the top 50th percentile subset of the system were very similar, so only the analysis results for the whole system are presented here.

3.5 Methodology for Comparing Crash Patterns and Systemic Risk On and Off the Parallel Network

This analysis focused on observed crash patterns in the region to see if BART facilities or service explain spatial variation in the prevalence, proportion, severity, types, contributing factors, or systemic risk factors of crashes between the Parallel Networks and the rest of the region. Standard descriptive crash variables and systemic roadway variables were included, stratified by Parallel Network status (Primary Parallel Route Network, Secondary Parallel Route Network, or rest of the region). The variables included were crash frequency, severity, modal involvement, lighting, time of day, contributing factors (intoxication), speed limit, number of through lanes, and motorist volume (AADT).

The questions this analysis aimed to address include:

- Does the Parallel Network perform better or worse than the rest of the streets in the region, in terms of crash frequency, severity, and density?
  - Hypothesis: BART serves higher-density, higher-activity areas, which may be more crash prone. Crash severity patterns may vary by time of day and prevailing congestion patterns, which constrain speeds and may reduce severity.
- Are the streets on the Parallel Network measurably different from streets in the rest of the region?
  - Hypothesis: BART serves high-demand origin-destination pairs. Streets serving the same trips may be wider, faster, and higher volume than other streets in the region. Many of the region's major freeways are likely captured on the Parallel System.

For each variable, the research team considered a suite of safety-related metrics:

1. Number and percentage of crashes happening on and off the Parallel Network,
2. Number and percentage of *severe* crashes happening on and off the Parallel Network,
3. Percentage of crashes that result in a severe outcome,
4. Density of crashes per 100 miles of roadway facilities on and off the Parallel Network, and

5. Density of *severe* crashes per 100 miles of roadway facilities on and off the Parallel Network.

Simple comparisons were made on these metrics. Statistical tests were not performed due to the non-random nature of the sample.

3.6 Methodology for Assessing the Effects of BART System Closures and System Expansions on Crash Patterns

This analysis focused on observed crash outcomes in the region around two naturally occurring experiments in BART's recent history. An experiment is a study in which the researchers can change an independent variable in a randomly selected group of subjects to measure the effect on an outcome of interest, and compare the effect to a group that did not experience the change. A *natural* experiment is one in which the change is not randomly assigned by a researcher, but instead caused by human or natural causes.

The BART strike can be thought of as a natural experiment because unrelated factors (i.e., the operator strike) caused BART service to change significantly and abruptly for a short duration (until the strike was resolved). BART system expansion can also be thought of in this sense, because service increases were rolled out over time to different parts of the region based on policy decisions.

These cases were selected for their sizeable impact on transportation in the region – and even still suffer from small sample size challenges that limit our ability to draw inferences. For this reason, more subtle service changes such as 2020 COVID-19 Pandemic-related service reductions or the reversal of those reductions were not considered as additional natural experiments.

3.6.1 Natural Experiment 1 – BART System Closures for Operator Strikes in 2013

In 2013, two labor strikes resulted in BART service being closed for a period of 4 to 5 days. The analysis compared whether a higher or lower than average frequency of severe crashes occurred on strike days as compared to non-strike days. Days were matched by weekday/weekend status and month of the year for the years 2012 to 2014. For both strike days and matched non-strike days, the average number of severe crashes per day was calculated and compared. This analysis was not stratified by either the Primary Parallel Route Network or the Secondary Parallel Route Network due to very small sample size.

3.6.2 Natural Experiment 2 – BART System Expansion Over Time

The BART system was significantly expanded over the 2010s, adding the Oakland Airport Connector in 2014, the Warm Springs extension in 2017, the eBART connections to Pittsburg Center and Antioch stations in 2018, and the Silicon Valley Phase I extension in 2020 (Milpitas and Berryessa/North San Jose stations). This analysis explored whether the Parallel System adjacent to the various expanded routes had different severe crash frequencies than the core part of the system that existed prior to 2013.

The BART system was grouped into three sections based on the waves of station openings: (1) the core part of the system that was open prior to 2016, expansion portions that opened between 2017 and 2019, and expansion portions that opened from 2020 onward. The Secondary Parallel

Route Network was split into three to align with these sections. The rate of severe crashes per year was measured within each of these sections of the Secondary Parallel Route Network over three time periods: 2012 to 2016, 2017 to 2020, and 2021 to 2023. The absolute and percentage difference in annual severe crash rates between the 2021 to 2023 period and the 2012 to 2016 period were calculated. These measures show how fast the annual rate of severe crashes grew on the three sections of the Secondary Parallel Route Network.

3.7 Methodology for Evaluating the Effects of BART Service and Ridership on Potential Countermeasure Opportunities

Road diets, or roadway reallocations, are one of the most effective countermeasures for reducing driver speeds, reducing severe conflicts, and creating additional space for people walking, biking, and rolling (e.g., adding bike lanes or shared use paths in the excess space from removed motor vehicle travel lanes). Figure 1 and the two pathways shown in Figure 2 and Figure 3 illustrate how shifting travel from roadways to BART might create opportunities to implement roadway reallocations. This analysis explores the potential for roadway reallocation countermeasures under existing conditions in the region as well as under four hypothetical scenarios of mode shift from driving to BART.

This analysis defined potential roadway reallocation candidates based on the following set of criteria:

- The existing number of through lanes is equal or greater than 4
- The functional class is not motorway/freeway or path
- The existing traffic volume is less than 15,000 to 20,000 vehicles per day[12]

The analysis then overlaid existing roadway data with the Primary Parallel (Roadway) Network described in Section 3.4 to flag facilities that either (1) already met the criteria to be a roadway reallocation candidate (these are the existing roadway reallocation candidates based on current volumes and number of lanes) or (2) would, in theory, meet the criteria to be a roadway reallocation candidate under various scenarios of BART service increases that offset existing traffic volume through mode shift (future roadway reallocation candidates). The existing roadway reallocation candidates are the roadway facilities with 4 or more through lanes that currently have volumes less than 15,000 to 20,000 vehicles per day. Future roadway reallocation candidates are identified as roads with 4 or more through lanes and volumes that would fall below 15,000 or 20,000 vehicles per day under various mode shift (volume reduction) scenarios. The volume reduction scenarios are expressed in terms of BART ridership growth relative to a baseline of 2023 existing midweek ridership. Future candidates can only be identified along the Primary Parallel Network because the analysis requires both traffic volume data and ridership data that have been allocated to the network. While traffic volume data are widely available, allocated ridership data are, by definition, only available for the Primary Parallel Network.

[12] FHWA-SA-17-021 describes streets with AADT in the 10,000 to 15,000 range as "good candidate[s] in many instances" and streets with AADT in the 15,000 to 20,000 range as "good candidates(s) in some instances." https://safety.fhwa.dot.gov/road_diets/resources/pdf/fhwasa17021.pdf

Freeways/motorways, which represent 38% of the Primary Parallel Network, were excluded in this section of the analysis because roadway reallocation research and guidance focus on non-freeway facilities (e.g., NCHRP 1036 Guide to Roadway Cross Sectional Reallocation). Nonetheless, freeway reduction or removal could be studied as appropriate countermeasures for parts of the BART Parallel System in future work.

The volume scenario measures included the following:

Table 2. Traffic Volume and BART Ridership Calculations under Existing Conditions and Four Ridership Growth Scenarios

BART Ridership Scenario	Traffic Volume	BART Ridership	Study Area
Existing Conditions	Volume Baseline (As reported from the Highway Performance Monitoring System (HPMS) and Replica, dates ranging 2021-2023)	Ridership Baseline (2023 average midweek daily ridership allocated to Primary Parallel Network; assumed to be zero off the Primary Parallel Network)	Entire five-county region
25% BART Ridership Growth	Volume Baseline MINUS 25% of Ridership Baseline	Ridership Baseline + 25%	Primary Parallel Network only
50% BART Ridership Growth	Volume Baseline MINUS 50% of Ridership Baseline	Ridership Baseline + 50%	Primary Parallel Network only
100% BART Ridership Growth	Volume Baseline MINUS 100% of Ridership Baseline	Ridership Baseline + 100%	Primary Parallel Network only
Return to 2019 Pre-Pandemic BART Ridership Levels	Volume Baseline MINUS (Difference between Ridership Baseline and 2019 average midweek daily ridership)	2019 Average midweek daily ridership	Primary Parallel Network only

While there are many safety countermeasures, roadway reallocation has stood the test of time as a proven countermeasure for more than three decades due to improving safety for all road users as well as its low cost and ease of implementation. Furthermore, screening for candidate locations is relatively straightforward, requiring only traffic information and the number of lanes, both of which are routinely collected. The scenario planning exercise of countermeasure opportunities in Section 2 (Approach and Methodology) discusses how candidate locations for roadway reallocation were selected in the BART region.

4 Results

4.1 Summary of BART's parallel roadway system

Figure 5 and Figure 6 show what the Primary and Secondary Parallel Route Networks look like mapped in the five-county region in which BART operates. The region contains approximately 17,800 miles of roadway facility. Of these, Table 3 shows that about 7,241 of these miles (41%) fall within BART's parallel network system, with 1,796 miles (10%) falling along the actual Primary Parallel Network segments. The remaining 10,585 miles fall outside of the Parallel System (rest of region or non-Parallel System).

About 60% of the five-county region's fatal and serious injury (KSI) crashes happen in the Secondary Parallel Route Network. Forty-three percent of KSI crashes happen on the 10% of network miles that comprise the Primary Parallel Network. The Secondary Parallel Route Network, and especially the Primary Parallel Network, have the highest density of KSI crashes per 100 miles in the region (50 and 145, respectively). These numbers speak to a disproportionate concentration of severe crashes along streets and freeways that serve the same origins and destinations as BART. In other words, people who drive or ride in passenger vehicles[13] instead of riding BART are exposed to a higher-than-average risk of severe crashes.

Table 3. Summary of Regional Network Miles by Primary and Secondary Parallel Route Network status.

Parallel Network Status	Number of Miles	Percentage of Miles	Number of KSI Crashes	Percentage of KSI Crashes	KSI Crashes per 100 Miles
Primary Parallel Network (subset of Secondary Parallel Network)	1,796	10%	2,608	43%	145
Secondary Parallel Network (includes the Primary Parallel Network)	7,241	41%	3,644	60%	50
Rest of Region or Non-Parallel Network	10,585	59%	2,383	40%	23
Regional Total	**17,826**	**100%**	**6,027**	**100%**	**34**

4.2 Results from Comparing Crash Patterns and Systemic Risk On and Off the Parallel System

This section examined crash patterns on BART's Primary and Secondary Parallel Route Networks compared to the rest of the region, off the Parallel Network. Most analyses were performed for both the Primary and Secondary Parallel Route Networks. Collectively, when results on the two versions of the system agreed, they are referred to simply as the "Parallel

[13] Other modes of travel were not considered in this analysis.

Systems". Crash patterns on and off the Parallel Networks differ from patterns off of the Parallel Networks in the rest of the region in several ways:

- Crashes are more numerous and more severe on the Parallel Networks than in the rest of the region.
- Off-peak crashes are more severe than peak-hour crashes in general, but the difference is more stark on the Parallel Networks than the rest of the region, suggesting the potential impacts of an overbuilt commuting roadway system that relies on congestion during the day to manage speed but operates at higher speeds at night.
- Motorists are overrepresented among crashes on the Parallel Networks, likely due to the proportion of the Parallel Networks that are restricted access freeway versus the rest of the region.
- Driving under the influence (DUI) is an important risk factor for severe crashes; DUI is slightly more common on the Parallel Systems than off of them.

The facilities on the Parallel Networks also differ from the rest of the region in many ways.

- The Secondary Parallel Route Network and, even more so, the Primary Parallel Route Network are composed of a larger proportion of freeways and arterial roadways, while the Non-Parallel Network has relatively more collectors and local streets.
- Streets on the Parallel Networks tend to be faster, wider, and carry higher volumes than other streets in the region.

These roadway facility patterns (higher functional class, higher speed, more lanes, and higher volumes) tend to be associated with more severe and total crashes in general, so these patterns may explain the overrepresentation of crashes on both the Primary and Secondary Parallel Route Networks.

4.2.1 Crash Patterns

In general, there were more crashes and more severe crashes on both the Primary and Secondary Parallel Route Networks than in the rest of the region. However, the severity rate (i.e., the percentage of crashes that results in a severe outcome) was slightly lower on the Secondary Parallel Route Network than off of it, (9% vs. 11%), as shown in the total row Table 4.

Table 4 also shows that both the relative frequency of severe crashes and the severity rate of all crashes varies considerably by time of day. In general, crashes tend to be more severe in darkness. There are relatively more severe crashes and a higher severity rate on the Secondary Parallel Route Network during late night hours, especially 12:00 to 5:59 AM, during most of which the only realistic option to travel is through the Parallel Network (because BART is generally not in operation between 1:00 to 5:00 AM on weekdays). About 22% of severe crashes on the Secondary Parallel Route Network happen between these hours, compared to only about 14% of severe crashes off the Parallel Network in the same timeframe. Additionally, the severity rate at this time of night is higher on the Secondary Parallel Route Network than off of it, despite being lower throughout the rest of the day. This pattern suggests that streets in the Parallel Network may see relatively higher driving speeds under uncongested conditions when BART is not operating.

These patterns are shown in Table 4 and Figure 7 for on and off Secondary Parallel Route Network only, though very similar results were observed for crash patterns when examining the Primary Parallel Route Network.

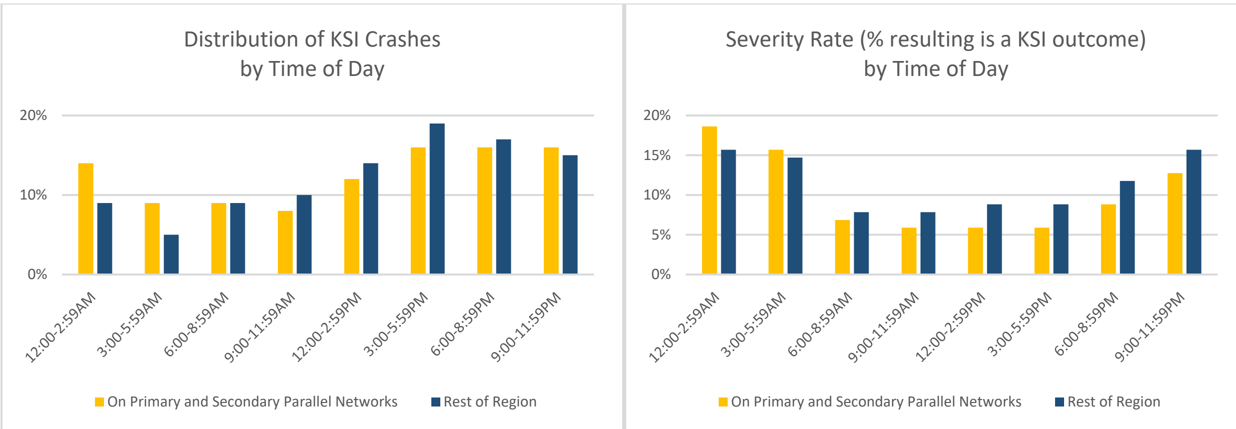

Figure 7. Distribution of KSI Crashes and Severity Rate On and Off the Secondary Parallel Route Network by Time of Day.

Table 4. Distribution of Severe Crashes and Severity Rate by Time of Day.

Time of Day	Percent of all Severe Crashes, by Time of Day			Severity rate (Percent resulting in severe outcome), by Time of Day		
	Percentage on Secondary Parallel Network	Percentage Rest of Region	Ratio Pct On / Pct Off	Percentage on Secondary Parallel Network	Percentage Rest of Region	Ratio Pct On / Pct Off
12:00-2:59AM	14%	9%	1.5	19%	16%	1.2
3:00-5:59AM	9%	5%	1.7	16%	15%	1.1
6:00-8:59AM	9%	9%	1.0	7%	8%	0.8
9:00-11:59AM	8%	10%	0.8	6%	8%	0.7
12:00-2:59PM	12%	14%	0.9	6%	9%	0.8
3:00-5:59PM	16%	19%	0.8	6%	9%	0.7
6:00-8:59PM	16%	17%	1.0	9%	12%	0.8
9:00-11:59PM	16%	15%	1.0	13%	16%	0.8
unknown	0%	1%	0.6	16%	30%	0.5
Total	100%	100%	1.0	9%	11%	0.8

An analysis of the crash report contributing factors variables showed that crashes involving drugs or alcohol are typically more severe than average, with about 18-21% of crashes involving driving/bicycling under the influence (DUI/BUI) resulting in a death or serious injury. The severity percentage for DUI crashes is highest on the Primary Parallel Route Network (21%), followed by the Secondary Parallel Route Network (19%) and rest of the region (18%). Conversely, the severity percentage for non-DUI crashes is higher off the Parallel System (10%) than on either the Primary Parallel Route Network or Secondary Parallel Route Network (8%). Crashes with a DUI/BUI violation are slightly more common on the Primary Parallel Route Network (17%) and Secondary Parallel Route Network (16%) than off of it (13%).

Crashes off the Secondary Parallel Route Network were slightly more likely to have a citation for unsafe speeds (24% vs. 23%), which may relate to the higher posted speeds of the Parallel Network on average (and therefore less opportunity to exceed the speed limit). These unsafe speed crashes were slightly more likely to result in death or serious injury off the Secondary Parallel Route Network than on it (8% vs. 6%). Results on the Primary Parallel Route Network were nearly identical to those on the Secondary Parallel Route Network.

4.2.2 Facility Patterns

Roadway functional classification (or roadway type) describes the intended purpose of the road, from local or residential streets serving primarily local access to freeways serving through traffic. Arterial roadways are facilities that typically serve a mix of local access and through movements. They tend to be designed for higher speeds despite having destinations that people may want or need to walk to.

As one might expect, the Primary and Secondary Parallel Route Networks contain a very different mix of roadway types than the rest of the region (see Table 5 and Figure 8). Unlike the previously described crash patterns, these facility patterns also differed *between* the Primary Parallel Route Network and the Secondary Parallel Route Network. The Primary Parallel Route Network is composed primarily of freeways (38%) and arterials (47%), despite these two functional classes combined only comprising about 30% of the entire five-county region's roadways at large. The Secondary Parallel Route Network (of which the Primary Parallel Route Network is part) is about 40% freeway and arterial, 15% collector, and 45% local. By contrast, the rest of the region (Non-Parallel System) is about 23% freeway and arterial, 22% collector, and 55% local.

Not only are the mileage totals and relative percentages different, but crash densities are highest on the Primary Parallel Route Network and elevated on the Secondary Parallel Route Network than off of it, regardless of functional class. Freeways experience about 44 severe crashes per 100 miles per year on the Secondary Parallel Route Network. Freeway segments outside the Parallel System only have 26 severe crashes per 100 miles. Arterials also show a major difference, with 29 KSI crashes per year per mile on the Secondary Parallel Route Network versus 18 off the Parallel System. Local streets, which usually have very low volumes and crash densities, have a KSI crash density over five times larger on the Primary Parallel Route Network (11 per year per mile) than off the Parallel Network (2 per year per mile), and the density is also substantially higher than the Secondary Parallel Route Network (3 per year per mile).

These statistics speak to a much higher-intensity roadway system operating in parallel to BART on both the Primary and Secondary Parallel Route Networks. This pattern is expected; BART and the roadway system were both designed to carry traffic to and from important regional destinations and serve commuting trips. When using a routing algorithm to assess the most likely streets people would drive on, the algorithm preferentially selected faster routes – which tend to be freeways and arterials. Nonetheless, this finding shows a pattern of higher-risk facilities operating as the region's backbone for travel.

Table 5. Miles and Severe Crash Density by Network Status and Functional Class.

Functional Class	Primary Parallel Network		Secondary Parallel Network		Rest of Region (Non-Parallel Network)		Entire Region[14]	
	Number of Miles	**KSI Crashes per Year per 100 Miles**	**Number of Miles**	**KSI Crashes per Year per 100 Miles**	**# Miles**	**KSI Crashes per Year per 100 Miles**	**Number of Miles**	**KSI Crashes per Year per 100 Miles**
Freeway	677	64	1,088	44	538	26	1,627	38
Arterial	850	46	1,843	29	1,947	18	3,790	23
Collector	202	21	1,062	11	2,285	8	3,348	9
Local	67	11	3,247	3	5,814	2	9,061	2
Total	**1,796**	**48**	**7,241**	**17**	**10,585**	**7**	**17,826**	**11**

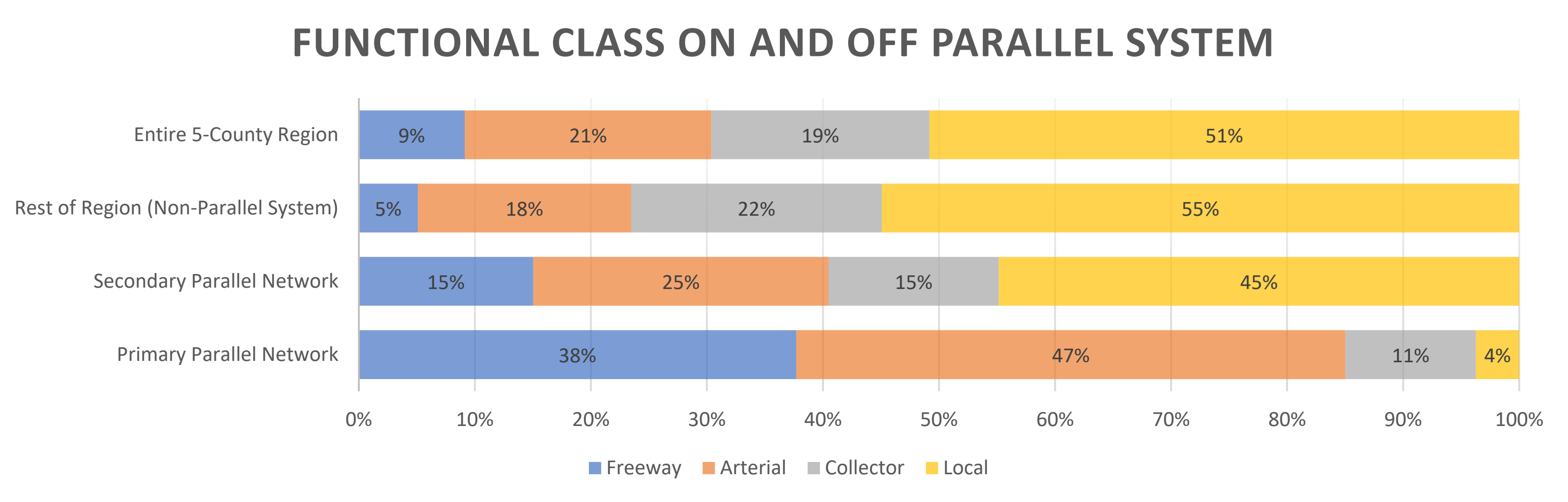

Figure 8. Percentage of roadway miles by functional class and Parallel System status.

[14] The Primary, Secondary, And Non-Parallel Network mileage column do not sum to the entire region's mileage because the Primary Parallel Network's facilities are *also* included in the Secondary Parallel Route Network.

Similar patterns appeared when looking at specific roadway characteristics, as shown in Table 6. This table summarizes the percentage of the regional network that exhibits the risk factor or roadway characteristic in each row as well as the density of severe crashes occurring along these facilities per 100 miles.

Higher posted speed limits (35 mph or greater) were more than twice as prevalent on the Primary Parallel Network (78%) than either the Secondary Parallel Route Network (38%) or rest of the region (31%). Further, even within this speed category, the density of KSI crashes per 100 miles was substantially higher on the Primary Parallel Network and Secondary Parallel Route Network than off it (147 and 93, respectively, versus 54). Having multiple (4 or more) travel lanes is another systemic risk factor for severe crashes. Like the posted speed limit, multi-lane roadways were more prevalent on the Primary Parallel Network than the Secondary Parallel Route Network or off the Parallel Network system, and the severe crash density was highest for the Primary Parallel Network.

Moderate and higher AADT categories mostly echoed this pattern as well. While moderate AADTs (7,501 to 15,000) were more common on the Secondary Parallel Route Network than either the Primary Parallel Network or the rest of the region, severe crash density along these facilities was tied between the Primary Parallel Network and the Secondary Parallel Route Network. Severe crash density off the Parallel System was less than half of the Primary Parallel Network and Secondary Parallel Route Network. At higher AADTs (15,001 to 20,000 and 20,001 or greater), the Primary Parallel Network had the greatest percentage of road miles in these categories. Higher AADTs were generally associated with higher severe crash densities, though the small subset of miles in the 15,001 to 20,000 bracket on the Secondary Parallel Route Network had a lower KSI crash density than the moderate AADT category.

Table 6. Summary of Miles and Severe Crash Density by Known Risk Factors On and Off the Parallel System.

	Primary Parallel Network		Secondary Parallel Route Network		Rest of Region (Non-Parallel System)	
Risk Factor	Percentage of Miles	KSI Per 100 Miles	Percentage of Miles	KSI Per 100 Miles	Percentage of Miles	KSI Per 100 Miles
Arterial	47%	137	25%	86	18%	55
Freeway	38%	192	15%	133	5%	81
Local	4%	33	45%	8	55%	7
4 or more Lanes	51%	196	22%	139	12%	86
Posted speed ≥ 35 mph	78%	147	38%	93	31%	54
7,501 - 15,000 AADT	15%	127	38%	127	5%	56
15,001 - 20,000 AADT	7%	139	3%	89	2%	73
20,001 or greater AADT	46%	204	16%	159	7%	85
High Injury Network	29%	244	15%	171	10%	120
Overall street network	100%	145	100%	50	100%	23

The difference between the systems in terms of speed, AADT, and number of lanes cannot be explained by freeways alone. A High Injury Network (HIN) was built for the five-county region as part of separate work. This HIN excluded freeways but included ramps. Despite only 41% of the region's non-freeway streets being on the Secondary Parallel Route Network (Table 3), over half (52%) of the region's HIN was on the Secondary Parallel Route Network. As Table 6 shows, the HIN comprised a larger percentage of the Primary Parallel Network's miles than the Secondary Parallel Route Network or the rest of the region, and the density of KSI crashes along the Primary Parallel Network's HIN segments was higher than any other single risk factor. These HIN findings underscore the previous findings about disparate safety conditions on the Parallel Systems, especially the Primary Parallel Network.

Further analysis of these risk factors reinforces findings from Figure 7 and Table 4: that time-of-day affects safety outcomes. Although the absolute number of severe crashes happening during non-operating hours for BART (i.e., 12AM to 6AM) is low, there are proportionately more late-night severe crashes on the Primary Parallel Route Network and Secondary Parallel Route Network than the rest of the region. and the differences follow predictable infrastructure-based patterns (Figure 9). On medium-volume streets with an AADT between 15,001 and 20,000, severe crashes during non-operating hours comprise 22 to 23% of all crashes on the Primary Parallel Route Network and Secondary Parallel Route Network. In the rest of the region, only 8% of severe crashes occur during non-operating hours.

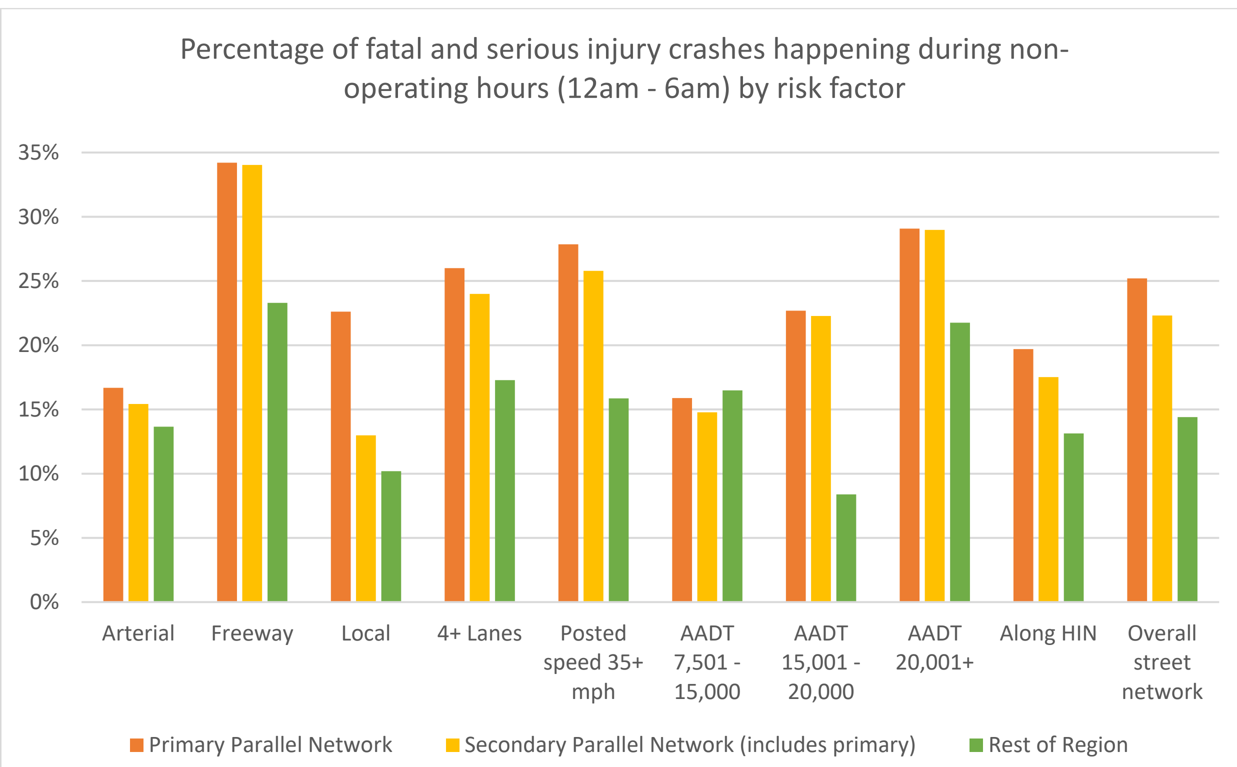

Figure 9. Percentage of fatal and serious injury crashes during BART's non-operating hours by risk factor.

4.3 Results from two natural experiments of the effects of BART system closures and system expansions

Two natural experiment scenarios, described in Section 3.6, offered the opportunity to see whether temporal changes in BART service were associated with changes in crash patterns. Unfortunately, the sample size of the first experiment (BART strikes in 2013) was too small to find discernible patterns, and the results of the service expansion scenario were too muddled to draw meaningful conclusions from. The results of these two experiments are briefly summarized below.

4.3.1 2013 BART Strikes

The 2013 BART strikes occurred over two periods. The system was closed Monday-Friday, July 1 to 5, and again Friday-Monday, October 18 to 21. To account for differences by day of week, Table 7 summarizes the number of KSI crashes per day by month and by day type (weekday vs. weekend) for strike days and non-strike days. The years 2012 to 2014 are used due to their similarity to 2013.

There were slightly more KSI crashes per day during the July strike (3.8 per day on 2013 July strike days and 3.6 on average across all other 2012 to 2014 July weekdays). In the October strike, the strike days appeared to have a lower average crash rate than reference weekday and weekend days in October 2012 to 2014. Because these patterns are subtle and based on a very low overall number of strike-day KSI crashes (e.g., 5, in the case of October weekends), there is have limited confidence in these numbers and do not advise making recommendations based on them.

Table 7. Summary of KSI Crash Totals by BART Strike Status, 2012 to 2014.

Month and Day Type	KSI Crashes on Non-strike Days	KSI Crashes on Strike Days	KSI Crashes per Day on Non-strike Days	KSI Crashes per Day on Strike Days	Number of Non-Strike Days	Number of Strike Days
June Weekdays	249		4.0		62	0
July Weekdays	**226**	**19**	**3.6**	**3.8**	**63**	**5**
August Weekdays	247		3.7		66	0
September Weekdays	286		4.5		63	0
September Weekends	138		5.1		27	0
October Weekdays	**284**	**7**	**4.2**	**3.5**	**67**	**2**
October Weekends	**100**	**5**	**4.5**	**2.5**	**22**	**2**
November Weekdays	263		4.2		63	0
November Weekends	129		4.8		27	0

4.3.2 System expansion over time

This white paper looked at BART system expansion over time in waves from 2012 to 2016, 2017 to 2020, and 2021 to 2023. In this analysis, we compared the rate of growth in KSI crashes from the 2012 to 2016 wave to the 2021 to 2023 wave. Table 8 shows that the largest number of severe crashes happens on the portion of the Parallel System that has served BART the longest: the stations that were open from the early days of 2012. Crashes in this area also grew the most, with a 35% increase from the first wave to the last. Because this is not normalized by volumes or job growth or any other factor that may explain variation, these results have limited utility.

Table 8. Comparison of KSI crashes per year from 2012-2016, 2017-2020, and 2021-2023

Parallel System Category	KSI Crashes per Year: 2012 to 2016	KSI Crashes per Year: 2017 to 2020	KSI Crashes per Year: 2021 to 2023	Delta (2012 to 2016) v. (2021 to 2023)	Percent Difference
Off the Parallel Network System	630	758	787	+157	+25%
BART service expansion from 2020 onward (Berryessa, Milpitas)	82	87	107	+25	+31%
BART service expansion from 2017 to 2020 (Antioch, Warm Springs, Pittsburgh Center)	106	137	137	+31	+29%
Core Parallel Network System (opened prior to 2016)	**719**	**948**	**971**	**+252**	**+35%**

4.4 Results from Evaluating the Effects of BART Service and Ridership on Potential Countermeasure Opportunities

4.4.1 Existing Conditions

The five-county region in which BART operates contains approximately 17,800 miles of roadway facility. Of these, Table 3 shows that about 8% (1,500 miles) appear to be existing roadway reallocation candidates based on the criteria described in Section 3.7 and Table 2. Approximately half of these (729 miles) fall within the Secondary Parallel Route Network, including 307 miles on the Primary Parallel Network. Some of these 729 miles may already be good candidates for reallocation. However, the 15,000 and 20,000 daily volume thresholds used to identify these candidates are a general rule of thumb, and many other factors affect suitability for this countermeasure. It is possible that some of these facilities may not yet be considered suitable candidates for roadway reallocation due to time-of-day travel patterns. Therefore, these 729 miles also represent potential opportunities where increases in BART ridership shifting from driving could increase the suitability of each segment for a roadway reallocation. A summary of the regional network miles by Parallel System status and existing roadway reallocation candidate status for non-freeway facilities with AADT less than or equal to 20,000 and 4 or more lanes, is provided in Table 9.

Table 9. Regional Network Miles by Parallel System and Existing Roadway Reallocation Candidate Status

Parallel Network Status	Miles of Existing Reallocation Candidates	Miles of Other Facilities	Total Network Miles	Percentage Reallocation Candidates
Primary Parallel Network	307	1,489	1,796	17%
Secondary Parallel Route Network	729	6,512	7,241	10%
Rest of Region (Non-Parallel System)	784	9,801	10,585	7%
Regional total	**1,513**	**16,313**	17,826	**8%**

Table 10 summarizes mileage and severe crash density among non-freeway streets with 4 or more lanes for the Primary Parallel Network, Secondary Parallel Route Network, and rest of the region (off the Parallel Network System). The table shows subtotals for AADT 0 to 20,000 and 20,001 or greater. The table also shows comparison groups for non-freeway streets with 1, 2, or 3 lanes for AADT 0 to 20,000 and 20,001 or greater.

Almost universally, streets with fewer lanes have a lower density of KSI crashes per year per 100 miles than streets with more lanes. Even at higher volumes (20,001 or greater), the KSI crash density is lower on 1 to 3-lane streets than 4 or more lane streets. Within 4 or more lane streets, KSI crash density is almost always higher at volumes more than 20,000 vehicles per day. These patterns suggest that reducing either the number of lanes or traffic volumes can save lives, and that reducing *both* lanes and volume will have the greatest impact.

On the Primary Parallel Network, there are 69 miles with AADT ranging from 15,001 to 20,000. An additional 29 miles have an AADT of 20,001 to 22,500. On the Secondary Parallel Route Network, 177 miles fall in this 15,001 to 22,500 AADT range. These marginal AADT streets (slightly below or slightly above the 20,000 rule-of-thumb) are the most likely to be influenced by increases in BART ridership such that traffic reductions – particularly during peak hour congestion – may increase suitability for roadway reallocations.

Table 12 through Table 15 show how the miles of roadway reallocation opportunities on the Routed Network change with various BART ridership increase scenarios. As noted in the Methodology section, due to data constraints, these BART ridership increase scenarios were only analyzed for the Primary Parallel Network, for which both traffic volumes and ridership information were available.

4.4.2 Road Diet Scenarios

Table 12 summarizes KSI crashes and crash reductions on roads eligible for roadway reallocation under various average midweek daily ridership scenarios, using AADT of 20,000 or less as the threshold for roadway reallocation eligibility within the Primary Parallel Network. Table 13 summarizes all crashes (all severities) for the same threshold. Table 14 and Table 15 show KSI crashes and all crashes, respectively, using a more conservative AADT threshold of 15,000 or less for roadway reallocation eligibility within the Primary Parallel Network. In each table, the number of miles that may be eligible for a roadway reallocation are shown, alongside the number of crashes happening along those miles. Using a Crash Reduction Factor (CRF) of 35% for a roadway reallocation ("road diet") from the California Local Road Safety Manual (LRSM)[15], we calculated estimates of the number of crashes that could be avoided by applying lane reduction countermeasures to these miles. Further, using crash cost parameters from the California LRSM, the research team converted these crash reduction estimates into crash *cost* reduction estimates.

[15] Caltrans. Local Roadway Safety Manual: A Manual for California's Local Road Owners. Version 1.7. (2024). https://dot.ca.gov/-/media/dot-media/programs/local-assistance/documents/hsip/2024/lrsm2024-v2.pdf

The ridership increase scenarios are based on average daily midweek ridership totals from 2023 for each origin-destination station pair, with the assumption that the increase in ridership would come from people switching modes from driving alone. As previously noted in Table 10, there are 307 miles of non-freeway streets with 4 or more lanes and AADT of 20,000 or less. Doubling BART's 2023 midweek ridership (100% increase) results in an increase of about 15 eligible miles, or a 5% increase over the baseline existing AADT (row 4 of Table 12; total of 322 eligible miles). Despite the relatively modest increase in miles, these additional streets lead to an even greater potential reduction in crashes.

The largest ridership increase scenario (i.e., increasing ridership to 2019 levels) had the largest impact on eligible miles and potential crashes reduced. Under the more generous scenarios (Table 12 and Table 13), severe crashes could be reduced by about 23% and all crashes by about 20%. In the more cautious scenarios (Table 14 and Table 15), over 30% of KSI crashes could be eliminated. The baseline cost of crashes happening on streets that would be eligible under the 2019 ridership scenario is over one billion dollars, and the cost savings range from $343 million (KSI crashes only) to $545 million based on this analysis of surface streets on the primary and secondary parallel networks.

Table 10. Distribution of Network Miles by AADT and Number of Lanes for Primary Parallel Network, Secondary Parallel Route Network, and Rest of Region

	Primary Parallel Network			Secondary Parallel Route Network			Rest of Region (Non-Parallel System)		
Existing AADT	Number of Miles	Percentage of Miles	Crashes per Year per 100 Miles	Number of Miles	Percentage of Miles	KSI Crashes per Year per 100 Miles	Number of Miles	Percentage of Miles	KSI Crashes per Year per 100 Miles
0 - 7,500	99	19%	33	323	30%	17	366	37%	15
7,501 - 15,000	140	27%	44	278	26%	32	251	26%	18
15,001 - 17,500	38	7%	43	71	7%	27	73	7%	19
17,501 - 20,000	31	6%	44	56	5%	29	53	5%	27
20,001 - 22,500	29	6%	62	50	5%	40	40	4%	30
22,501 - 25,000	32	6%	66	52	5%	46	32	3%	19
25,001 or greater	152	29%	59	240	22%	42	168	17%	20
Total	**521**	**100%**	**49**	**1,071**	**100%**	**30**	**984**	**100%**	**18**

Table 11 Distribution of Network Miles by AADT Category and Number of Lanes Category for Primary Parallel Network, Secondary Parallel Route Network, and Rest of Region

	Primary Parallel Network			Secondary Parallel Route Network			Rest of Region (Non-Parallel System)		
Existing AADT	Number of Miles	Percentage of Miles	Crashes per Year per 100 Miles	Number of Miles	Percentage of Miles	KSI Crashes per Year per 100 Miles	Number of Miles	Percentage of Miles	KSI Crashes per Year per 100 Miles
Subtotal 4 Lanes: 0 to 20,000 AADT	*307*	*59%*	*40*	*729*	*68%*	*25*	*743*	*76%*	*17*
Subtotal 4 Lanes: 20,001 or greater AADT	*214*	*41%*	*60*	*342*	*32%*	*42*	*240*	*24%*	*22*
1 to 3 Lanes Comparison, 0 to 20,000 AADT	*527*		*29*	*4,207*		*9*	*5,805*		*7*
1 to 3 Lanes Comparison, 20,001 or greater AADT	*62*		*51*	*103*		*35*	*102*		*30*

Table 12. KSI Crashes and Crash Reductions on Roads Eligible for Roadway Reallocation under Various Average Midweek Daily Ridership Scenarios.

Ridership Scenario	Miles of Roadway Reallocation Eligible Streets	Percentage Increase in Eligible Roadway Miles by Scenario	Eligible Miles as a % of Total Routed Network Miles	Baseline KSI Crashes	KSI Crashes Reduced	Percentage Increase in KSI Crash Reduction by Scenario	Baseline KSI Crash Cost (Millions)	Crash Cost Value from KSI Crashes Reduced (Millions)
Baseline / Existing AADT	307	0.0%	17.1%	362	127	0.0%	$1,057M	$370M
25% Increase in BART Ridership	311	1.3%	17.3%	369	129	1.9%	$1,076M	$377M
50% Increase in BART Ridership	314	2.1%	17.5%	374	131	3.3%	$1,088M	$381M
100% Increase in BART Ridership	322	4.8%	17.9%	403	141	11.3%	$1,171M	$410M
Return to 2019 BART Ridership	327	6.5%	18.2%	444	155	22.7%	$1,292M	$452M

Table 13. Total Crashes and Crash Reductions on Roads Eligible for Roadway Reallocation under Various Average Midweek Daily Ridership Scenarios.

Ridership Scenario	Miles of Roadway Reallocation Eligible Streets	Percentage Increase in Eligible Roadway Miles by Scenario	Eligible Miles as a % of Total Routed Network Miles	Baseline Total Crashes	Total Crashes Reduced	Percentage Increase in Total Crash Reduction by Scenario	Baseline Total Crash Cost (Millions)	Crash Cost Value from Total Crashes Reduced (Millions)
Baseline / Existing AADT	307	0.0%	17.1%	4,162	1,457	0.0%	$1,600M	$560M
25% Increase in BART Ridership	311	1.3%	17.3%	4,269	1,494	2.6%	$1,633M	$571M
50% Increase in BART Ridership	314	2.1%	17.5%	4,341	1,519	4.3%	$1,654M	$579M
100% Increase in BART Ridership	322	4.8%	17.9%	4,614	1,615	10.9%	$1,769M	$619M
Return to 2019 BART Ridership	327	6.5%	18.2%	5,001	1,750	20.2%	$1,936M	$678M

Table 14. KSI Crashes and Crash Reductions on Roads Eligible for Roadway Reallocation under Various Average Midweek Daily Ridership Scenarios Using a More Conservative AADT Threshold.

Ridership Scenario	Miles of Roadway Reallocation Eligible Streets	Percentage Increase in Eligible Roadway Miles by Scenario	Eligible Miles as a % of Total Routed Network Miles	Baseline KSI Crashes	KSI Crashes Reduced	Percentage Increase in KSI Crash Reduction by Scenario	Baseline KSI Crash Cost (Millions)	Crash Cost Value from KSI Crashes Reduced (Millions)
Baseline / Existing AADT	239	0.0%	13.3%	273	96	0.0%	$802M	$281M
25% Increase in BART Ridership	244	2.1%	13.6%	295	103	8.1%	$863M	$302M
50% Increase in BART Ridership	248	4.1%	13.8%	304	106	11.4%	$887M	$310M
100% Increase in BART Ridership	259	8.3%	14.4%	324	113	18.7%	$940M	$329M
Return to 2019 BART Ridership	267	11.7%	14.8%	358	125	31.1%	$1,037M	$363M

Table 15. Total Crashes and Crash Reductions on Roads Eligible for Roadway Reallocation under Various Average Midweek Daily Ridership Scenarios Using a More Conservative AADT Threshold.

Ridership Scenario	Miles of Roadway Reallocation Eligible Streets	Percentage Increase in Eligible Roadway Miles by Scenario	Eligible Miles as a % of Total Routed Network Miles	Baseline Total Crashes	Total Crashes Reduced	Percentage Increase in Total Crash Reduction by Scenario	Baseline Total Crash Cost (Millions)	Crash Cost Value from Total Crashes Reduced (Millions)
Baseline / Existing AADT	239	0.0%	13.3%	3,018	1,056	0.0%	$1,194M	$418M
25% Increase in BART Ridership	244	2.1%	13.6%	3,185	1,115	5.5%	$1,274M	$446M
50% Increase in BART Ridership	248	4.1%	13.8%	3,347	1,171	10.9%	$1,319M	$462M
100% Increase in BART Ridership	259	8.3%	14.4%	3,613	1,265	19.7%	$1,407M	$492M
Return to 2019 BART Ridership	267	11.7%	14.8%	4,009	1,403	32.8%	$1,551M	$543M

5 Conclusions

5.1 Key findings or recommendations

This white paper documented evidence that the roadway system serving trips parallel to BART's origins and destinations performs worse than average for the region on several traffic safety metrics. As noted in the results, people who drive or ride in passenger vehicles instead of riding BART are exposed to a higher-than-average risk of severe crashes. Table 16 summarizes key findings and outstanding research questions for each of the three analyses presented in this white paper.

BART's unique role in regional transportation may be an important key for unlocking new gains in traffic safety. Specifically, stopping and ultimately reversing investments in highway and roadway expansion is an important first step for addressing the epidemic of traffic deaths and serious injuries in the United States and in the five-county region. An overbuilt roadway system designed to meet peak-hour needs for motorists results in unsafe conditions outside of peak hour and becomes even deadlier when traffic volumes are drastically lower, as they are overnight. These safety consequences are uniformly worse for people walking, bicycling, and riding a motorcycle than for those driving a motor vehicle. Conversely, a transit system designed to accommodate peak-hour needs retains its utility off-peak without this unintended traffic safety consequence.

Further, many roads in the region may be eligible or nearly eligible for safety countermeasures like roadway reallocations. Increases in BART service and ridership may unlock eligibility for these and more streets to implement impactful safety countermeasures at a more widespread scale than would be possible without BART.

Table 16. Summary of Key Study Findings from Three Analyses.

	Analysis 1: crash patterns and systemic risk factors	Analysis 2: BART closure and expansion scenarios	Analysis 3: countermeasure opportunities
Key questions addressed	Would the parallel system, or roads that drivers would take to get to the same destinations if BART did not exist, be more or less safe than the rest of the region?	Do changes in the BART system improve safety outcomes?	Does improving BART service create new opportunities for roadway safety measures?
Evidence so far	Traveling on the parallel system is less safe than on roads in the rest of the region. BART operations are not making the roads more or less safe. The underlying roadway characteristics (higher-speed, wider streets, higher volumes, far more exposure, etc.) contribute to these streets being riskier. The parallel system has wider and faster facilities that support higher vehicle volumes. If BART did not exist, people would be driving instead of taking BART, which would expose them to much higher levels of risk than even people driving other routes in the region. These findings underscore the importance of Analysis 3.	No solid evidence. Sample size from the strikes is too small. Network growth over time is confounded with different land use and network characteristics.	Probably. There already appear to be a lot of unrealized potential roadway reallocation opportunities, based on AADT alone. There are some segments that are marginal for roadway reallocation on present AADT where BART ridership increases could bring the facilities below the threshold and into roadway reallocation candidacy.
Questions and Opportunities for Future Research	Does a further exploration of time-of-day variations in both ridership and roadway volumes explain why the Parallel System is so much more dangerous? I.e., can we further confirm that building roadway capacity for peak hour Bay Area roadway traffic makes safety conditions off-peak unsafe? Are there differences late in the evening before and after BART service terminates for the day?	Strikes and smaller service disruptions are not viable due to small sample size. More detailed analysis of network growth could be done, but we do not expect meaningful results.	Does a further exploration of time-of-day variations in volume and ridership illuminate areas where BART is necessary or critical for recommendation of roadway reallocations?
What can we conclude?	When planning for population growth and increased travel demand, improving the BART system is a preferable option to expanding roadways. Off-peak travel on the parallel system is already dangerous, and roadway expansions would only make this worse. Prioritize investing in BART and pairing with roadway reallocations, such as road diets, to improve road safety.	N/A	The region already has many opportunities for roadway reallocations, and there are some facilities where growth in ridership could pull enough drivers off of a road to bring it into a roadway reallocation eligible AADT range. Decreasing the convenience of driving relative to BART will further amplify this effect.

5.2 Limitations and areas for further study

This study used descriptive, systemic, and geospatial analysis to explore the relationship of the BART system to traffic safety in the Bay Area region and estimate the extent to which increases in BART service may contribute to regional safety goals. As with any analysis, there are some notable limitations with our data and methodology, and there are several unanswered questions that may be addressed through future research.

The roadway system that serves the same origins and destinations as BART is distinctly different from the roadway system throughout the rest of the region in many ways. Both BART and the roadway system were designed as they were under assumptions and priorities about travel demand, and in particular, peak hour travel demand. This portion of the region has a high density of jobs, destinations, and housing, and demographics are different. Differences in safety outcomes between the Parallel Systems and the rest of the region may not be directly attributable to BART service, and further exploration of these differences may illuminate more about BART's role in traffic safety in the region.

Many of our findings hint at time-of-day variation by which the Parallel Systems are slower, more congested, and potentially safer during peak hour commuting times than late night hours when BART is not operating and traffic volumes are low. However, there is also evidence that lower AADT in general is not a safety risk, outside of the reliance on congestion to slow traffic. Further analysis of time-of-day variation in ridership and traffic volumes may help differentiate between the effect of modest traffic reductions (as seen in off-peak daytime and evening hours) versus substantial traffic reductions (as seen in the late night and early morning hours). While there is a concern that AADT reduction strategies may lead to increases in severe crashes, similar to what was observed during the COVID-19 pandemic and lockdowns, it is likely that more modest reductions increase rather than decrease safety.

This memo did not account for differences between travel modes. Some road users are more vulnerable than others – in particular, non-motorized road users, and it would be important to validate whether these findings hold true separately for motorists, pedestrians, and bicyclists. Overbuilt, commuting-oriented roadway systems may have a disparate impact on more vulnerable road users.

The definition of roadway reallocation candidate groups together all non-freeway facilities with 4 or more lanes. However, there may be marked differences in the safety performance of 4 lane streets versus 6 lane streets. A more granular analysis may help refine both the identification of roadway reallocation candidates and the estimation of their potential benefits.