Societal Impacts of a Complete Street Project in a Mixed Urban Corridor: Case Study in Pittsburgh

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Abstract: Complete streets facilitate multimodal travel by improving both transportation access and safety by emphasizing the user, not the automobile. This case study evaluates the impacts of a complete street retrofit on a mixed urban corridor in Pittsburgh. Forbes Avenue, originally a 4-lane urban arterial (two lanes in each direction, with no dedicated bike lanes), was reduced to three lanes (one lane in each direction and a center turn lane) and two bike lanes. A quantitative before-and-after analysis was conducted using multiple data sources. Results indicate that traffic volumes decreased by 11%–31%, bicycle counts increased by 160% and 280% during the peak AM and PM hours, respectively, and average PM2.5 concentrations were reduced from 9.1 $\mu g/m^3$ to 7.6 $\mu g/m^3$ when compared to preretrofit conditions. During construction (August 2018–July 2019), vehicle and pedestrian safety were not adversely impacted. Additionally, no crashes were reported by the Pennsylvania Department of Transportation in the five months following project completion. Results from this analysis can help inform the decision-making process for transportation planners exploring complete street projects with similar community and roadway traffic characteristics. **DOI:** 10.1061/(ASCE)IS.1943-555X.0000609.

Introduction

Complete streets are roadways designed to accommodate multiple modes of transportation to improve access and safety for all community members. Such projects seek to improve active and public transit infrastructure (e.g., bike lanes, sidewalks, and bus shelters) to both promote sustainable modes of travel and improve access for the nondriving population. Other examples include dedicated bus lanes, reduction in automobile lanes, sidewalk widening, increased vegetation, transit signal priority, among others (Sousa and Rosales 2010). In this research, specific outcomes from a complete street reconstruction project in Pittsburgh, were analyzed. Multiple sources of data were collected (e.g., traffic volumes and speeds, bicycle counts, transit ridership, air quality, and crash frequencies) and analyzed to help quantify the costs and benefits for complete street projects. This is a prototype of a smart mobility project that involves new technologies, multiple modes, and measures to improve bike, pedestrian, and vehicle safety.

Complete street projects can provide numerous benefits to communities through improvements to safety, accessibility, and sustainability (Anderson et al. 2015). To create additional space for infrastructure improvements, automobile lanes are often reduced, and this is referred to as a road diet. While road diets often result in numerous direct and indirect benefits, the reduction of automobile lanes can also lead to higher travel costs from congestion and increased travel times. However, traffic calming measures are often implemented to improve bicycle and pedestrian safety. Since project location, the built environment, public transit options, and specific project goals all affect outcomes in diverse ways, local analysis is required to accurately quantify benefits and provide insight for future decision making in the Pittsburgh region. This project seeks to assess changes in vehicle crashes, vehicle counts, travel speed, air quality, bicycle counts, and public transit ridership before and after complete street reconfiguration using a case study. Data were collected for this study from various sensors and cameras deployed throughout the corridor.

Literature Review

Complete streets have been growing in popularity in recent years due to low project costs and numerous community benefits. In Anderson et al. (2015), of the 37 complete street projects analyzed, 74% cost less than the average Federal Highway Administration (FHWA) estimates of normal-cost arterials. These costs are estimated for minor arterial realignment projects in urban areas. Benefits vary by project location and goals but often include reductions in crash frequencies and improved access for the nondriving population. According to ASCE policy statement 537, 25% of walking trips occur on roadways with no sidewalks, and only 5% of bike trips have bike lanes available. Additionally, motorist-centric roadways limit mobility options for the one-third of Americans who do not drive (ASCE 2011).

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Complete street projects often require a reduction in automobile lanes to accommodate improved infrastructure for walking, biking, and public transit. Depending on traffic volumes, reconfiguration can result in delays for the automobile traveler. While several case studies have found a decrease in traffic speeds after complete street retrofits (FHWA 2017; Noland et al. 2015), other studies have found no change in traffic speeds (FHWA 2017; City of Orlando 2002). In a case study in Seattle, WA, a 3.2-km (2-mi) stretch of roadway (7,100–11,000 vehicles/day) was converted from four lanes (two lanes each way) to three lanes (one lane each way with a center turn lane). Transit times through the corridor remained unchanged after the retrofit (FHWA 2017). In a similar study in Orlando, FL, travel times were reduced by 5% during the PM peak in the southbound direction but increased by 25% during the AM peak in the northbound direction (City of Orlando 2002). From a speeding perspective, all studies that analyzed instances of speeding (FHWA 2017; Nixon et al. 2017; Anderson et al. 2015) found large reductions in speeding incidents. Anderson et al. (2015) found that in three complete streets projects in Seattle, WA, the count of speeders (defined by >10 mph over the speed limit) was reduced by 90%, 69%, and 75%, respectively.

Traffic volumes can also be affected by lane reconfiguration and/or lane reduction. When road diet sections observed average daily traffic volumes greater than 20,000 vehicles/day, it was estimated that neighboring streets will observe increased traffic volumes because congestion on the road-diet section increases to a point where traffic begins to divert to alternate routes (Huang et al. 2002; Sallaberry 2000). Other similar studies observed a decrease in vehicle counts after the retrofit (FHWA 2017; City of Orlando 2002; Sallaberry 2000; Nixon et al. 2017). In the study by Nixon et al. (2017), traffic counts were reduced after project completion and nearby corridors (without a retrofit) observed no increase in traffic volume. This observation indicates that either vehicles are being diverted to drastically different routes, or there is some local mode shift.

Complete streets address accessibility and sustainability by accommodating a diverse set of travel modes. Multimodal corridors provide additional travel opportunities for the nondriving population while also addressing sustainability, defined by Jeon and Amekudzi (2005), as projects that "impact the environment, the economy, and social well-being." Designs often incorporate improved active and public transit infrastructure (e.g., wider sidewalks, bike lanes, dedicated bus lanes, among others). Numerous studies have found significant growth in bicycle traffic after a complete street retrofit (FHWA 2017; City of Orlando 2002; Gudz et al. 2016; Sallaberry 2000; Anderson et al. 2015; Fine and Tapase 2017; Barnes and Schlossberg 2013; Zhu et al. 2016). The overall increase in bicycle traffic is dependent on many factors; however, all study projects observed significant upticks in bicycle traffic ranging from 30%–243%. Few studies analyzed changes in public transit ridership along complete streets corridors. A case study in Seattle (FHWA 2017), determined that transit ridership increased by 30%. Additionally, of the seven case studies analyzed by Anderson et al. (2015), six observed increased bus ridership. The one case where a decrease in transit ridership was observed can be attributed to transit service changes along the corridor. Additionally, from an air quality standpoint, Zhu et al. (2016) found that complete street corridors observed a decrease in ultrafine particulates (UFP) ($-1{,}300\ \text{particles/cm}^3$) and a small reduction in PM2.5 ($-0.3\ \mu\text{g/m}^3$) compared to incomplete street locations. A similar study in Santa Monica, CA found UFP concentrations decreased by $4{,}200\ \text{particles/cm}^3$ and no significant change in PM2.5 concentrations (Shu et al. 2014). Both studies used mobile sensing units to collect on-roadway particulate matter concentrations.

From a safety standpoint, numerous studies have analyzed accident counts before and after complete street retrofits. Of the 13 case studies mentioned in a report by the Federal Highway Administration (FHWA 2017), crashes were reduced from 9% to 65% after a complete street retrofit. Crashes decreased in all case studies. In a report by the Pedestrian and Bicycle Information Center (Thomas 2013) that summarized six road-diet studies, accidents decreased by 19% and 47% in urban and rural areas, respectively. A case study in Orlando, FL, found a 34% decrease in crash rate (per million vehicle miles) and a 64% decrease in injury rate along a 20,000 vehicles/day corridor (City of Orlando 2002). Huang et al. (2002) analyzed 12 road-diet sites along with 25 comparison sites and found that road-diet sites observed a 6% reduction in crashes compared to control sites. A similar study by Pawlovich et al. (2006) analyzed 15 road-diet sites and 15 comparison sites in Iowa and found a 25% reduction in crash frequency and 19% reduction in crash rate in the road-diet locations. Noland et al. (2015) found a 19% reduction in vehicle crashes along a complete streets site in New Brunswick, NJ. The study also concluded that safety benefits outweighed any additional costs from added travel time in the study region. A study conducted by Hanson and Botchwey (2018) focused on pedestrian and bicycle accidents and found that two out of the three projects observed a reduction in accidents. The one corridor with increased pedestrian accidents did not have continuous walking/biking infrastructure improvements throughout the corridor.

To summarize the existing literature, complete streets retrofits seek to improve multimodal options through urban corridors. While specific project goals vary, most projects observe one or more of the following outcomes: increase in bicycle/walking traffic, increase in public transit ridership, improved air quality, or reduction in crash rates and frequencies. Because of the large variation in project outcomes across locations, there is a need to study such projects in different locations with diverse project goals. Additionally, many case studies focus on one, or a few metrics (e.g., air quality or traffic accidents). To adequately quantify the benefits of a complete streets project, a holistic approach is required to assess and recommend such projects to local transportation planners. Three contributions to the existing literature are highlighted as follows:

- High-resolution, multimodal data sources are collected (traffic counts/speeds, bus ridership, bicycle counts, air quality measurements, and crash frequencies) continuously for a two-year period to quantify outcomes across a diverse set of metrics.
- Quantitative analysis was conducted with unique project characteristics (e.g., 13,000 vehicles/day, the corridor connects the residential area with a business district, the corridor is adjacent to a major university, and urban).
- Project outcomes are compared with projections from a local engineering study.

Through this analysis, a more complete picture regarding the potential benefits of a complete street retrofit is gained to help inform industry best practices.

The remainder of this paper is organized as follows. Project Information and Data characterizes the specific complete street project in Pittsburgh. Data sources used for the before-and-after analysis are also discussed. Sections Automobile Traffic, Vehicle Traffic Volume, and Vehicle Traffic Speeds discuss vehicle count analysis methods and impacts to vehicle traffic volumes and vehicle speeds. The Engineering Study Comparison compares traffic volume projections to observed traffic counts. Bicycle counts, public transit ridership, air quality, and crash counts present before-and-after results for each of the defined metrics. The Discussion provides a summary of the results and compares results with previous literature. The Conclusion outlines specific project characteristics, makes recommendations about data collection and analysis techniques for future project analyses, highlights study limitations, and discusses future work.

Project Information and Data

Forbes Avenue, located in Pittsburgh, is a major arterial of approximately 10 km (6 mi) that serves both major business districts in the city; the downtown central business district and the Oakland business district (home to two major universities and a large hospital system). Up until the late 1960s, the corridor consisted of two automobile lanes (one in each direction) and two centered tracks for streetcars. After the retirement of Pittsburgh streetcars, the Forbes Avenue corridor was converted to a 4-lane arterial (two lanes in each direction) without bicycle lanes. In 2019, a complete street reconfiguration was completed in the heart of Carnegie Mellon University's campus along Forbes Avenue between Margaret Morrison and Craig Street (see Fig. 1 for details). The corridor, approximately 1 km (2/3 mi) in length, bisects and directly serves Carnegie Mellon University (CMU) while also connecting the Squirrel Hill residential neighborhood with the Oakland business district. Construction began in August 2018 and finished in July 2019. Fig. 2 shows before-and-after reconfiguration images facing west, taken on CMU campus, and facing the University of Pittsburgh. The average annual daily traffic in this corridor was 13,000 vehicles per day on Forbes Avenue prior to the retrofit. Included in the reconfiguration was

- Reduction of vehicle lanes from four to three with the center lane dedicated to turning movements.
- Introduction of bike lanes.
- Addition of a pedestrian crosswalk with signals.
- Reconfiguration and relocation of several intersections and adoption of advanced, adaptive traffic signals.

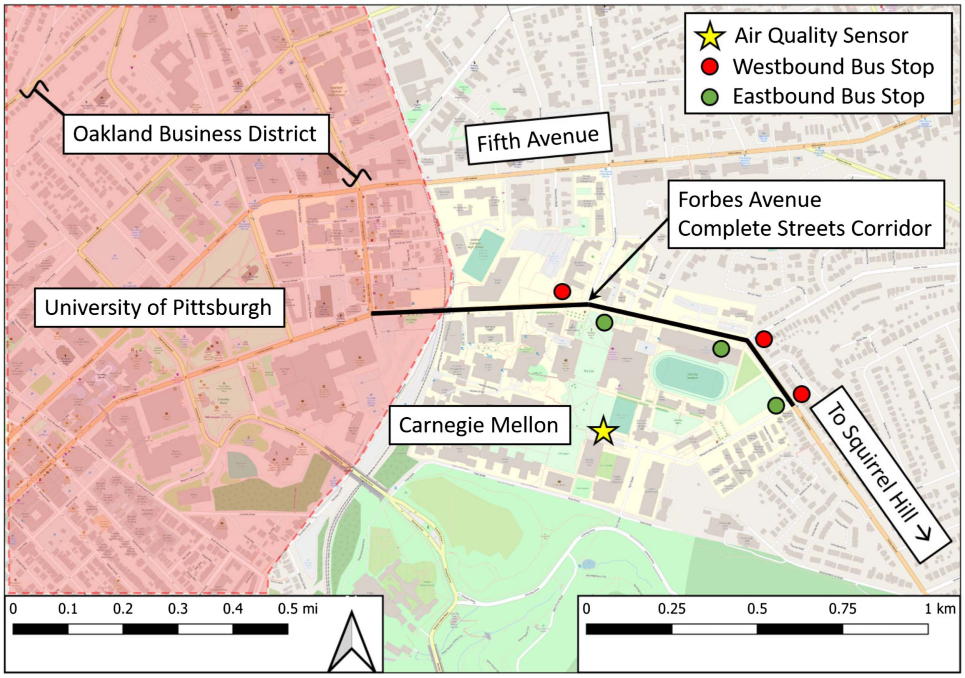

Fig. 1. Complete streets corridor. (Base map and data from OpenStreetMap and OpenStreetMap Foundation.)

Fig. 2. Forbes Avenue Street configuration pre- and post-retrofit. (Images by Chris T. Hendrickson.)

Table 1. Data summary

Data	Source	Use
Traffic counts	Video camera installed along the corridor	Vehicle counts along Forbes Ave.
Traffic speeds	INRIX	Vehicle speeds at Forbes and Fifth
Bicycle counts	Video camera installed along the corridor	Bicycle counts along Forbes Ave.
Air quality	Sensors installed at Carnegie Mellon	PM2.5, NO_2, CO concentrations
Public transit ridership	Port Authority of Allegheny County	Bus ridership along Forbes Ave.
Crash counts	Pennsylvania Dept. of Transportation	Crash incidents along Forbes Ave.

- Construction of improved bus turn outs, new streetlights, new pavement, and new street furniture.

The realignment reduced automobile lanes from four (3 m width) to three (3 m width) with the inclusion of two bicycle lanes (1.5 m width). The project construction included utility coordination and relocation (water, sewer, and electric), five new traffic signals with communications, new paving, street furniture, landscaping/tree trimming, signage, new pedestrian crossing, improved drainage, re-striping, and several new concrete curb ramps. Total project costs were on the order of \$4 million (~\$4 million/km). To provide context, estimates provided by the Federal Highway Administration classify projects costing approximately \$2.3 million/km as "normal-cost" and \$8 million/km as "high-cost." These estimates are provided for minor arterial realignment projects in urban settings (Anderson et al. 2015). However, many of the benefits observed in this study could likely be achieved at much lower costs (e.g., re-striping costs only). To support this claim, Des Moines, IA spent approximately \$300,000 on restriping, benches, planters, and bike racks and found a 57% reduction in crashes, even with higher traffic volumes (Anderson et al. 2015).

This study was motivated by the Forbes Avenue Reconfiguration Study (GAI Consultants 2015), which presented a reconfiguration approach that "would calm traffic and would better meet the needs of motorists, transit riders, pedestrians, and bicycles" in the complete street corridor. Project duration lasted one year due to many holdups including utility coordination and relocations. Multiple stakeholders were involved, and numerous delays were observed due to communication and coordination among multiple parties.

The total duration for the research project was two years (Fall 2017–Fall 2019). During this period, it is assumed that population characteristics and/or land use in the nearby community remain stable, which could influence the before-and-after results. Pittsburgh's median income increased from \$44 k to \$45.8 k from 2017 to 2018. The total number of commuters remained unchanged at 150 k for both years. The White and Asian population proportions were similar in both years; however, the African American population dropped from 23.6% in 2017 to 23.4% in 2018 (US Census Bureau 2018). The 2019 data have not been released; however, large changes in population characteristics between these years is not expected.

The project analyzes multiple sources of data to provide a more complete summary of complete street benefits that can be used by local planning agencies during the decision-making process. Table 1 summarizes the data used for analysis and their various sources.

Table 2. Periods used for traffic volume analysis

Period	Week selected
Before	April 9–13, 2018
During	October 15–19, 2018
After	October 7–11, 2019

Automobile Traffic

Impacts to traffic volumes and speeds are expected to change after the Forbes Avenue complete street retrofit because the number of vehicle lanes was reduced from two lanes in each direction to one lane in each direction with a center turn lane. Traffic volumes are presented for three time periods; (1) before construction (up through August 2018), (2) during construction (August 2018–July 2019), and (3) after construction (August 2019–present). The during construction period is included because the construction phase lasted for one year, which likely had implications to the traffic metrics presented due to transient construction operations. The after construction period was selected to begin in August 2019 because construction finished during July.

Vehicle Traffic Volume

To collect traffic counts data for the time periods of interest, a camera was installed in March 2018 on the Carnegie Mellon campus in a building adjacent to the complete streets corridor to collect and store traffic data. The morning peak is defined for times between 7:30 a.m.–9 a.m., and the evening peak is defined for times between 4:30 p.m.–6 p.m. The peak periods were chosen based on the peak-periods outlined by the preconstruction engineering study (GAI Consultants 2015). Videos were stored in five-minute segments (e.g., 7:30 a.m.–7:35 a.m. and 7:35 a.m.–7:40 a.m.) during morning and evening peaks.

To determine the traffic volumes for the selected periods, one week was selected for each period for analysis and only weekdays were analyzed. All three weeks (one for each period) were selected to occur during either the spring or fall semester to control for peak student populations attending Carnegie Mellon University or the University of Pittsburgh. The weeks selected are shown in Table 2.

For each day, nine five-minute videos were selected for the morning peak (7:30 a.m.–7:45 a.m., 8:00 a.m.–8:15 a.m., 8:30 a.m.–8:45 a.m.) and evening peak (4:30 p.m.–4:45 p.m., 5:00 p.m.–5:15 p.m., 5:30–5:45 p.m.) to determine the traffic counts during each period. Hourly counts were then calculated by multiplying the observed counts for each five-minute segment by 12 to get a representative hourly count. The results are shown in Figs. 3 and 4.

In all cases, traffic volumes were reduced after reconfiguration. To test the significance of the traffic volume changes, a one-tailed t-test with unequal variances was conducted. The reduction in traffic volumes was significant to the 95% level in all cases when comparing the before and after cases. The morning peak for eastbound traffic and both the morning and evening peak for westbound traffic observed reductions in vehicle counts ranging from 11% to 21%. The one case with higher traffic volumes to begin with (evening peak for eastbound traffic) observed a larger reduction in traffic volume after the complete street retrofit. The mean hourly traffic counts for this case dropped from 789 vehicles/h in the before period to 548 vehicles/h in the after period, a 31% reduction.

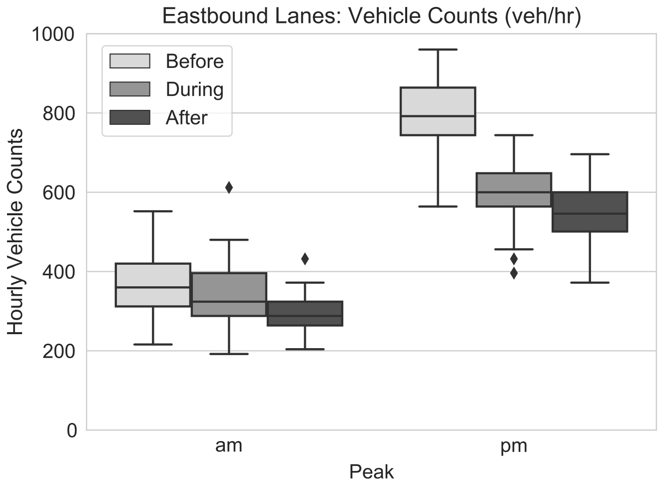

Fig. 3. Eastbound traffic volumes.

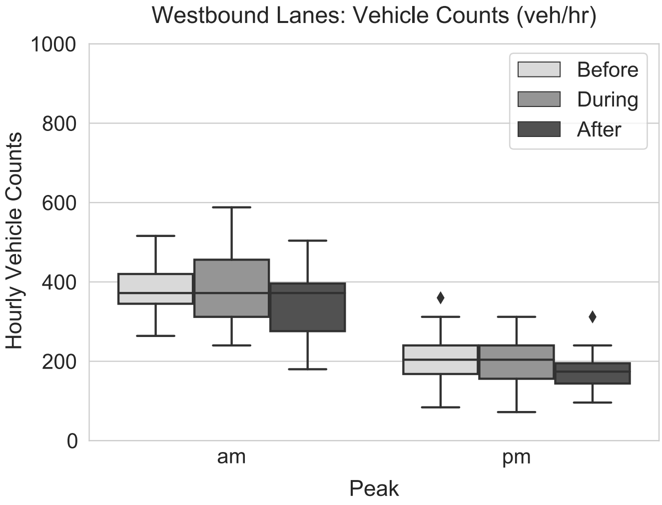

Fig. 4. Westbound traffic volumes.

Table 3. Mean travel speeds before and after reconfiguration

Street	Direction	Peak	Before (km/h)	After (km/h)	Difference (km/h)	Significance level
Forbes avenue	Eastbound	a.m.	26.7	22.0	−4.7	0.01[a]
		p.m.	25.3	16.6	−8.7	0.01[a]
	Westbound	a.m.	22.4	14.2	−8.2	0.01[a]
		p.m.	18.8	14.8	−4.0	0.01[a]
Fifth avenue	Eastbound	a.m.	28.0	27.8	−0.2	>0.1
		p.m.	25.1	23.8	−1.3	0.05[b]
	Westbound	a.m.	14.0	15.1	1.1	0.05[b]
		p.m.	20.1	24.0	3.9	0.01[a]

[a] Significant at the 99% level.
[b] Significant at the 95% level.

The case with higher traffic volumes to begin with observed the steepest reduction in traffic counts after the retrofit.

Vehicle Traffic Speed

INRIX (2020) probe-based traffic speed data were used to compare traffic speeds before and after the complete streets retrofit. Only real-time data were used to calculate traffic speeds along road segments of interest. Since data were available for the fall semester in 2017, comparative weeks were selected (September 11–15, 2017 and September 9–13, 2019) to analyze traffic speeds before and after reconstruction. The weeks differ from the vehicle counts data mentioned in the previous section because vehicle count data were not available in the fall of 2017. Additionally, a parallel corridor (Fifth Avenue, shown in Fig. 1) was analyzed for the same periods to study the effects of diverting traffic on a nearby corridor. Table 3 displays the average vehicle speeds before and after the reconfiguration for both directions during both morning and evening peaks.

From Table 3, Forbes Avenue traffic speeds were reduced in all cases. Mean travel speeds were reduced by 4.0–8.7 km/h (2.5–5.4 mph), or by 15%–37%. All reductions were significant using a one-tailed t-test with unequal variances. No clear trend can be observed along Fifth Avenue. Traffic speeds increased in the westbound direction but decreased in the eastbound direction. Not all changes were significant and the differences in speeds between before and after periods were minimal. From this, a conclusion can be made that diverting traffic from Forbes Avenue did not adversely affect traffic speeds on Fifth Avenue. The results also indicate that the reconfiguration was effective in calming traffic along Forbes Avenue.

Engineering Study Comparison

In the reconfiguration study by GAI Consultants (2015), a local engineering firm, existing traffic conditions were evaluated to estimate the traffic impacts for the proposed complete street reconfiguration. In addition to signal timing and turn lane analysis, the study also projected future traffic flows through the corridor one year after the completion of the project. These projections were used to design the realignment and avoid problematic queues. Table 4 compares before and after traffic volumes for the GAI study and the observed values from this study.

The GAI study used a 0.25% annual growth rate to project traffic volumes after the reconfiguration and make recommendations regarding signal timing and turn lane design. Before traffic counts were similar for both CMU and GAI volume counts. The GAI projected (after) traffic volumes were 19%–33% higher compared to observed traffic counts. This result indicates that the 0.25% growth rate for similar complete street projects might be conservative.

Bicycle Counts

Improved accessibility and safety for active transit modes is a common goal for complete street projects. The addition of bike lanes, pedestrian crosswalks, and traffic calming measures create

Table 4. Traffic volume comparison of GAI study and observed values

Period	Peak	Eastbound (GAI projections)	Eastbound (observed)	% Difference	Westbound GAI projections	Westbound observed	% Difference
After	a.m.	357	289	−19	512	341	−33
	p.m.	816	548	−33	226	174	−23

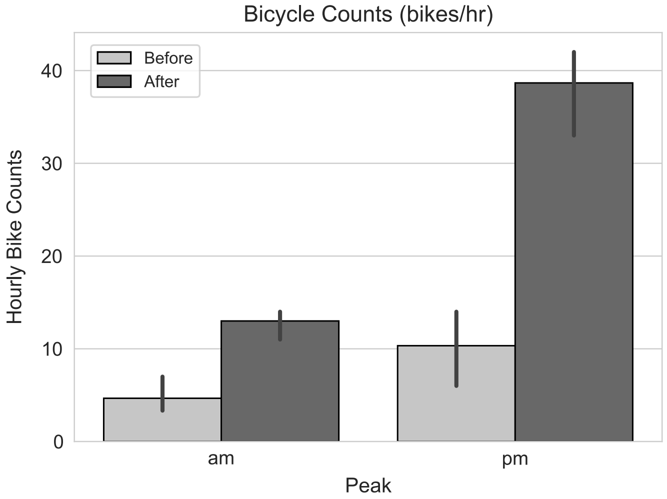

Fig. 5. Before and after bicycle counts.

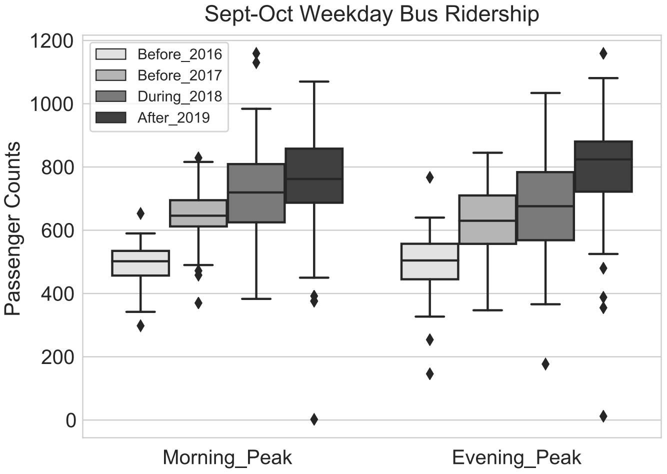

Fig. 6. Before and after bus ridership.

a safer environment for active commuters, and an increase in bicycle traffic is expected after the retrofit. In this analysis, three weekdays in April 2018 and September 2019 are selected for the before and after periods, respectively. The before and after weeks were selected to capture days with similar weather conditions (e.g., temperature and precipitation). Archived videos were used to count bicycle traffic for each period. One hour of video was selected for both the morning (8–9 a.m.) and afternoon peak (5–6 p.m.) periods and total bicycles using the roadway were counted for comparison. One-hour videos were selected because bicycles are rare and multiplying a five-minute video by 12 to achieve an equivalent hourly volume would be incorrect. Precipitation was not observed during the selected days. Fig. 5 plots total bicycle traffic before and after the retrofit.

Average bicycle counts grew from 5 to 13 bicycles/hour during the morning peak (+160%) and from 10 to 38 bicycles/hour during the evening peak (+280%). The fact that the corridor connects residential neighborhoods to a nearby business district likely influences the large increase in bicycle traffic. While only a few select days were used in this analysis, the sheer magnitude of the increase indicates that more bicycle commuters feel safe using the complete street corridor and matches large anecdotally observed increases in bike lane users.

Public Transit Ridership

The Forbes Avenue corridor is one of two major bus corridors (the other being Fifth Ave.) connecting numerous residential neighborhoods to both major business districts in Pittsburgh. However, our interest centers around the bus stops located within the complete street corridor, therefore, the analysis was limited to three stops eastbound and three stops westbound within the reconfiguration zone (see Fig. 1 for stop locations). This analysis method primarily looks at travelers commuting to and from Carnegie Mellon University, as it is the only large destination within the corridor extents.

Bus ridership data was obtained from the Port Authority of Allegheny County for two years prior to the retrofit up through the fall of 2019. All weekdays in September and October were used from 2016 to 2019 for this analysis. Because commuters affiliated with Carnegie Mellon might not follow the typical 9–5 workday due to class schedules, larger time windows for the morning (7 a.m.–10 a.m.) and evening (4 p.m.–7 p.m.) peak periods were used. Egress counts at all six bus stops were used for morning ridership counts, and boardings at all six bus stops were used for evening ridership counts. The growth in student enrollment remained constant at 1% growth between 2016 and 2019, and the number of buses serving the region during morning and evening peaks also remained constant. Both universities provide students with prepaid bus cards and have done so since before 2016. Fig. 6 plots total bus ridership counts (egress or boardings) for the morning and evening peaks for the different periods of interest.

Fig. 6 shows that bus ridership along the complete street corridor has observed a steady increase since 2016. Median morning peak riders arriving at Carnegie Mellon stops increased from 502 in 2016 to 646 (+28%), 719 (+11%), and 762 (+6%) in 2017, 2018, and 2019, respectively. Median evening peak riders boarding at Carnegie Mellon increased from 504 in 2016 to 630 (+25%), 676 (+7%), and 824 (+22%) in 2017, 2018, and 2019, respectively. The increase in bus ridership was significant at the 95% level when comparing before and after conditions using a one-tailed *t*-test with unequal variances. Since the student population and the number of buses serving the area have remained constant, it is difficult to attribute the ridership changes to any specific known factor. Bus ridership does still increase after the complete street retrofit, but based on the upward trend, it is difficult to attribute the increase in ridership to the complete street project itself. Access to bus stops adjacent to the Carnegie Mellon campus did not change during the complete street project, so only small changes in bus ridership were expected. However, as the campus continues to develop north of Forbes Avenue, it will be interesting to monitor transit ridership in the years to come.

Air Quality

Air quality sensors were installed on Carnegie Mellon campus 275 m (900 ft) south from the complete street corridor to measure PM2.5, NO_2, and CO concentrations. Sensors were installed in 2017 and remained installed through the end of October 2019. The sensors recorded concentrations every 15 min throughout this period. The months of September and October were selected for analysis to limit seasonal fluctuations in PM2.5. Fig. 7 plots average daily PM2.5 concentrations for each period. Fig. 8 plots average hourly PM2.5 concentrations with 95% confidence intervals.

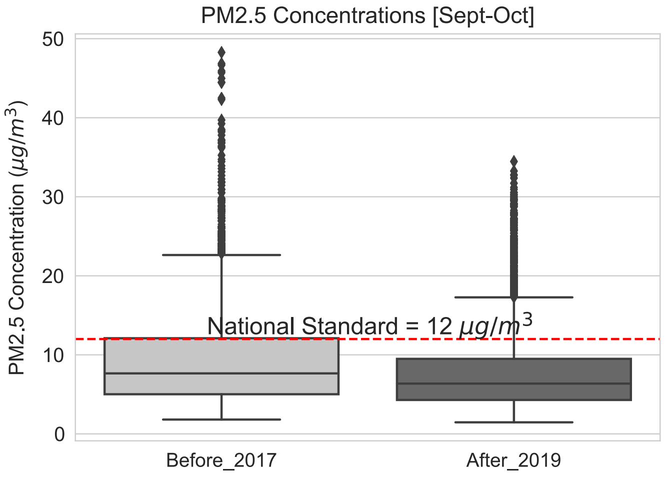

Fig. 7. Average PM2.5 concentrations.

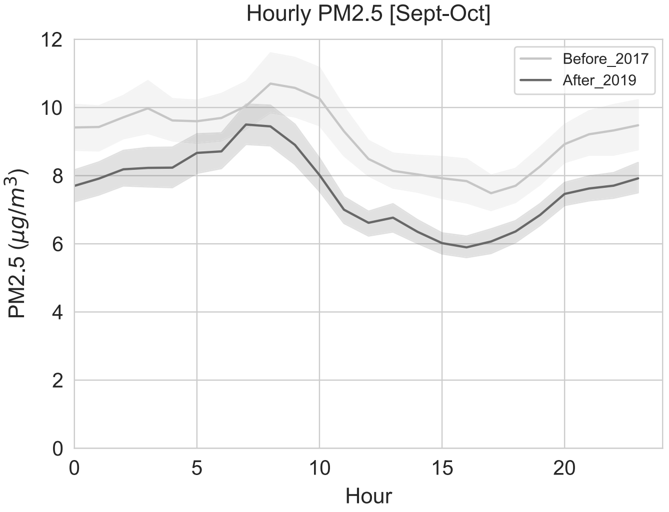

Fig. 8. Hourly PM2.5 concentrations.

The mean PM2.5 concentration decreased from 9.1 $\mu g/m^3$ to 7.6 $\mu g/m^3$ after the completion of the complete street retrofit. In both periods, the inner quartile range remained below the 12 $\mu g/m^3$ national standard set by the Environmental Protection Agency (EPA) in 2012. The time series plot illustrates daily fluctuations of PM2.5 with 95% confidence intervals. There is a morning peak in PM2.5 concentrations; however, a dip is observed during the evening peak, seeming to indicate that other factors are influencing PM2.5 concentrations beyond the roadway corridor.

NO_2 and CO concentrations were also collected for analysis. Both NO_2 and CO are emitted from burning fossil fuels and were selected to understand if the reduction in vehicle counts along the Forbes Avenue corridor contributed to improved air quality in the nearby region. Figs. 9 and 10 plot all average daily concentrations for NO_2 and CO for the same time periods mentioned previously. The EPA 1-h concentration standard is 100 ppb for NO_2 and 35,000 ppb for CO. In both cases, the measured concentrations are well below the national standard. The national standard concentration for CO was not plotted in Fig. 10 because the measured values are well below, which would effectively squeeze out the actual measurement data.

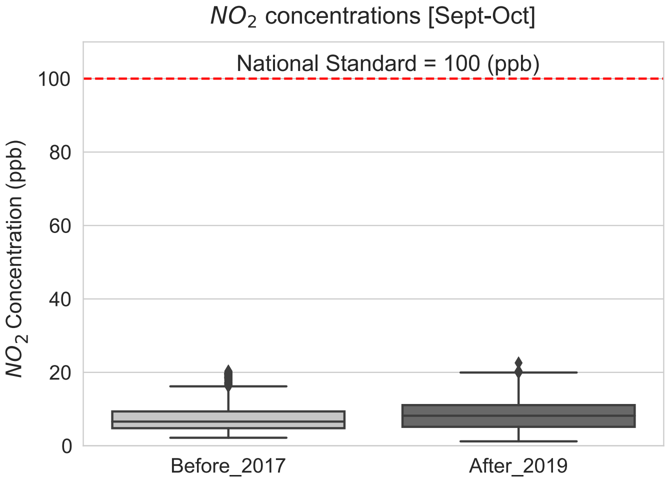

Fig. 9. Average daily NO_2 concentrations.

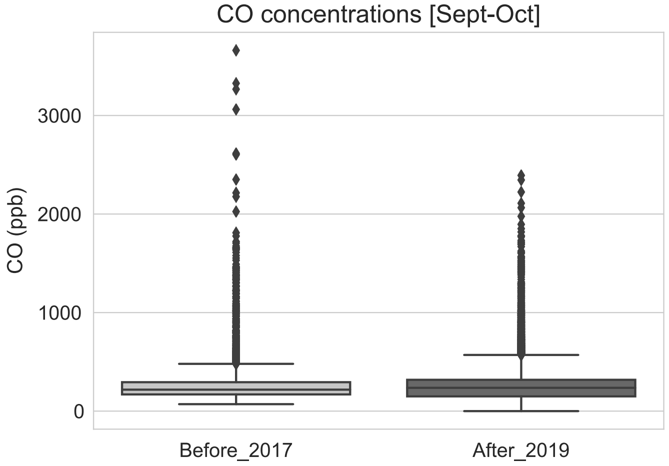

Fig. 10. Average daily CO concentrations.

Table 5. Estimated emissions savings

Period	PM2.5 (g/h)	NO_2 (g/h)	CO (g/h)
Morning Peak	−0.65	−23	−315
Evening Peak	−1.64	−60	−810

The mean NO_2 concentrations increased from 7.5 ppb to 8.4 ppb and the CO concentrations decreased from 267 ppb to 245 ppb after the reconfiguration. While significant using a one-sided t-test with unequal variances, these changes are small, and, in both cases, the concentrations are well below the 1-h concentration standard set by the EPA.

Observed vehicle counts decreased by 120 vehicles/hour and 300 vehicles/h during the morning and evening peaks, respectively. Using emissions estimates from the USEPA (USDOT 2009), emissions savings were estimated assuming light-duty vehicles, daily temperature range between 60° and 84°, and traffic speeds of 44.4 km/h (27.6 mph). Table 5 summarized the estimated savings due to reductions in vehicle counts along the complete street corridor.

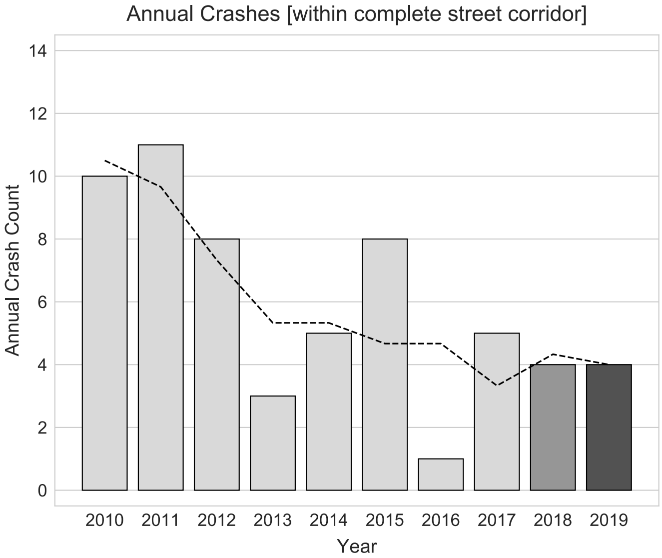

Fig. 11. Annual crash counts along the complete street corridor.

Crash Counts

Crash frequencies were obtained from the Pennsylvania Department of Transportation for the years 2010–2019. Crash data includes all incidents involving a motor vehicle. Fig. 11 plots annual crashes that occurred within the complete street corridor.

From Fig. 11, a downward trend in annual crash frequencies can be observed. Vehicle and pedestrian safety were not adversely impacted during construction or in the months following the reconfiguration. Annual accidents are plotted; however, no accidents were observed after the completion of the complete street project (after July 2019). By observation, annual crash counts decreased during and after the complete street retrofit compared to preretrofit years. These decreases are likely due to reductions in traffic volumes and vehicle speeds along the complete street corridor. However, complete street impacts on annual crash frequency will require monitoring for several years following the reconfiguration. Since traffic speeds and volumes have both decreased and pedestrian crosswalks and dedicated bike lanes were added, an increase in crashes in subsequent years is not expected.

Discussion

In this study, multiple sources of data were collected to provide a more complete picture regarding the benefits from a complete street retrofit project. A reduction in traffic volumes and speeds were observed upon completion of the retrofit. Local traffic network impacts were not observed, as traffic speeds were not affected on a nearby parallel corridor (Fifth Avenue). The number of bicycle commuters using the corridor increased drastically after the addition of bike lanes. Morning peak counts increased 160% and evening peak counts increased 280%. An upward trend in bus ridership was observed through the corridor, with the highest levels of bus ridership occurring after the complete street retrofit. While student and faculty enrollment have stayed steady over the past four years, other factors may be influencing the increase in bus ridership, which include possible bus service changes along nearby routes. Bus service changes, safer drop off points, and walking infrastructure due to complete street redesign, and existing transit incentives for students are likely the main contributors to this increase.

The observed reduction in traffic volumes in combination with large increases in bicycle traffic and bus ridership provides evidence that some mode shift is occurring. Traffic speeds along an adjacent corridor were also unaffected, supporting the idea that large volumes of traffic were not diverting to other local corridors. This behavior is consistent with a study conducted along Telegraph Avenue in Oakland, CA. The study found the mode share of pedestrians, cyclists, and public transit users increased from 26% to 28% after a complete street reconstruction. A bicycle intercept survey along this same corridor found that 8% of riders shifted travel modes after the reconstruction was complete (Fine and Tapase 2017). Although actual vehicle counts were not collected along Fifth Avenue, from the speed data (which is correlated with the number of vehicles traveling through the corridor) analysis, along with the bicycle and bus ridership counts, an inference can be made that users were likely switching modes instead of using alternative routes.

PM2.5 concentrations were reduced by 1.5 $\mu g/m^3$ after the retrofit. The inner quartile range for both before and after periods were below the national EPA standard of 12 $\mu g/m^3$. Small changes in NO_2 and CO concentrations were observed, and like PM2.5, NO_2 and CO concentrations were well below EPA standards during both before and after periods. Local roadway emission reductions are estimated based on reduced vehicle counts (see Table 5). It is important to note that particulate matter concentrations decrease as a function of distance from the roadway (Zhu et al. 2011) due to atmospheric conditions and wind speeds. Therefore, it is difficult to attribute the full decrease in PM2.5 concentrations to changing roadway conditions alone.

During construction, vehicle crash frequency did not increase, indicating that the reconfiguration construction did not adversely impact road safety. This is significant as the retrofit took over a year to complete. In the immediate months following project completion (August–December 2019), no crashes were observed along the complete street corridor. However, after data is limited, annual crash frequencies must continue to be monitored to evaluate longer-term benefits. With the addition of pedestrian crossings and dedicated bike lanes and the observation that both traffic speeds and volumes decreased after project completion, a future increase in crash frequencies is not expected.

To draw more general conclusions regarding the benefits from complete street projects, previous complete street (or road diet) studies are compared with the results from this study in Table 6. Studies were selected with similar characteristics (i.e., daily traffic volumes and length of the corridor) for comparison. Previous studies typically select one or a few metrics to evaluate based on specific project goals; however, when taken in aggregate, results from this study seem to corroborate previous results. All previous studies that evaluated traffic counts found reductions in traffic volumes after a complete street retrofit. The reductions from previous studies ranged from 6% to 29% which are similar to the reductions found in this analysis (11%–31%). From previous studies, the number of bicycle trips after the retrofit was found to increase by 14%–243%, which are also similar to the results obtained from this study (+160% a.m. and +280% p.m.). The largest increases in bicycle traffic from previous work were found near university locations. Previous studies have also found that transit ridership increased and PM2.5 concentrations decreased after a complete street retrofit. Additionally, all previous studies concluded that crash frequencies were reduced after the retrofit. This study also finds increased transit ridership, reduced PM2.5 concentrations, and reduced crash frequencies. However, crash frequencies will require continued monitoring to make any strong conclusions.

Table 6. Comparison with previous studies

Author(s) and year	Defining characteristics	Traffic count	Traffic speed	Bicycle count	Bus ridership	Air quality	Crash counts	Study outcomes
Sallaberry (Sallaberry 2000)	• 22,000 vehicles/day	X	—	X	—	—	X	• Reduction in traffic counts (−10%) • Increased traffic nearby roads (+1% − 8%) • Increased bicycle counts (+144%) • Reduction in total collisions (−16%)
City of Orlando (2002)	• 20,000 vehicles/day	X	—	—	—	—	X	• Reduction in vehicle counts (−12%) • Reduction in crashes (−34%) • Reduction is side-street traffic (−4%) • Increased bicycle trips (+30%)
Pawlovich et al. (2006)	• 15 test sites • 15 control sites	—	—	—	—	—	X	• Crash frequency reduced (−25.2%)
Zhu et al. (2016)	• 1 km (0.6 mi) • 900–1,200 vehicles/day	—	—	—	—	X	—	• Decrease in ultrafine particulates • Decrease in PM2.5 (−0.3 $\mu g/m^3$)
Anderson et al. (2015)[a]	Surveyed 37 projects	X	—	X	X	—	X	• Reduced crashes in 70% of projects • Increased bike trips in 22 of 23 projects • Reduced vehicle counts −19 of 33 sites • Bus ridership increased at 6 of 7 sites
Gudz et al. (2016)	• 1.3 km (0.8 mi) • Major University	—	—	X	—	—	—	• Increase in bicycle trips (+243%)
Nixon et al. (2017)	• 1.3 km (0.8 mi) • 20,000 vehicles/day	X	—	—	—	—	—	• Reduction in AM vehicle counts (−23%) • Reduction in PM vehicle counts (−12%)
FHWA (2017)[a]	• 6,000–15,000 • Restriping only	—	—	—	—	—	X	• Reduction in crashes (−32%–58%)
	• 1.6 km (1 mi) • 5 to 3 lanes	X	X	X	—	X	X	• Decrease vehicle speeds (−1%–4%) • Reduction in crashes • Increased bike flow • Decreased vehicle counts (−18%–29%) • Increased emissions
	• 0.8 km (0.5 mi) • 11,000 vehicles/day	—	X	X	—	—	X	• Crash frequency reductions • Vehicle speed reductions • Increased bicycle ridership
	• 3.2 km (2 mi) • 16,000 vehicles/day	—	—	X	—	—	—	• Bicycle use tripled along the corridor
	• 1.6 km (1 mi)	—	X	—	—	—	X	• Traffic speed reductions of 5–9 mph • Reduction in overall crashes (−30%)
	• 3.2 km in length • 7,100–11,000 vehicles/day	—	—	—	X	—	—	• Increase in bus ridership (+30%)
	• 1.5 km in length • 13,000 vehicles/day	X	—	X	—	—	X	• Reduction in vehicle counts (−6%) • Increase in bicycle trips (+35%) • Reduction in collisions (−14%)
This study	• 1.6 km (1 mi) • 13,000 vehicles/day	X	X	X	X	X	X	• Reduction in vehicle counts (−11%–31%) • Reduction in traffic speeds (–4–8.7 km/h) • Increased bike trips (+160%/ + 280%) • Increase in transit ridership • Reduction in PM2.5 concentrations • No observed crashes in first 6 months following project completion

Note: Bold values differentiates previous studies from this study.

[a] Indicates a report that summarizes numerous studies with little detail regarding each study's methods.

Conclusion

The results obtained from this research can be used to inform future complete street projects in the Pittsburgh region and in other regions with similar characteristics. Because outcomes vary by location, reconfiguration design, and roadway traffic volumes, it is important to quantify outcomes across many locations for a variety of different project types. This case study analyzed a corridor (one kilometer in length) along a major, urban arterial supporting approximately 13,000 vehicles per day. The corridor is also located on a major bus corridor connecting many residential neighborhoods to both large Pittsburgh business districts and two major universities.

Project costs were approximately \$4 million/km, which are similar to FHWA's cost estimates for normal-cost arterials (\$2.3 million/km) (Anderson et al. 2015). However, this project involved many costs associated with utility coordination/relocations for water, sewer, and electric. The project also involved repaving, five new traffic signals with communications, landscaping, street furniture, signage, and several new concrete curb ramps. Many of the observed benefits can likely be achieved by simply restriping, which would drastically reduce project costs.

Historically, many traffic studies, including much of the literature reviewed on complete street projects, randomly select a handful of days to observe traffic conditions to assess various impacts based on project objectives. This is often conducted by manually counting traffic and assuming the on-site days are representative of normal traffic conditions. However, with advancements in sensing and information systems, new more efficient methods of data collection can be employed to evaluate various project outcomes. In this study, a home security camera (~\$200) was used to continuously monitor and store traffic information for two years. With advancements in machine learning techniques, traffic volume analysis can be automated and monitored over long periods with the ability to process large amounts of data. Additionally, cheap air quality sensors were installed to collect and store air quality data every 15 min for the duration of the project. This eliminates the need to send field engineers to collect on-roadway air quality measurements. Additionally, with continual collection, seasonal fluctuations in air quality can be controlled for improved accuracy. Finally, various organizations and private companies collect a wide variety of transportation-related data that can be fused to assess numerous project outcomes more comprehensively and robustly. For example, the Port Authority of Allegheny County collects bus ridership and trajectory data and releases the data for other parties. INRIX (2020) collects high-resolution, spatio-temporal traffic speed data every five minutes on numerous roadway segments throughout Pittsburgh with probe vehicles that can be purchased through a membership option. Both data sources were incorporated in this analysis for improved results. In conclusion, new, cost-effective technologies enable improved data collection and analysis automation, which, if utilized in similar transportation impact studies, can improve results and lower the costs of future studies.

While this study aimed to quantify numerous impacts (traffic counts and speeds, bicycle counts, bus ridership, air quality, crash frequencies) based on study goals, other important metrics were omitted that might be of interest in future studies. For example, ultrafine particulate matter along the corridor, pedestrian counts and behavior, and vehicle classification. Ultrafine particulate matter monitoring would require additional sensors to be placed near the roadway with the ability to collect and store data throughout the project duration. Pedestrian counts and behavior, along with vehicle classification would require a similar video camera being installed with more advanced computer vision algorithms to quantify impacts.

One limitation to this work includes the amount of data collected for the after period and the data collection locations. In this research, several months of data were collected for the after period with similar amounts of data for the before period. However, more valuable insights can be quantified if several years of data can be acquired for the after phase. As data become available, longer-term impacts can be quantified. Data were also limited to the Forbes Avenue corridor except for traffic speed data along a parallel corridor (Fifth Ave.). With the addition of more cameras and air quality sensors along parallel corridors, a more regional analysis can be conducted.

A second limitation was the placement of the air quality sensors. Because the sensors were installed 275 m (900 ft) from the roadway, on-roadway air quality was not analyzed. Since previous research has found that particulate matter concentrations decay as a function of roadway distance (Zhu et al. 2011), it is recommended to install air quality sensors along the roadway itself to obtain more detailed results regarding roadway air quality.

Finally, computer vision algorithms were developed to automate traffic and bicycle counts to process data more efficiently. Camera placement locations were limited to CMU-owned buildings with WiFi to avoid periodic retrieval of data. However, due to the distance of the camera from the corridor itself, the algorithms were not able to identify bicycles. A second lesson learned was to ensure camera views were free from future obstruction. Due to the long project timeline, vegetation growth limited algorithm accuracy in the after phase. For these reasons, manual counts were conducted and presented in this analysis.

Data Availability Statement

Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request.

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