Pollute-and-Ride: Emissions from Bay Area Rapid Transit Station Access

Riley J. O'Brien

ABSTRACT

Using a combination of surveys, GIS, and secondary data, I estimated the daily per-passenger emissions of greenhouse gases and criteria air pollutants attributed to passengers entering five San Francisco Bay Area Rapid Transit (BART) stations. I found that access emissions generally increase as station area density decreases and parking availability increases, and that access emissions differ significantly between most stations. Additionally, I found that access emissions contribute the majority of volatile organic compound (VOC), carbon monoxide (CO), and nitrogen oxide (NO_x) emissions at each station, as well as the majority of greenhouse gas (GHG) emissions at two stations. Analyzing potential alternative travel scenarios, I found that GHG, VOC, CO, and NO_x emissions would likely increase without park-and-ride facilities, while particulate matter (PM) and sulfur oxide (SO_x) emissions would likely decrease without park-and-ride. These results suggest that removing station parking may increase emissions and that improving pedestrian and bicycle access to BART stations is a more sustainable choice. Further research on BART park-and-ride is warranted to ensure desirable policy outcomes.

KEYWORDS

Park-and-ride, greenhouse gas emissions, air pollution, GREET, ArcMap

INTRODUCTION

The rise of fossil-fueled transportation since the Industrial Revolution has resulted in both widespread economic growth and significant environmental damage (Banister et al. 2011, Andress et al. 2011). Although the use of low-cost petroleum as a transportation fuel has facilitated the movement of goods and people around the world (Banister et al. 2011), researchers are alarmed by the transportation sector's increasing greenhouse gas emission rate (Dearing 2000, Banister et al. 2011, Andress et al. 2011). Economists predict that transportation will account for half of the world's total carbon dioxide (CO_2) emissions by 2050 (Banister et al. 2011), the year by which emissions must be drastically reduced to prevent a catastrophic global temperature increase (IPCC 2013). Additionally, medical researchers have found a link between other transportation air pollutants, especially NO_x, and respiratory complications such as asthma (Friedman et al. 2001). These impacts can be reduced in part by lowering the number of vehicles used per-person (Banister et al. 2011), which occurs when automobile users switch to mass transit modes such as bus and rail. However, emissions resulting from rail infrastructure construction (Chester and Horvath 2009), coupled with a decreasing trend in transit ridership (Feitelson 1994), have made it difficult to ensure that a given rail project is environmentally beneficial.

Compared to automobiles, passenger rail generally consumes less energy and emits less pollution on a per-passenger basis (Fels 1975, Chester and Horvath 2009). This is particularly true for electric-powered rail, which generally contributes less pollution than diesel-powered rail and does not emit pollution through vehicle exhaust (Kolpakov and Reich 2013). However, electricity generation is the primary source of certain pollutants such as SO_x, meaning a shift to electric rail may actually increase total SO_x emissions (Chester and Horvath 2010). Passengers may also use automobiles to access the rail station, increasing the emissions of the overall trip (Cervero 1995). While the provision of station parking can increase transit ridership (Merriman 1998), it may also increase automobile traffic if existing transit riders are encouraged to drive to the station (Parkhurst 1995). Although these automobile trips are often very short, they contribute substantial emissions through cold start and hot soak processes. The cold start process refers to the heating of an automobile engine after being started, which results in emissions beyond those generated during normal operation. The hot soak process similarly refers to the emissions that result as the engine cools down after being shut off (de Nazelle et al. 2010). The uncertain consequences of such trips has suggests that researchers should study park-and-ride facilities in greater detail.

Although researchers have examined park-and-ride emissions in other areas (Truong 2013, Mingardo 2013, Gan and Wang 2013), no study has analyzed park-and-ride emissions resulting from Bay Area Rapid Transit (BART). Built in the 1970s, BART serves the San Francisco Bay Area, specifically the counties of Alameda, Contra Costa, San Mateo, and the city and county of San Francisco. Early BART planners hoped that the system would decrease automobile use by encouraging higher-density land-use patterns, yet density has only increased significantly along the Market Street corridor in San Francisco (Cervero and Landis 1997). Reflecting its inconsistent development patterns, access mode choice varies significantly across the BART system, with the percentage of those walking to the station in 2008 ranging from 3% to 81% and the percentage of those driving or carpooling to the station ranging from 2% to 92% (BART 2008). Trip distance and the availability of a car may predict an individual's propensity to walk to the station, while density and parking availability may predict a given station's proportion of walk trips (Loutzenheiser 1997). Additionally, the proportion of those biking to the station increased between 1998 and 2008 as bicycle-friendly infrastructure and policies were implemented at several stations (Cervero et al. 2012). Despite extensive research on BART's accessibility, no study has explicitly studied the emissions that result from BART access.

This study aimed to estimate the access mode split at each station, quantify the emissions resulting from access to various BART stations, compare access and total emissions between stations, and estimate access and total emissions under various park-and-ride scenarios. I analyzed emissions of greenhouse gases (GHG) as well as five of the "criteria air pollutants" regulated under the Clean Air Act: volatile organic compounds (VOC), carbon monoxide (CO), nitrogen oxides (NO_x), particulate matter less than 10 μm in diameter (PM_{10}), and sulfur oxides (SO_x). I predicted that walking to the station would be most popular at high-density stations with low parking availability, while driving to the station would be most popular at low-density stations with high parking availability. I also predicted that access and total emissions would be lowest at high-density, low-parking stations, as these characteristics would encourage less automobile use and lower trip distances, and that emissions would be highest at low-density, high-parking stations.

METHODS

Study sites

To determine how access emissions vary between BART stations, I chose five stations that represent variation in density and parking availability across the 44-station system: 19th Street, Lake Merritt, Ashby, Walnut Creek, and Dublin/Pleasanton. 19^{th} Street is at the center of Downtown Oakland, surrounded by high-density, mixed-use development. Lake Merritt, at the southern end of downtown Oakland, is in a heavily urbanized but less dense area than the 19^{th} Street station. Ashby's south Berkeley location is less dense than the aforementioned station areas, yet it contains a mix of land uses not found in outlying suburbs. The Walnut Creek station is located near a commercial district and some high density development, but it is otherwise surrounded by low-density suburbs. Finally, the Dublin/Pleasanton station, straddling the border of the cities of Dublin and Pleasanton, is in the least dense area of the six stations, with land uses completely segregated. Unlike most BART stations, 19^{th} Street lacks on-site parking. Lake Merritt offers 207 parking spaces for BART users, while Ashby offers 715 spaces, Walnut Creek offers 2,089 spaces, and Dublin/Pleasanton offers 2,973 spaces, each for $1.50 per day.

Data collection

To collect data on mode choice, vehicle choice, vehicle occupancy, and distance traveled, I surveyed 25 people at each of the five stations. To estimate emissions during commute hours, when ridership is generally highest (BART 2008), I surveyed each passenger between 7 and 10 am on Wednesdays and Thursdays in February 2014. During each station visit, I stood near the fare gate and asked those entering the station if they would like to take my survey. I asked each respondent which mode they used to access the station and proceeded depending on their response. I asked automobile users for the year, make, and model of their vehicle, how many people occupied the vehicle, whether they were dropped off or parked at the station, and the nearest major intersection to the start of their trip. I asked bus and other transit riders which line they rode and which stop they boarded at, and whether they had access to an automobile. I asked those who walked or biked to the station for the nearest major intersection to the start of their trip and whether they had access to an automobile. Finally, I asked each respondent for their destination BART station, the purpose and frequency of their trip, and demographic questions on age, education level, and income (Appendix A).

To obtain information on station and vehicle characteristics, I used data from BART and the EPA. I used BART data to obtain the average daily ridership at each station in February 2014 and the distance between each study station and each destination station. I used EPA's fueleconomy.gov website to obtain the fuel economy and weight class of each automobile reported in the survey.

Data analysis

Spatial analysis

To determine the distances of each survey respondent's trip, I used Esri's ArcMap software to find and measure the route between their stated trip origin and the station (Esri 2014). I plotted each trip origin along with the five study stations and all stations reported as destinations in the survey. Using ArcMap's "Find Route" feature, I determined the location and distance of the optimal route from each origin to the study station and the optimal route from each origin to the destination station. I assumed that the latter represents the route that passengers would use to drive directly to their destination rather than use BART.

Emissions analysis

To calculate the GHG emissions of each automobile trip, I used fuel economy data for each vehicle as inputs in the GREET model. Developed by Argonne National Laboratory, GREET uses hundreds of modifiable parameters to calculate the emissions resulting from the production, distribution, and use of most automobile fuels. The model's output is a set of emission factors for several pollutants in units of mass per unit distance traveled per vehicle (ANL 2013). For this study, I modified the model year and fuel economy parameters with data from fueleconomy.gov to calculate a unique GHG emission factor for each vehicle in the study. Subsequently, I multiplied these emission factors by the distance traveled and divided by each vehicle's occupancy to obtain the total GHG emissions from the access portion of the trip. GREET did not separate cold start and hot soak emissions from operational emissions and thus I did not distinguish between them in my analysis of GHG emissions.

To calculate the criteria air pollutant emissions of each automobile trip, I used vehicle class and model year data as inputs in the EMFAC model. The EMFAC model, developed by the California Air Resources Board, provides emission factors for VOC, CO, NO_x, PM_{10}, and SO_x in units of mass per unit distance traveled. Although EMFAC does not provide unique emission factors based on fuel economy, they are specific to the vehicle's model year and weight class. Because EMFAC's weight classes were less specific than those provided by the EPA, I assumed that vehicles within a particular EPA class were in the EMFAC class with the most similar weight range. I multiplied these emission factors by the distance traveled, added a constant term representing cold start and hot soak emissions, and divided by each vehicle's occupancy to obtain the total emissions from each access trip.

To calculate the emissions of each bus trip, I used the EMFAC model for both greenhouse gas and criteria air pollutant emissions. For trips made on full-size public buses, I used "Urban Bus" as the vehicle class and aggregated across all model years. For trips made on private shuttles, I used "Medium Duty Truck" as the vehicle class, as most minivans are within that category, and aggregated across all model years. I multiplied the resulting bus emission factors by the distance traveled to the station and divided by the reported occupancy to obtain emissions for each access trip made by bus. To calculate the emissions of each BART trip, I used operational emission factors derived by Chester (2008). I multiplied the BART emission factor by the distance between each station to obtain the total emissions of the BART portion of the trip. Finally, I added each trip's BART emissions to the previously calculated access emissions to obtain the total emissions of each trip.

Statistical analysis

To determine if any differences in access emissions are statistically significant, I performed a Kruskal-Wallis equality-of-populations rank test for each pollutant. For pollutants in which a significant difference was identified, I followed the Kruskal-Wallis test with a Wilcoxon rank-sum test to compare emissions between each of the 10 possible station pairs. I performed both the Kruskal-Wallis and Wilcoxon rank-sum tests in Stata (Statacorp 2013).

Scenario analysis

To assess the influence of the current park-and-ride system on total emissions, I constructed four alternative transportation scenarios. The first scenario, "No P&R, 100% Auto Reduction," represents total emissions per current passenger if nobody drives to the station, and instead walks or bikes to BART. I calculated these emissions by including only the on-BART portion of the emissions calculated in the original analysis. The second scenario, "No P&R, 50% Auto Reduction," represents total emissions per current passenger if those who accessed the station by automobile instead had driven directly to their destination while the other half had walked or biked to BART. I calculated these emissions by multiplying each trip's emission factor by the distance between the trip origin and the BART station reported as the destination, dividing by occupancy, and dividing by 2 to reflect the 50% reduction. The third scenario, "No P&R, No Auto Reduction," represents total emissions per current passenger if all current auto users had driven directly to their destination. I calculated the emissions of this scenario as described for the "No P&R, 50% Auto Reduction" scenario without dividing total emissions by 2. The fourth scenario, "No P&R, Increased Auto Use," represents total emissions per current passenger if all passengers with access to an automobile instead had driven directly to their destination. I calculated the emissions of this scenario by multiplying the average emission factor across the entire sample by the distance between each origin and each destination station for all respondents that reported having access to a car.

RESULTS

I received a total of 25 responses at each study site for a total of 125 responses. Four of the respondents provided incomplete information regarding their trip's origin, mode, or destination. An additional six respondents provided unclear information regarding trip origin, mode, or destination. Twenty respondents chose to withhold some or all of the requested demographic information.

Demographics

The average age of respondents was 40.6 years, with a standard deviation of 12.6 years and little variation from station to station (Table 1). The Lake Merritt sample consisted of the youngest group of respondents, while the Walnut Creek sample consisted of the oldest group of respondents. No station's average age was more than one standard deviation away from the average age of the entire sample.

Table 1. Age of respondents by station.

Station	**# of responses**	**Mean**	**Median**	**Maximum**	**Minimum**	**Standard Deviation**
19th Street	24	39.50	37	69	23	11.51
Ashby	25	40.16	39	60	23	12.60
Dublin/Pleasanton	19	41.84	39	64	22	10.02
Lake Merritt	25	34.00	33	63	13	11.09
Walnut Creek	21	49.10	48	79	25	13.66
Total	114	40.60	39	79	13	12.63

The majority of respondents (82.2%) reported having a Bachelor's degree or higher, with 30.5% reporting possession of a Master's degree or higher and 9.3% reporting possession of a JD, MD, or PhD (Table 2). Ashby respondents had the highest college graduation rate, while 19th Street had the highest proportion of Bachelor's degree holders, and Lake Merritt had the highest proportion of JD, MD, and PhD recipients.

Table 2. Education level of respondents by station

Station	**# of responses**	**High School**	**Some College**	**Associate's**	**Bachelor's**	**Master's**	**JD/MD/PhD**
19th Street	23	4.3%	4.3%	0%	47.8%	34.8%	4.3%
Ashby	25	0%	8%	4%	44%	36%	8%
Dublin/Pleasanton	19	5.3%	5.3%	0%	52.6%	26.3%	5.26%
Lake Merritt	24	4.3%	8.7%	0%	43.5%	26.1%	17.4%
Walnut Creek	22	0%	13.6%	0%	36.4%	36.4%	13.6%
Total	118	1.7%	7.6%	1.7%	42.4%	30.5%	9.3%

A preponderance of respondents (34.3%) reported household pre-tax incomes between $50,000 and $100,000 per year. Walnut Creek respondents reported the highest proportion of incomes above $200,000 out of the five stations, while Lake Merritt respondents reported the highest proportion of incomes below $100,000 and Ashby respondents reported the highest proportion below $50,000 (Table 3).

Table 3. Income level of respondents by station

Station	**# of responses**	**Less than $50,000**	**$50,000-$100,000**	**$100,000-$200,000**	**Above $200,000**
19th Street	23	13.0%	52.2%	26.1%	8.7%
Ashby	24	37.5%	16.7%	33.3%	12.5%
Dublin/Pleasanton	16	6.3%	31.3%	43.8%	18.8%
Lake Merritt	24	20.8%	50%	12.5%	16.7%
Walnut Creek	18	16.7%	16.7%	38.9%	27.8%
Total	105	20%	34.3%	29.5%	16.2%

Travel characteristics

In total, 40.8% of respondents arrived at the station on foot, while 37.6% arrived via automobile, 11.2% arrived via bicycle, and 8.8% arrived via mass transit. 19th Street respondents overwhelmingly walked to the station, with 72% walking, 12% biking, 8% riding another form of transit, and only 4% driving to the station. Lake Merritt respondents included a significant portion of walkers and drivers, with 48% walking, 12% biking, 4% riding transit, and 36% driving to the station. Ashby respondents primarily walked or biked to the station, with 48% walking, 20% biking, 8% riding transit, and 24% driving. Walnut Creek residents primarily drove to the station, with 28% walking, 4% biking, 8% riding transit, and 56% driving. Dublin/Pleasanton respondents overwhelmingly drove to the station, with 8% walking, 8% biking, 16% riding transit, and 68% driving to the station (Figure 1).

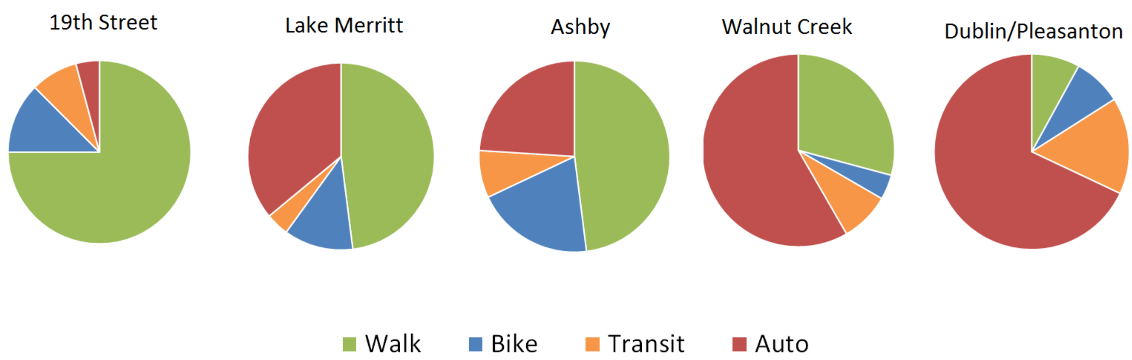

Figure 1. Mode choice by station

The majority (85.6%) of respondents were on their way to or from work at the time of the survey, with little variation from station to station. Walnut Creek had the highest proportion (96%) of work-bound respondents, while 19th Street had the lowest proportion (75%). A significant proportion (6.8%) of total respondents were on their way to or from school at the time of the survey, while smaller proportions of respondents reported social/recreational, shopping, or other reasons for their trip. Additionally, the majority (77.1%) of respondents claimed to make the same trip at least four times per week. This proportion was the highest at Lake Merritt, where 92% of respondents reported making their trip at least four times per week. Ashby had the lowest proportion of respondents (64%) who took the same trip at least four times a week.

The most popular BART destination among respondents was the Montgomery station in downtown San Francisco, with 28.9% of respondents traveling there at the time of the survey. Lake Merritt had the highest proportion of Montgomery-bound trips (44%), while Walnut Creek had the lowest proportion (20.8%). A significant minority (15.7%) of total respondents reported Embarcadero, also in downtown San Francisco, as their destination.

A total of 48 respondents arrived to the station via automobile. On average, their automobiles were roughly 10 years old, with the oldest reported automobile released in 1989 and the newest in 2013. 17% of the respondents reported arriving in a vehicle using non-conventional fuel or propulsion, either in the form of diesel fuel or hybrid-electric drive. According to fueleconomy.gov, the average fuel economy of the respondents' vehicles was 20.77 miles per gallon, with a standard deviation of 6.44 miles per gallon. The most efficient vehicle reported, the 2006 Toyota Prius, had a fuel economy of 48 miles per gallon, while the least efficient, the 2004 Lincoln Navigator, had a fuel economy of only 11 miles per gallon.

Greenhouse gas emissions

Per-passenger greenhouse gas emissions were highest at Dublin/Pleasanton and lowest at 19th Street, with access emissions contributing the majority of GHG emissions at Dublin/Pleasanton and Walnut Creek. The average Dublin/Pleasanton trip emitted 5.7 kg CO_2-equivalent of GHG (kgCO_2eq) en route to BART and 3.5 kgCO_2eq on BART for a total of 9.2 kgCO_2eq during the entire trip. The average 19th Street trip emitted 0.051 kgCO_2eq en route to BART and 0.93 kgCO_2eq on BART for a total of 0.98 kgCO_2eq during the entire trip. Overall, greenhouse gas emissions increased as parking availability increased and as station area density decreased (Figure 2).

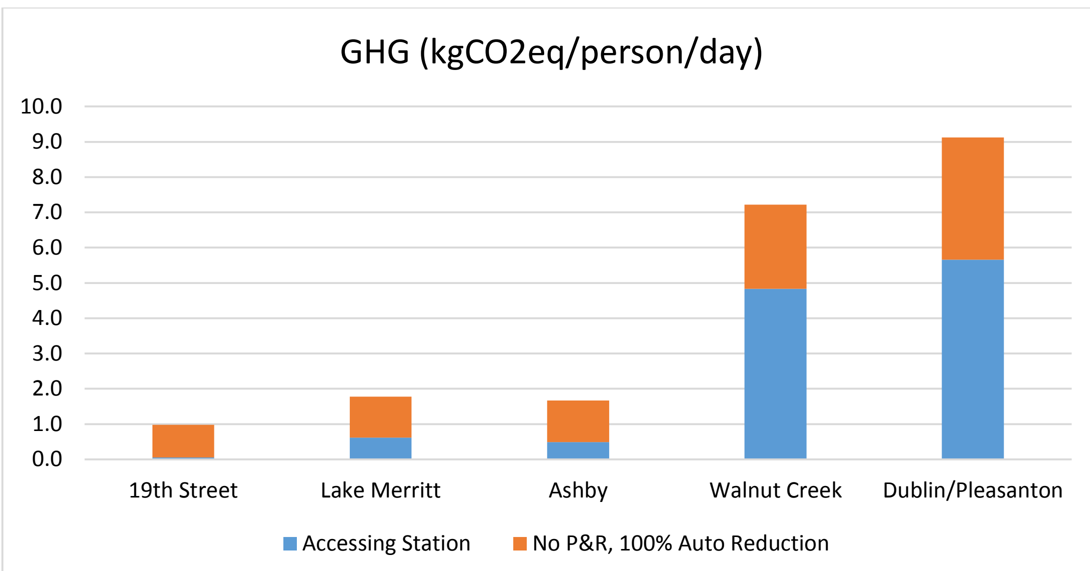

Figure 2. Daily per-passenger GHG emissions by station

Results of the Kruskal-Wallis test indicated a statistically significant difference in access GHG emissions between stations. For each pollutant, I rejected the null hypothesis that access emissions were equal at each station with a p-value of 0.0001. As a result, I performed a Wilcoxon rank-sum test on each station-pair for each pollutant. GHG emissions differed significantly between all station-pairs with the exception of 19th Street-Ashby, Ashby-Lake Merritt, and Dublin/Pleasanton-Walnut Creek (Appendix B).

According to the scenario analysis, greenhouse gas emissions among current passengers would increase as park-and-ride decreases and automobile use increases at each of the five stations (Figure 3). The "No P&R, 100% Auto Reduction" scenario would result in the lowest emissions at each station, while the "No P&R, Increased Auto Use" scenario would result in the highest emissions at each station.

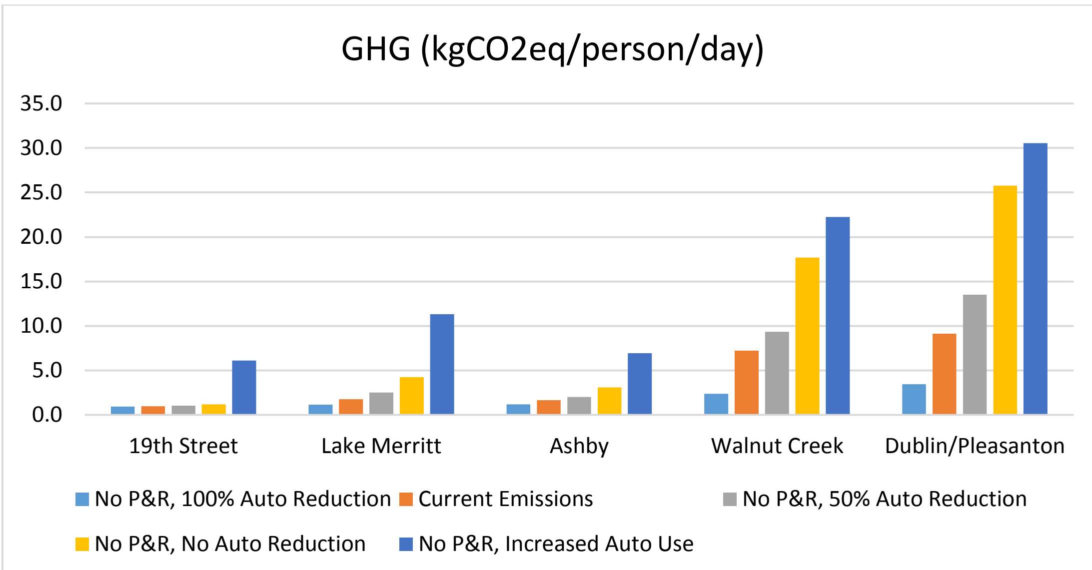

Figure 3. GHG emissions by BART riders under constructed scenarios.

Criteria air pollutant emissions

Per-passenger criteria air pollutant emissions were highest at Dublin/Pleasanton and lowest at 19th Street, with some pollutants primarily emitted during station access and others primarily emitted on BART. The average Dublin/Pleasanton trip emitted 5.8 g VOC, 34.5 kg CO, 6.9 g NO_x, 0.24 g PM_{10}, and 19.6 g SO_x. The average 19th Street trip emitted 0.39 g VOC, 2.4 kg CO, 0.71 g NO_x, 0.057 g PM_{10}, and 5.2 g SO_x. Emissions of VOC, CO, and NO_x occurred mainly during station access, with a substantial proportion resulting from cold start and (in the case of VOC) hot soak processes (Figure 4, Figure 5, Figure 6). Emissions of PM_{10} and SO_x occurred mainly through electricity generation for BART operation, with a small proportion of PM_{10} resulting from station access (Figure 7, Figure 8).

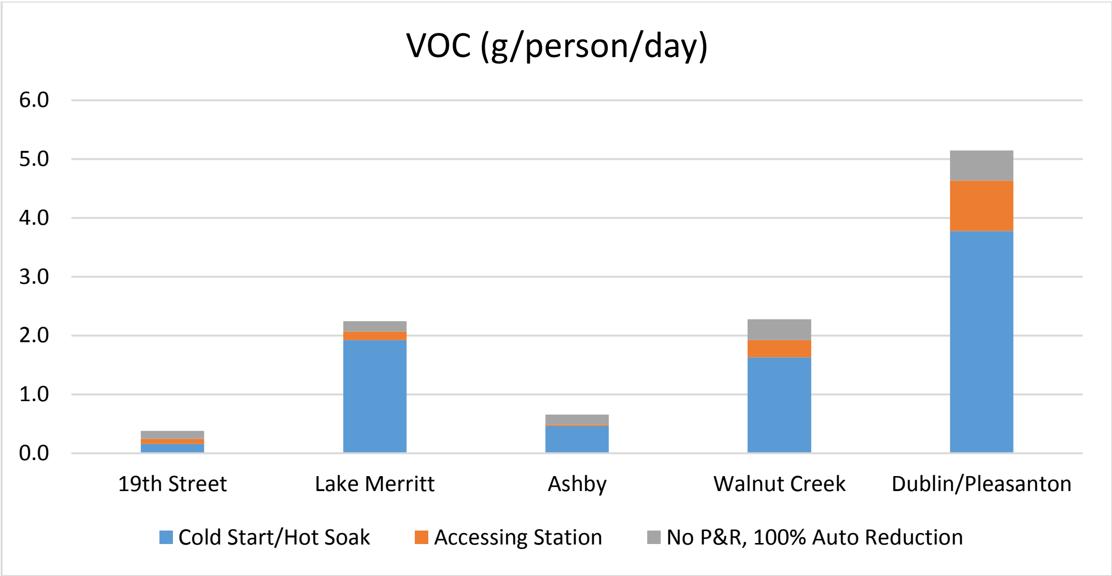

Figure 4. Daily per-passenger VOC emissions by station

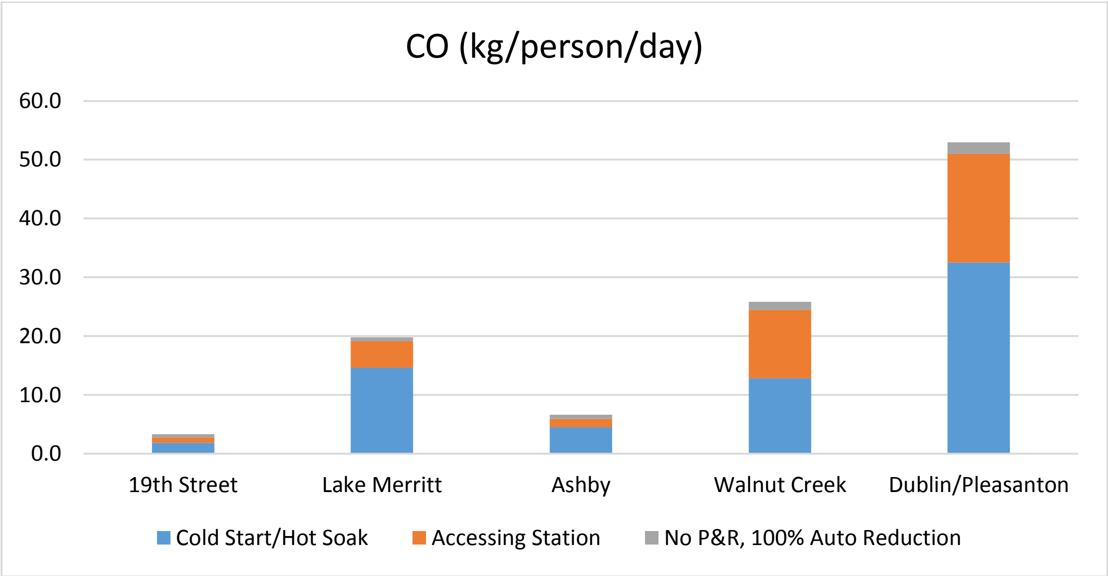

Figure 5. Daily per-passenger CO emissions by station

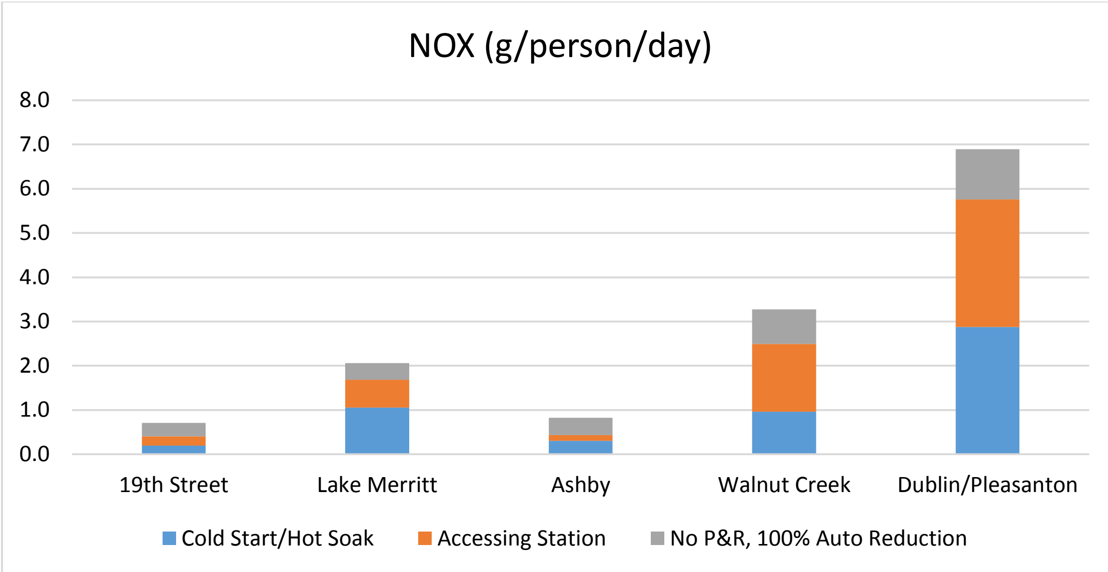

Figure 6. Daily per-passenger NO_x emissions by station

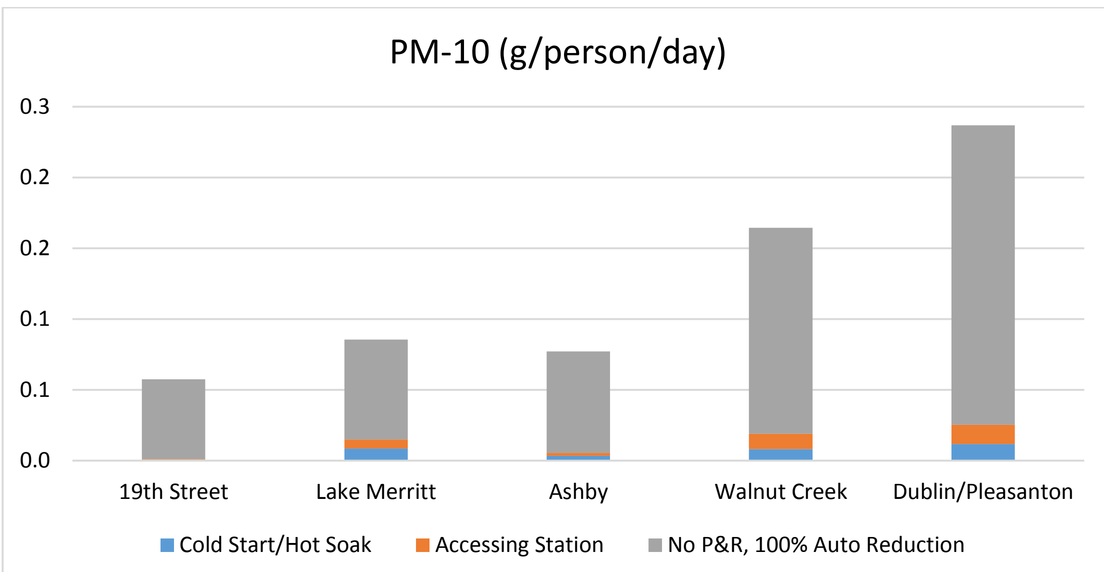

Figure 7. Daily per-passenger PM_{10} emissions by station

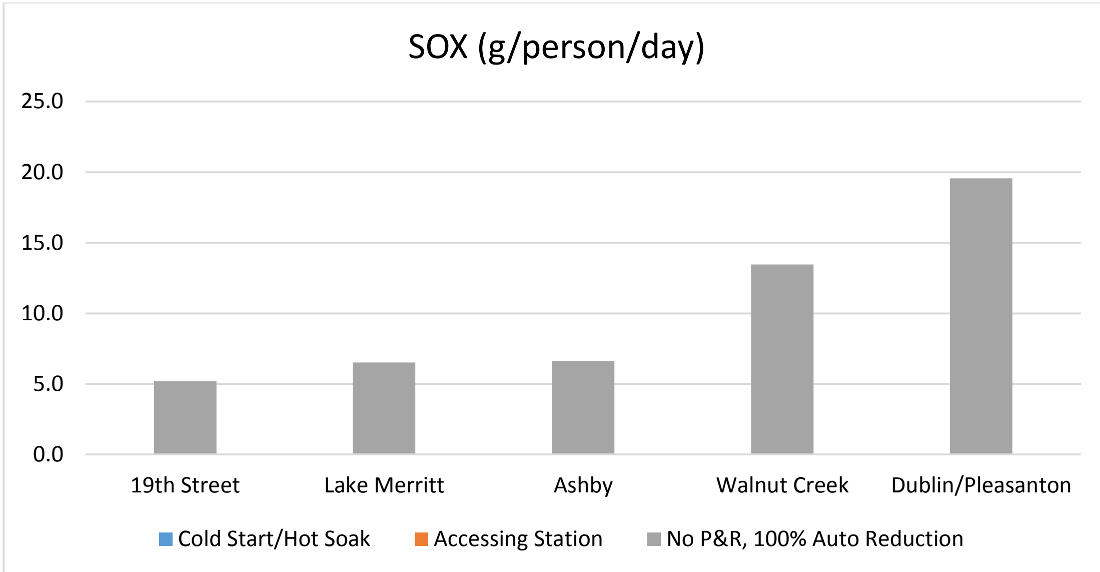

Figure 8. Daily per-passenger SO_x emissions by station

Results of the Kruskal-Wallis test indicated a statistically significant difference in access emissions between stations for all five criteria air pollutants. For each pollutant, I rejected the null hypothesis that access emissions were equal at each station with a p-value of 0.0001. As a result, I performed a Wilcoxon rank-sum test on each station-pair for each pollutant. VOC emissions differed significantly between all pairs except 19^{th} Street-Ashby, Ashby-Lake Merritt, and Lake Merritt-Walnut Creek. CO and PM_{10} emissions differed significantly between all pairs except 19^{th} Street-Ashby, Ashby-Lake Merritt, Lake Merritt-Walnut Creek, and Dublin/Pleasanton-Walnut Creek. NO_x emissions different significantly between all pairs except 19^{th} Street-Ashby, 19^{th} Street-Lake Merritt, Ashby-Lake Merritt, Lake Merritt-Walnut Creek, and Dublin/Pleasanton-Walnut Creek. SO_x emissions differed significantly between all station-pairs with the exception of 19^{th} Street-Ashby, Ashby-Lake Merritt, and Dublin/Pleasanton-Walnut Creek (Appendix B).

According to the scenario analysis, a decrease in park-and-ride and an increase in automobile use would generally increase emissions of VOC, CO, and NO_x while decreasing emissions of PM_{10} and SO_x among current passengers (Figure 9, Figure 10, Figure 11, Figure 12, Figure 13). The "No P&R, 100% Auto Reduction" scenario would result in the lowest VOC, CO, and NO_x emissions at each station, while the "No P&R, Increased Auto Use" scenario would result in the highest VOC, CO, and NO_x emissions at each station. The current state results in higher PM_{10} and SO_x emissions than any of the four alternative scenarios, while the "No P&R, Increased

Auto Use" would result in the lowest SO_x emissions at each station and the lowest PM_{10} emissions at 19^{th} Street and Ashby. The "No P&R, 50% Auto Reduction" would result in the lowest PM_{10} emissions at Lake Merritt, Walnut Creek, and Dublin/Pleasanton.

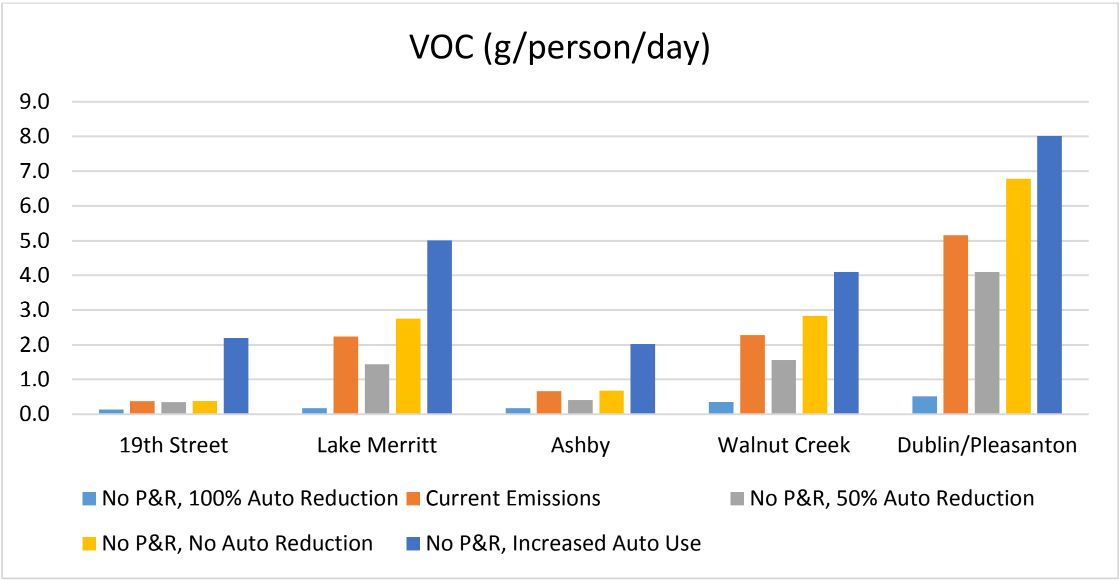

Figure 9. VOC emissions by BART riders under constructed scenarios.

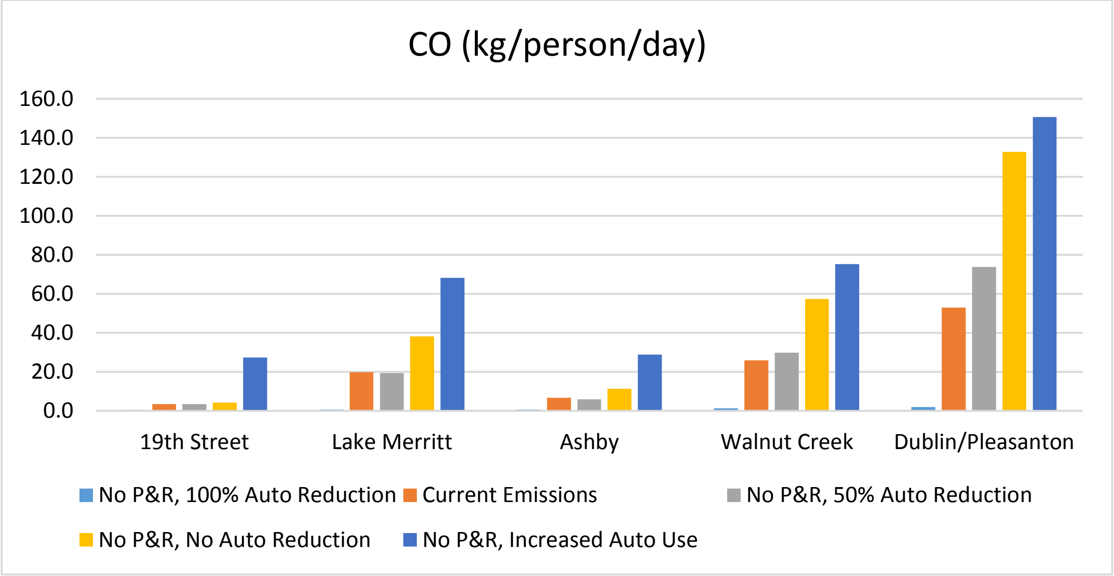

Figure 10. CO emissions by BART riders under constructed scenarios.

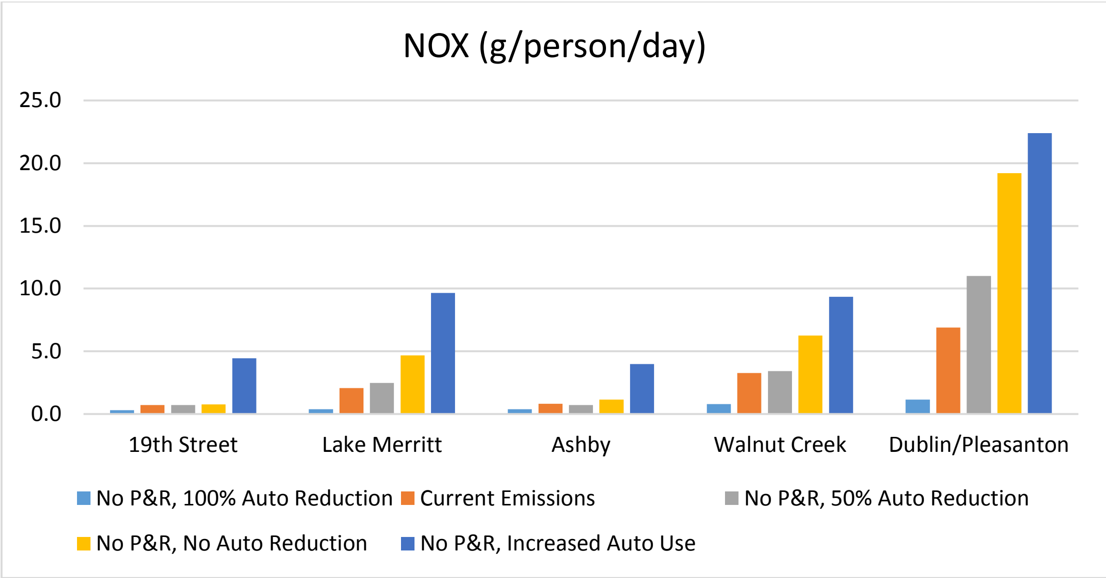

Figure 11. NO_x emissions by BART riders under constructed scenarios.

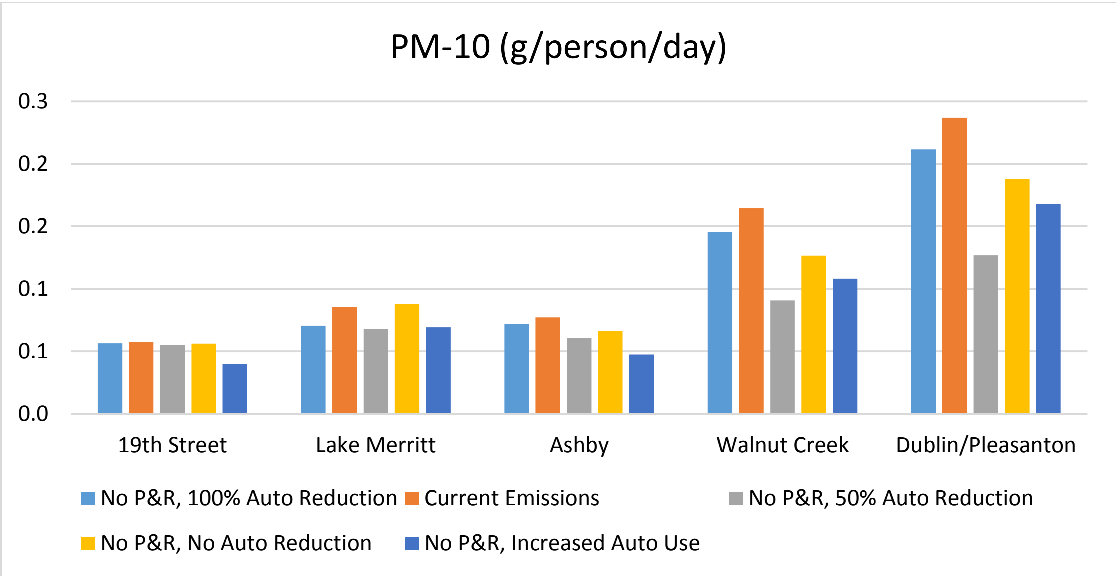

Figure 12. PM_{10} emissions by BART riders under constructed scenarios.

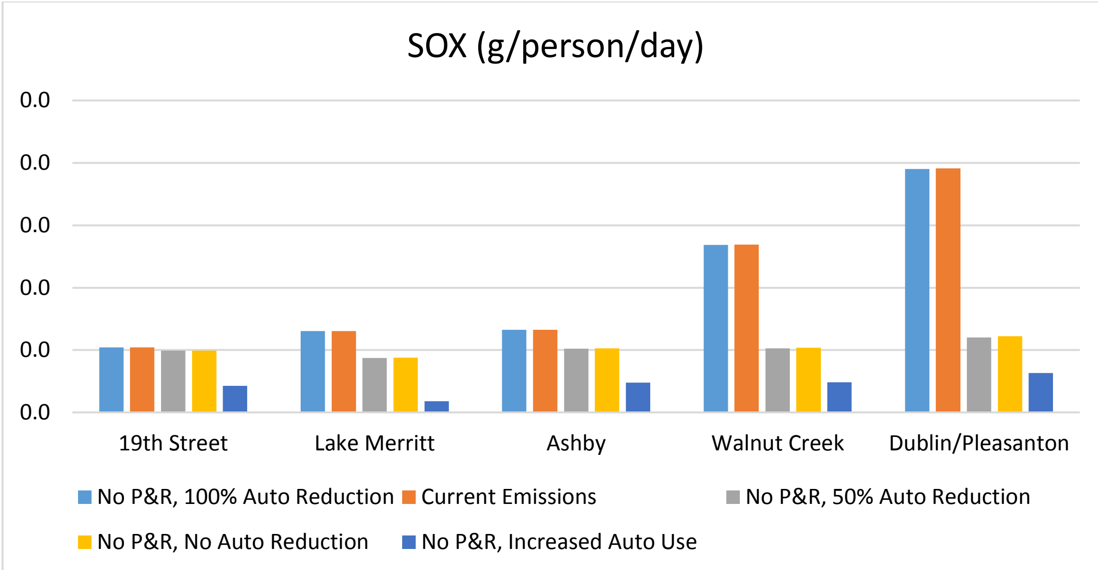

Figure 13. SO_x emissions by BART riders under constructed scenarios.

DISCUSSION

The results of this study largely confirmed my prediction that automobile use and access emissions would increase as density decreased and parking availability increased. However, deviations from this trend suggest that density and parking are not the sole determinants of emissions. As per-passenger emissions under scenarios without park-and-ride would increase for most pollutants in all but the most optimistic scenario, BART's park-and-ride facilities provide important emissions reductions. Despite these benefits, the emissions of many park-and-ride BART trips must be reduced in order to meet climate change mitigation goals. While changes to BART parking policy should be considered, improvements to pedestrian and bicycle access offer stronger potential for emissions reductions.

Demographics

At each station, respondents demonstrated a similar age profile, yet reported higher income levels compared to respondents in the larger 2008 BART Station Profile Study (BART 2008), suggesting that this study effectively represented the overall population of riders. The 25-44 age group was the most common at each station except Walnut Creek in both studies, where the most common age group was 45-64. A larger discrepancy exists between this study and the 2008 BART study with regards to income. At each station, respondents reported income levels higher than those reported by their 2008 counterparts, yet this does not necessarily suggest that this sample was biased. Respondents in 2008 mailed their survey to the researchers, and a higher perception of privacy may have encouraged lower and more honest stated income levels. The 2008 survey was more extensive, and thus may have required more time to complete than this study's survey, discouraging those with a higher opportunity cost of time. Additionally, the population's average income has increased in nominal terms since 2008 and thus the discrepancy may simply reflect a combination of inflation and increased wages.

Travel characteristics

Mode choice results generally confirmed my prediction that automobile use would increase as density decreased and parking availability increased, while the increased bicycle use compared to previous studies suggested a continuing trend toward bike access. With no available parking and very dense surroundings, 19th Street had the highest rate of pedestrian access and the lowest rate of automobile access as expected. Dublin/Pleasanton, with the highest amount of parking and least dense surroundings, had the lowest rate of pedestrian access and the highest rate of automobile access as expected. These findings are consistent with those in the 2008 study, in which the vast majority of 19th Street passengers walked to the station, while the vast majority of Dublin/Pleasanton passengers drove to the station (BART 2008). In addition, bicycle access increased at all five stations compared to 2008 (BART 2008). As bicycle access had also increased at many stations between 1998 and 2008 (Cervero et al. 2012), this suggests that bicycles continue to gain popularity as an access mode. It also gives support for continued improvement of bicycle infrastructure at BART stations, as infrastructure played a key role in the increase between 1998 and 2008 (Cervero et al. 2012).

Greenhouse gas emissions

Greenhouse gas emissions generally confirmed the predicted trends, as access emissions increased as density decreased and parking availability increased. As expected, access emissions were lowest at 19th Street, where density is highest and parking is unavailable, and highest at Dublin/Pleasanton, where density is lowest and parking availability is highest. As access emissions contributed the majority of per-trip emissions for the average passenger at Dublin/Pleasanton and Walnut Creek, this reinforced previous findings that access emissions contribute substantially to overall trip emissions (Mathez et al. 2013). However, access emissions were higher at Lake Merritt than Ashby despite Lake Merritt having lower-density surroundings and fewer parking spaces, suggesting that parking and density do not fully predict a station's access emissions. This deviation from expected trends suggests that policies to reduce access GHG emissions should not focus entirely on increasing density and reducing parking.

The comparison of emissions under different travel scenarios indicates that park-and-ride contributes to a substantial reduction in per-passenger GHG emissions, although access emissions must be reduced at some stations to meet climate change mitigation goals. At each station, the elimination of park-and-ride would increase total GHG emissions for all scenarios except for the unrealistic "No P&R, 100% Auto Reduction" scenario. This suggests that BART's park-and-ride facilities likely contribute to the reduction of GHG emissions, echoing similar findings for other transportation systems (Truong 2013, Gan and Wang 2013). However, this does not imply that current park-and-ride trips are sustainable. For instance, California Executive Order S-3-05 established a GHG emissions target of 80% below 1990 levels to be reached by 2050 (Schwarzenegger 2005). As the state emitted 427 $MtCO_2eq$ of GHG in 1990 (CARB 2007), this equates to 6.2 $kgCO_2eq$/person/day if averaged across California's current population. The average BART trip originating at Walnut Creek and Dublin/Pleasanton emits more than that amount when access emissions are included.

Criteria air pollutant emissions

Criteria air pollutant emissions generally followed expected trends, as access emissions increased as density decreased and parking availability increased. As with GHG emissions, per-person criteria air pollutant access emissions were lowest at 19th Street and highest at Dublin/Pleasanton. However, the extent to which access emissions contributed to total trip emissions varied significantly between pollutants, suggesting access emissions are a greater concern for some pollutants than others. The scenario analysis reflected this variation, as the elimination of park-and-ride facilities would increase emissions of VOC, CO, and NO_x and decrease emissions of SO_x and PM_{10} for most scenarios. The finding that SO_x emissions decrease as passengers switch from BART to automobile-only trips is consistent with research on other electric rail systems (Chester and Horvath 2010) and suggests a tradeoff between SO_x and PM_{10} emissions and emissions of other pollutants. However, as the majority of SO_x and PM_{10} emissions resulted from BART operation and thus electricity generation, these emissions do not occur locally but instead at the site of power generation. As such, SO_x and PM_{10} emissions due to BART are not likely to have the same human health impacts as VOC, CO, and NO_x emissions, which are particularly harmful when emitted along busy roads (Kim et al. 2004). However, SO_x in particular is known to have harmful ecological impacts, specifically through the formation of acid rain (Smith et al. 2011), and thus SO_x emissions at power plants should not be ignored.

Limitations and future directions

A variety of issues limited the effectiveness and reach of my study. The relatively small sample size of 25 passengers per station likely resulted in higher variability than would exist with a larger sample. Additionally, the small sample size made each station's sample more susceptible to outliers and other sources of bias. The ability for potential respondents to decline to take the survey likely contributed to some bias as well. As each survey began with a brief description of its purpose, younger and more educated people may have been more willing to respond upon learning that the survey was for an undergraduate research project. Indeed, passengers at stations with a lower average age and higher average education level than the overall sample participated at a higher rate than passengers at stations with a higher average age and lower average education level. Additionally, the selection of stations limited the external validity of the results for the BART system as a whole. As each study site is located in either Alameda or Contra Costa County, the trends found in this study may not apply to BART stations in San Mateo county or San Francisco, or to other Bay Area rail systems such as CalTrain.

This study could be improved and expanded upon in a variety of ways. More samples at each station would alleviate the issue of small per-station sample size. Specifically, a sample size of 100 at each station would decrease variability and vulnerability to outliers while increasing the study's statistical power. The inherent bias embedded in the response rate could be decreased by deploying more people to perform surveys at a given time and location, a modification which would also increase the practicality of obtaining more samples. The study's external validity could be enhanced by expanding the number of study sites to include a larger proportion of the overall BART system, including at least one station in each Bay Area sub-region served by BART. External validity with regards to other transit systems could be enhanced through a comparative study of access emissions between systems. In addition, behavioral or economic studies of BART park-and-ride would provide greater insight into how policy changes would affect emissions.

Broader implications

This study has strong implications for sustainable BART policy, including support for an altered fee structure and improved pedestrian and bicycle infrastructure. Given the unclear relationship between station parking and emissions, simply reducing the number of parking spaces at each station is not likely to reduce emissions. Moreover, such an action would likely reduce BART ridership and thus would cause economic harm (Merriman 1998). Replacing some station parking with transit-oriented development may counteract the loss in ridership (Willson and Menotti 2007), but such action would not necessarily reduce emissions. An increase in the parking fee could cause passengers to walk, bike, or ride a bus to the station (Habib et al. 2013), but it may also cause drivers to abandon BART and drive directly to their destination. One potential solution to this issue would be to increase the parking fee while decreasing BART fares such that the average park-and-ride trip would stay the same in price.

Aside from adjustments to station parking, improvements to pedestrian and bicycle infrastructure are likely to reduce access emissions. Policies such as improved sidewalks and greater pedestrian connectivity between roads are likely to encourage higher rates of pedestrian access (Cervero 2001). Additionally, bicycle access rates are likely to continue increasing if bike-friendly design and infrastructure is expanded (Cervero et al. 2012). For passengers that are too far from the station to walk or bike, feeder buses are a potential alternative to automobiles (Chandra et al. 2013). However, research has shown that less-occupied buses can produce higher per-passenger emissions than automobiles (Chester and Horvath 2009), suggesting that feeder buses would only reduce emissions if riders are clustered along corridors. As such, pedestrian and bicycle improvements appear to be the strongest choice for reducing access emissions, although any such policy must be implemented in a way that ensures economic and social sustainability in addition to its environmental benefits (Jeon et al. 2013).

ACKNOWLEDGEMENTS

I greatly appreciate the support provided my mentors, instructors, and loved ones. Tim Lipman extensively assisted me in developing my methodology, executing my analysis, and setting realistic goals along the way. Without his encouragement and expertise, my research would not have reached this point. Rachael Marzion provided crucial assistance with GIS, walking me through numerous tasks in ArcMap that I would not have mastered on my own. In addition, Rachael thoroughly reviewed the individual components of this thesis, offering constructive feedback that helped solidify my approach and refine my writing. Kurt Spreyer and Patina Mendez led an engaging senior research course, which provided the structure and support necessary to produce this material. My amazing girlfriend Kara has supported me throughout this process, discussing ideas for topics, tolerating 4 a.m. alarms on mornings of surveys, proofreading portions of my work, and most importantly providing emotional support in times of frustration and stress. Finally, my father Kelan has encouraged and inspired me throughout my life with his strength, optimism, and compassion.

REFERENCES

Andress, D., T. D. Nguyen, and S. Das. 2011. Reducing GHG emissions in the United States' transportation sector. Energy for Sustainable Development 15:117–136.

ANL [Argonne National Laboratory]. 2013. GREET. UChicago Argonne, LLC, Chicago, Illinois, USA.

BART [Bay Area Rapid Transit]. 2008. 2008 BART station profile study. BART Marketing and Research Department and Corey, Canapry & Galanis Research. BART, Oakland, California, USA.

Banister, D., K. Anderton, D. Bonilla, M. Givoni, and T. Schwanen. 2011. Transportation and the environment. Annual Review of Environment and Resources 36:247–270.

CARB [California Air Resources Board]. 2007. Resolution 07-55. Agenda item no.: 7-12-4. CARB, Sacramento, California, USA.

Cervero, R. 1995. Rail access modes and catchment areas for the BART system.

Cervero, R. 2001. Walk-and-ride: factors influencing pedestrian access to transit. Journal of Public Transportation 7.

Cervero, R., B. Caldwell, and J. Cuellar. 2012. Bike-and-ride: build it and they will come.

Cervero, R., and J. Landis. 1997. Twenty years of the Bay Area Rapid Transit system: land use and development impacts. Transportation Research Part A: Policy and Practice 31:309–333.

Chandra, S., M. E. Bari, P. C. Devarasetty, and S. Vadali. 2013. Accessibility evaluations of feeder transit services. Transportation Research Part A: Policy and Practice 52:47–63.

Chester, M. V. 2008. Life-cycle assessment of passenger transportation in the United States. Dissertation, University of California, Berkeley, California, USA.

Chester, M. V., and A. Horvath. 2010. Life-cycle assessment of high-speed rail: the case of California. Environmental Research Letters 5:014003.

Chester, M. V., and A. Horvath. 2009. Environmental assessment of passenger transportation should include infrastructure and supply chains. Environmental Research Letters 4:024008.

De Nazelle, A., B. J. Morton, M. Jerrett, and D. Crawford-Brown. 2010. Short trips: an opportunity for reducing mobile-source emissions? Transportation Research Part D: Transport and Environment 15:451–457.

Dearing, A. 2000. Technologies supportive of sustainable transportation. Annual Review of Energy & the Environment 25:89.

Esri. 2012. ArcMap version 10.1. Esri Inc., Redlands, California, USA.

Feitelson, E. 1994. The potential of rail as an environmental solution: setting the agenda. Transportation Research Part A: Policy and Practice 28:209–221.

Fels, M. F. 1975. Comparative energy costs of urban transportation systems. Transportation Research 9:297–308.

Friedman M.S., K.E. Powell, L. Hutwagner, L.M. Graham, and W. Teague. 2001. Impact of changes in transportation and commuting behaviors during the 1996 Summer Olympic Games in Atlanta on air quality and childhood asthma. Journal of the American Medical Association 285:897–905.

Gan, H., and Q. Wang. 2013. Emissions impacts of the park-and-ride strategy: a case study in Shanghai, China. Procedia - Social and Behavioral Sciences 96:1119–1126.

Habib, K., M. Mahmoud, and J. Coleman. 2013. Effect of parking charges at transit stations on park-and-ride mode choice. Transportation Research Record: Journal of the Transportation Research Board 2351:163–170.

IPCC [Intergovernmental Panel on Climate Change]. 2013. Climate change 2013: the physical science basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, New York, New York.

Jeon, C. M., A. A. Amekudzi, and R. L. Guensler. 2013. Sustainability assessment at the transportation planning level: Performance measures and indexes. Transport Policy 25:10–21.

Kim, J. J., S. Smorodinsky, M. Lipsett, B. C. Singer, A. T. Hodgson, and B. Ostro. 2004. Traffic-related air pollution near busy roads. American Journal of Respiratory and Critical Care Medicine 170:520–526.

Kolpakov, A., and S. Reich. 2013. Role of electric drive transit technologies in reducing greenhouse gas emissions. Pages 420–429 Urban Public Transportation Systems 2013. American Society of Civil Engineers.

Loutzenheiser, D. 1997. Pedestrian access to transit: model of walk trips and their design and urban form determinants around Bay Area Rapid Transit stations. Transportation Research Record: Journal of the Transportation Research Board 1604:40–49.

Mathez, A., K. Manaugh, V. Chakour, A. El-Geneidy, and M. Hatzopoulou. 2013. How can we alter our carbon footprint? Estimating GHG emissions based on travel survey information. Transportation 40:131–149.

Merriman, D. 1998. How many parking spaces does it take to create one additional transit passenger? Regional Science and Urban Economics 28:565–584.

Mingardo, G. 2013. Transport and environmental effects of rail-based park and ride: evidence from the Netherlands. Journal of Transport Geography 30:7–16.

Parkhurst, G. 1995. Park and ride: could it lead to an increase in car traffic? Transport Policy 2:15–23.

Schwarzenegger, A. 2005. Executive order S-3-05. Office of the Governor, Sacramento, California, USA.

Smith, S. J., J. van Aardenne, Z. Klimont, R. J. Andres, A. Volke, and S. Delgado Arias. 2011. Anthropogenic sulfur dioxide emissions: 1850–2005. Atmospheric Chemistry and Physics 11:1101–1116.

Statacorp. 2013. Stata version 13.1. Statacorp LP, College Station, Texas, USA.

Truong, L. C. 2013. The effect of park-n-rides on greenhouse gas emissions.

Willson, R., and V. Menotti. 2007. Commuter parking versus transit-oriented development: evaluation methodology. Transportation Research Record: Journal of the Transportation Research Board 2021:118–125.

APPENDIX A: Survey instrument

Station:	Survey #:
Date:	Time:

Trip Information

How did you arrive to the station today? *(continue in column below answer)*

□ Walk/Bike	□ Automobile	□ Bus/Train/Trolley	□ Other
Did you walk or bike? □ Walk □ Bike What is the nearest major intersection to the start of today's trip? __________________ & _________________ Do you own or have access to a car? □ Yes □ No Are you walking or biking because parking is limited? □ Yes □ No	Did you park nearby? □ Yes, at station □ Yes, not at station □ No, dropped off What is the nearest major intersection to the start of today's trip? __________________ & _________________ What year is the car? __________________ What make is the car (eg. Toyota)? __________________ What model is the car (eg. Hybrid Camry)? __________________	How large was the bus? □ Smaller than most □ Average □ Larger than most Was it a hydrogen fuel cell bus? □ Yes □ No Which route did you take to the station? __________________ Which stop did you originally board at? __________________ &_________________ About how many people were in the vehicle? __________________ Do you own or have access to a car? □ Yes □ No	How did you arrive at the station today? __________________ What is the nearest major intersection to the start of today's trip? __________________ & _________________ Please offer a brief description of the vehicle or method in which you arrived: __________________ __________________ __________________ __________________

	How many people were in the car? ____________________		Do you own or have access to a car? □ Yes □ No

Station:	Survey #:
Date:	Time:

Additional Information

At which station will you be leaving BART? ______________________________

What is the purpose of this trip?

☐ Work ☐ School ☐ Shopping ☐ Social/Recreation ☐ Other

How often do you make this trip?

☐ Daily ☐ 1-3 times a week ☐ 1-3 times a month ☐ Not regularly

What is your age? __________ years

What is your highest level of education?

☐ Some high school ☐ High school degree ☐ Some college ☐ Associate's

☐ Bachelor's ☐ Master's ☐ PhD/JD/MD ☐ Other__________

What is your household's annual pre-tax income?

☐ Under $50,000 ☐ $50,000-$100,000 ☐ $100,000-$200,000 ☐ Above $200,000

APPENDIX B: Wilcoxon rank-sum results

Table B1. **P-values of Wilcoxon rank-sum test comparing GHG emissions between each station pair. * indicates a statistically significant difference at the 5% level.**

Station	**19th Street**	**Ashby**	**Dublin/Pleasanton**	**Lake Merritt**	**Walnut Creek**
19th Street	-	0.2197	0.0000*	0.0294*	0.0000*
Ashby	-	-	0.0001*	0.3036	0.0005*

Dublin/Pleasanton	-	-	-	0.0024*	0.9243
Lake Merritt	-	-	-	-	0.0085*
Walnut Creek	-	-	-	-	-

Table B2. **P-values of Wilcoxon rank-sum test comparing VOC emissions between each station pair. * indicates a statistically significant difference at the 5% level.**

Station	**19th Street**	**Ashby**	**Dublin/Pleasanton**	**Lake Merritt**	**Walnut Creek**
19th Street	-	0.3398	0.0000*	0.0498*	0.0005*
Ashby	-	-	0.0001*	0.2670	0.0057*
Dublin/Pleasanton	-	-	-	0.0110*	0.0435*
Lake Merritt	-	-	-	-	0.0800
Walnut Creek	-	-	-	-	-

Table B3. **P-values of Wilcoxon rank-sum test comparing CO emissions between each station pair. * indicates a statistically significant difference at the 5% level.**

Station	**19th Street**	**Ashby**	**Dublin/Pleasanton**	**Lake Merritt**	**Walnut Creek**
19th Street	-	0.3398	0.0000*	0.0498*	0.0004*
Ashby	-	-	0.0001*	0.2670	0.0035*
Dublin/Pleasanton	-	-	-	0.0058*	0.0788
Lake Merritt	-	-	-	-	0.0684
Walnut Creek	-	-	-	-	-

Table B4. **P-values of Wilcoxon rank-sum test comparing NO_x emissions between each station pair. * indicates a statistically significant difference at the 5% level.**

Station	**19th Street**	**Ashby**	**Dublin/Pleasanton**	**Lake Merritt**	**Walnut Creek**
19th Street	-	0.4046	0.0000*	0.0660	0.0004*
Ashby	-	-	0.0000*	0.2670	0.0027*
Dublin/Pleasanton	-	-	-	0.0035*	0.0829
Lake Merritt	-	-	-	-	0.0721
Walnut Creek	-	-	-	-	-

Table B5. P-values of Wilcoxon rank-sum test comparing SO_x emissions between each station pair. * indicates a statistically significant difference at the 5% level.

Station	19th Street	Ashby	Dublin/Pleasanton	Lake Merritt	Walnut Creek
19th Street	-	0.2197	0.0000*	0.0294*	0.0000*
Ashby	-	-	0.0002*	0.3716	0.0005*
Dublin/Pleasanton	-	-	-	0.0038*	0.9810
Lake Merritt	-	-	-	-	0.0059*
Walnut Creek	-	-	-	-	-

Table B6. P-values of Wilcoxon rank-sum test comparing PM_{10} emissions between each station pair. * indicates a statistically significant difference at the 5% level.

Station	19th Street	Ashby	Dublin/Pleasanton	Lake Merritt	Walnut Creek
19th Street	-	0.2958	0.0000*	0.0399*	0.0001*
Ashby	-	-	0.0002*	0.2910	0.0044*
Dublin/Pleasanton	-	-	-	0.0230*	0.2167
Lake Merritt	-	-	-	-	0.1366
Walnut Creek	-	-	-	-	-