Multimodal Transportation 4 (2025) 100192

Contents lists available at ScienceDirect

Multimodal Transportation

journal homepage: www.elsevier.com/locate/multra

Full Length Article

Changes in crash types and contributing factors after bus rapid transit (BRT) infrastructure installation in Albuquerque, New Mexico

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ARTICLE INFO

Keywords:
Bus rapid transit
Contributing factor
Crash type
Public Transportation
Road Safety

ABSTRACT

Bus rapid transit (BRT) is an increasingly popular form of public transportation that seeks to achieve the speed and reliability of fixed rail with the flexibility and affordability of a bus system. In this paper, we examine safety outcomes before and after the construction of BRT infrastructure, specifically investigating how different crash types and contributing factors changed for all motor vehicle crashes and for pedestrian crashes. New Mexico Department of Transportation (NMDOT) provided crash data for the Central Avenue corridor of the Albuquerque Rapid Transit (ART) system in Albuquerque, NM. The construction of ART correlated with significant reductions in crashes attributed to excessive speed (for all modes) and left turning vehicles (for all modes and pedestrians). Crashes attributed to excessive speed decreased by 19.1 % ($p = 0.059$) after ART construction while crashes attributed to excessive speed resulting in fatal or serious (KA) injury decreased 100.0 % ($p < 0.001$). Although the number of KA pedestrian crashes increased 15.2 % ($p = 0.272$), KA pedestrian crashes involving a left-turning motor vehicle decreased by 80.0 % ($p = 0.070$). For all modes, crashes involving left-turning vehicles decreased by 34.8 % ($p < 0.001$) and crashes involving left-turning vehicles resulting in a KA injury decreased by 87.5 % ($p = 0.009$). This research provides insights into the multimodal traffic safety implications of the burgeoning public transportation mode of BRT.

1. Introduction

Public transportation has seen increasing innovation and investment in recent years as people have become more aware of the necessity for efficient and diverse transit systems. With this growing interest in public transportation, cities must choose which type of transit to invest in An increasingly popular option is bus rapid transit (BRT), which replicates some of the advantages of rail with features like high capacity and frequency, dedicated right-of-way, and platform boarding while being more affordable and flexible than rail. BRT is still a relatively new system in North America. The recently constructed Albuquerque Rapid Transit (ART) system was the first BRT system in the US to be awarded the gold ranking based on its design by the Institute for Transportation & Development Policy (ITDP) (ITDP, 2017).

Such a novel form of transit should undergo a close examination of its impacts on the roadway and surrounding community. In this paper, we examine how the construction of the ART system impacted motor vehicle crash rates and frequencies for various crash types and contributing factors. We include analyses on overall motor vehicle crashes and pedestrian-involved crashes and for

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https://doi.org/10.1016/j.multra.2025.100192
Received 8 May 2024; Received in revised form 15 August 2024; Accepted 20 August 2024

Fig. 1. A station along the Albuquerque Rapid Transit (ART) BRT line.

different injury severities. Better understanding contributing factors and crash types will help illuminate the mechanisms behind any changes in traffic safety outcomes. Such findings may help other cities that are considering the implementation of a BRT system to estimate the traffic safety impacts for their own system.

Our area of study was the Central Avenue corridor in Albuquerque, NM where ART was implemented with major construction finishing in summer 2018. We studied the Central Avenue ART system because it is both a high-quality BRT system that received the first gold ranking from ITDP for BRT design (ITDP, 2017) while simultaneously being located in an area with extant traffic safety issues. For instance, according to the National Highway Traffic Safety Administration's (NHTSA) Fatality Analysis Reporting System (FARS), New Mexico has had the highest pedestrian fatality rate for seven of the last ten years and has had one of the five highest rates for the last decade (NHTSA, 2022). Additionally, the US News and World Report identifies Albuquerque as the second most dangerous city in the US for drivers, with Central Avenue being identified as a critical high-injury corridor in the region by the Mid-Region Council of Governments' (MRCOG) High Fatal and Injury Network (MRCOG, 2022; Pointer, 2023). This provides a unique opportunity to examine the impact of high-quality BRT on a critical safety corridor for pedestrians and drivers.

We obtained our crash data from the New Mexico Department of Transportation (NMDOT). The time periods we examined were April 2015 to October 2016 for the "before" period and June 2018 to December 2019 for the "after" period. For each 19-month period, we split the crash data into several categories related to reported crash type and contributing factor. From this information, we tested our hypothesis that the ART system would be correlated with fewer crashes involving turning vehicles and excessive speeds. Our findings inform other cities that wish to install BRT of the impacts such a system has on road safety.

The next section explores the theory behind BRT's possible correlation with traffic safety. We then describe our data collection efforts and statistical methodology in more detail. This is followed by our results and conclusions.

2. Background

BRT is a bus-based public transportation system that delivers higher quality service than a traditional bus system. To be considered a BRT system, the system must have dedicated bus lanes, a median-aligned busway, intersection treatments to prioritize bus operations, pre-board fare collection, and stations that are level with bus boarding areas (ITDP, 2020). Signalization along the BRT corridor typically prioritizes the BRT buses and there are turning restrictions for other vehicles to ensure efficient bus operations. These design measures prevent BRT buses from waiting in traffic and avoid delays from queues as passengers are boarding the buses.

The first true BRT was opened in Curitiba, Brazil in 1974 (Weinstock et al., 2011). Since then, BRT systems have been implemented around the world with many in South America and east Asia. ITDP developed a BRT ranking system based primarily on the design criteria detailed above. Rankings include basic, bronze, silver, and gold BRT systems. Of the 126 BRT systems that are recognized by ITDP worldwide, ten are in U.S. cities (ITDP, 2020). While Colombia has six gold-ranked BRT systems and Brazil has four gold-ranked BRT systems, the Albuquerque Rapid Transit (ART) BRT system was the first U.S. BRT system to be awarded the ITDP gold standard (ITDP, 2017) (Fig. 1). However, that ranking was based on the system design and is now being reevaluated to account for operating conditions.

While enhancing public transit operations is the primary purpose of BRT, it would be beneficial to also determine BRT's impact on traffic safety. This is a critically important point because the arterials that host these BRT systems are oftentimes the roadway type that makes up cities' High Fatality and Injury (HFIN) networks. An exhaustive literature review performed by Vecino-Ortiz and Hyder on the topic found only four pieces of research that empirically explored the relationship (Vecino-Ortiz and Hyder, 2015). There was a 60 % reduction in serious injuries on the Caracas corridor and a 48 % reduction on the Norte-Quito-Sur corridor after implementation of the Transmilenio BRT system in Bogota, Colombia (Vecino-Ortiz and Hyder, 2015). This was better than the 39 % reduction in serious injuries observed across the city over the same period, although this overall decrease confounded the BRT findings and makes it difficult to prove any causality (Bocarejo et al., 2012). Furthermore, there were localized increases in serious injuries observed along the corridor, possibly due to higher vehicle speeds and increased pedestrian exposure near the BRT stations.

A study of the Delhi BRT Corridor found that there was a 43 % reduction in fatal crashes in the first year of operation (Tiwari and Jain, 2012). In the following year, they added rumble strips to the bus lane and experienced only two fatal crashes, an overall reduction of 76.5 %. This study was limited in its time frame and only observed the first two years of operation. They also found that road users' trip times decreased an average of 19.7 %. These time savings were experienced primarily by cyclists and BRT users who made up 56 % of roadway users while private motor vehicles experienced increased travel times.

Izadi et al. studied the BRT corridor in Rasht, Iran (Izadi et al., 2020). This corridor experienced 36 % and 43 % reductions in motor vehicle crashes in the first and second years of operation, respectively, compared to the year before operations began. There was an increase in crashes with the barrier fence in the first year of operation, but this decreased in the second year of operation, possibly because road users became more accustomed to the new infrastructure. In the third year of operation, there were no fatal crashes.

Kitali et al. studied the BRT system in Dar es Salaam, Tanzania, the third official BRT system to be constructed in Africa (Kitali et al., 2023). This paper looked specifically at crashes involving BRT buses. There were 926 crashes during the first five years of operation, resulting in 28 fatalities and 178 injuries. They utilized text mining to obtain the cause of these crashes from crash report narratives. They found that the majority of the crashes involved a passenger vehicle while a smaller portion involved trucks, pedestrians, and bajaji (tricycles). Text mining results concluded that the majority of crashes were due to a driver or pedestrian illegally entering the bus lane. According to Kitali et al., this is less of an issue in developed countries due to stricter legal systems and surveillance.

Duduta et al. performed an analysis across several BRT systems and found a 60 % reduction in road fatalities on the BRT system in Bogota, Colombia, and a 50 % reduction in road fatalities on the BRT system in Guadalajara, Mexico (Duduta et al., 2012). However, once again there were general decreases in road fatalities observed across the study cities which confounded the results. As a counterpoint to the other successes detailed here, the BRT system in Delhi, India, saw road fatalities more than double. Roadway factors that were found to increase the probability of a collision included the number of legs and lanes per leg, counterflow, level pedestrian crossing, and left turns (Duduta et al., 2012).Specifically examining our ART study corridor in Albuquerque, preliminary research found that all motor vehicle crashes on the ART corridor dropped by 8.2 % after the ART installation and serious and fatal injuries dropped by 64.9 % (compared with 6.1 % and 5.7 % decreases, respectively, for control segments along the same corridor) (Bia and Ferenchak, 2022). Interestingly, although a meta-analysis by Theofilatos et al. found that a unit increase in work zone length was correlated with a 2.368 times increase in crash incidence rate, motor vehicle crashes actually decreased during ART construction by 13.0 % and fatal/serious injury crashes decreased by 48.6 % (Theofilatos et al., 2017). Pedestrian crashes on the ART corridor increased by 9.3 % after the ART installation and pedestrian serious and fatal injuries dropped by 27.3 % (compared with increases of 26.7 % and 13.3 %, respectively, for control segments along the same corridor) (Bia and Ferenchak, 2022).

We now transition from our discussion of the relationship between BRT and road safety outcomes to discuss research exploring the possible mechanisms behind those relationships. We could not find any research specifically exploring the impact of BRT infrastructure on crash types and contributing factors. However, road diets have been shown to improve safety by reducing speeds and decreasing turning conflicts (Knapp et al., 2014). The ART infrastructure was like a road diet in that it reduced general travel lanes along much of the corridor.

A study of a proposed BRT corridor design on Chicago's Ashland Avenue suggests that BRT systems may provide traffic calming effects because of the complete street design, although the study did not quantitatively examine that claim (Sukaryavichute and Prytherch, 2018). A past study of the ART corridor backs up this idea of BRT as traffic calming, finding that motor vehicle 85th-percentile speeds along the ART corridor were reduced by 11.5 % from 32.3 mph to 28.6 mph, which is an especially important range for vulnerable road-user safety outcomes (Joshi et al., 2024).

On the other hand, Cervero and Kang found that a BRT system installation in Seoul, South Korea, correlated with increases of 7.6 %, 3.4 %, and 6.1 % in the operating speeds of cars in lanes other than the designated BRT lanes at three study locations (Cervero and Kang, 2011). Because these two studies exploring the relationship between BRT systems and vehicle speeds are seemingly contradictory and are only presented in limited contexts, there is certainly need for more research on the topic. Furthermore, we were unable to find any research related to BRT impacts on other driver behaviors such as distraction or aggressive driving behavior.

Another way that BRT infrastructure may influence safety outcomes is by restricting turning movements for vehicles. We looked at several studies that collected geometric and crash data to determine the relationship between roadway characteristics and crash rates. Brown and Tarko found that urban arterials that have a raised median with no openings between signalized intersections experienced fewer crashes than similar corridors with no median (Brown and Tarko, 1999). They also determined that there was a positive relationship between crash rates and density of access points, defined as the intersection of a local street or driveway and an arterial; this relationship was particularly strong for fatal and injury crashes (Brown and Tarko, 1999). Similarly, Xu et al. found that higher densities of driveways and median openings were correlated with higher crash rates on urban arterials (Xu et al., 2013). Schultz et al. similarly found that raised medians were associated with lower crash rates while density of access points and signalized intersections were associated with higher crash rates on urban arterials (Schultz et al., 2010). The relationship between signalized intersections and high crash rates found by Schultz et al. was especially strong for more severe crashes. Le et al. examined the safety impacts of stop-controlled right-in-right-out (RIRO) intersections (Le et al., 2018). RIRO intersections occur when a driveway or small street intersects an urban arterial with a median, allowing for only right turns onto and out of the arterial. Since many BRT systems have raised medians in the middle of the roadway to prevent vehicles from turning left over the center bus-only lanes, unsignalized intersections on BRT corridors often function as RIRO. Le et al. found that RIRO intersections experienced significantly fewer crashes compared to full-movement three-legged intersections. They determined crash modification factors of 0.55, 0.32, and 0.20 for total crashes, intersection-related crashes, and fatal and injury intersection-related crashes, respectively. However, they also found potential for downstream signalized intersections to experience an increase in crashes after RIRO implementation.

3. Data & methods

For our crash analyses, we needed to count crash data within certain geographies related to the Central Avenue corridor. The data needed for our crash analyses therefore fell into two categories: 1) crash data and 2) geographic boundaries.

We obtained the crash data used in this study from NMDOT. The NMDOT crash database is compiled from crash data reported by police departments across New Mexico. Police officers responding to a reported motor vehicle crash complete a Uniform Crash Report (UCR), which is a standardized form used by agencies statewide. Reported motor vehicle crashes occurring on public roadways and involving one or more motor vehicles that resulted in death, personal injury, or at least $500 in property damage are entered into the NMDOT crash dataset. No account is kept of unreported crashes, and the database does not include crashes on private property. Once the UCRs are submitted to NMDOT from police agencies across New Mexico, the data is then cleaned and formatted by the Geospatial & Population Studies (GPS) unit at the University of New Mexico and then returned to NMDOT. Specifically, GPS completes checks of various validation rules such as searching for null values or compliance with other formatting rules. If validation issues are identified, the original reporting agency is queried regarding the noncompliance. If the reporting agency is not able to provide more information, then the field may be marked as an unknown value. GPS also geocodes each crash so that the data can be analyzed geospatially. For this study, we used crash data from 2015 to 2019 which therefore covered our entire study period (as detailed below when we discuss the reasons for selecting our specific study period). We filtered the crash data by contributing factor and crash type, which is further detailed in the methodology below.

Municipal limits and road centerlines were provided in geographic information system (GIS) format by the city of Albuquerque's Planning Department. This data was publicly available for download from the city of Albuquerque's website. All data was in the New Mexico State Plane-Central Zone, Feet (NAD 83) projection and was downloaded in ESRI shapefile format.

We did not incorporate exposure data directly into our study as this paper was not concerned with overall crash rates (which were already explored for this corridor in Bia and Ferenchak, 2022) but was instead focused on the proportion of total crashes that fell into each crash type and contributing factor category. If there had been a change in traffic exposure along the BRT corridor, that exposure change would have been consistent across all the crash type and contributing factor categories. It would have been interesting to obtain exposure data for distinct vehicle movements such as left turns, but such detailed exposure data was not available for the study corridor.

We first selected all Central Avenue segments that experienced ART construction. We then created a 100-foot buffer around each study road segment since crashes were not located exactly on the roadway centerlines. A buffer distance of 100 feet adequately captured all crashes on Central Avenue without capturing crashes located on adjoining roadways. Once buffers were established for each BRT segment, we performed spatial joins to count the total number of reported motor vehicle collisions that occurred in each study polygon for each month of the analysis period.

The BRT construction began in November 2016 and major construction was completed in summer 2018. We therefore defined the "before" period as April 2015 through October 2016 and the "after" period as June 2018 through December 2019. It is important to note that there were no ART buses operating in the ART designated bus lanes during the "after" period because of operational issues with the buses. The "after" period is therefore when the major infrastructure was completed but there were no BRT buses yet operating on the BRT system. There were buses operating on the Central Avenue corridor in both the before and after periods, but these were the traditional buses operating on the outside lanes of Central Avenue during both study periods.

For the time frames specified above, we analyzed all reported motor vehicle crashes, all reported motor vehicle crashes resulting in a fatal or serious (KA) injury, all pedestrian crashes, and all pedestrian crashes resulting in a KA pedestrian injury. We compared crash type and contributing factor counts using one-tailed *t*-tests to see whether there were any significant changes in crash frequency before versus after implementation of the ART infrastructure. T-tests were appropriate to compare the before/after mean values as the crash data – broken out by month – was determined to be normally distributed. We highlighted all statistically significant results in our tables, focusing specifically on results that reached 95 % confidence but also noting results that reached 90 % confidence, a methodology that has been employed by past traffic safety research (Ferenchak, 2023; Ferenchak and Marshall, 2019a, 2019b). To understand the relative frequency of different crash types and contributing factors, we examined the proportions of crash types as percentages of total crashes both before and after BRT construction.

For the contributing factor and crash type analyses, we combined several factors and types into broader categories for ease of interpretation (Table 1). For crash type, there were several subcategories of the "Other Vehicle" classification: "From Opposite Direction", "Left Turn", "Rear End", "Right Turn", and "Sideswipe".

We did not analyze contributing factors for pedestrian crashes as 70.7 % of pedestrian crashes were contributed to either pedestrian error or alcohol/drug involvement, which did not inform us of how the BRT infrastructure may have impacted pedestrian safety. NMDOT states that "Pedestrian error includes failing to yield to right of way, crossing outside of a crosswalk, and other actions" (NMDOT, 2021). In practice, the pedestrian error designation is a catch-all category that is used when more detailed information

Table 1
Categorization of crash types and contributing factors.

Analysis categories for crash types and contributing factors	Associated crash types and contributing factors that were combined					
Excessive Speed	Excessive Speed	Speed Too Fast for Conditions				
From Opposite Direction	Other Vehicle – From Opposite Direction					
Left Turn	Other Vehicle – Both Turn Left/Entering at Angle	Other Vehicle - From Opposite Direction/One Left Turn	Other Vehicle - From Same Direction/Both Turn Left	Other Vehicle - From Same Direction/One Left Turn	Other Vehicle - One Left Turn/Entering At Angle	Other Vehicle - One Vehicle/Making A U-Turn
Rear End	Other Vehicle - From Same Direction/Both Going Straight	Other Vehicle - From Same Direction/Rear End Collision				
Right Turn	Other Vehicle - Both Turn Right/Entering at Angle	Other Vehicle - From Opposite Direction/One Right Turn	Other Vehicle - From Same Direction/Both Turn Right	Other Vehicle - From Same Direction/One Right Turn	Other Vehicle - One Right Turn/Entering at Angle	
Sideswipe	Other Vehicle - Both Going Straight/Entering at Angle	Other Vehicle - From Opposite Direction/Sideswipe Collision	Other Vehicle - From Same Direction/Sideswipe Collision			

Table 2
Entire BRT corridor contributing factor frequencies for all modes (statistically significant decreases based on one-tailed *t*-tests are shaded in green).

Contributing Factor	All Modes All Severities					All Modes KA				
	Before	After	Change	% Change	p	Before	After	Change	% Change	p
Alcohol/Drug Involved	74	59	-15	-20.3%	0.068	9	5	-4	-44.4%	0.156
Disregarded Traffic Signal	124	116	-8	-6.5%	0.335	4	3	-1	-25.0%	0.364
Driver Inattention	**425**	**366**	**-59**	**-13.9%**	**0.043**	**7**	**2**	**-5**	**-71.4%**	**0.049**
Excessive Speed*	94	76	-18	-19.1%	0.059	**9**	**0**	**-9**	**-100.0%**	**<0.001**
Failed to Yield Right of Way	**216**	**122**	**-94**	**-43.5%**	**<0.001**	**8**	**0**	**-8**	**-100.0%**	**0.018**
Following Too Closely	168	155	-13	-7.7%	0.218	1	3	2	200.0%	0.152
Improper Lane Change	41	32	-9	-22.0%	0.145	1	0	-1	-100.0%	0.162
Improper Overtaking	16	14	-2	-12.5%	0.386	1	0	-1	-100.0%	0.162
Made Improper Turn	49	45	-4	-8.2%	0.339	0	0	0	0.0%	N/A
None	**54**	**32**	**-22**	**-40.7%**	**0.009**	0	0	0	0.0%	N/A
Other Improper Driving	41	43	2	4.9%	0.406	3	1	-2	-66.7%	0.152
Pedestrian Error	28	29	1	3.6%	0.450	8	6	-2	-25.0%	0.318
Other	110	87	-23	-20.9%	0.085	0	1	1	N/A	0.162
TOTAL KNOWN	**1,440**	**1,176**	**-264**	**-18.3%**	**<0.001**	**51**	**21**	**-30**	**-58.8%**	**<0.001**
Missing Data	211	223	12	5.7%	0.366	4	1	-3	-75.0%	0.079

Table 3
Entire BRT corridor contributing factor proportions (for known crashes) for all modes (statistically significant decreases based on one-tailed *t*-tests are shaded in green).

Contributing Factor	All Modes All Severities			All Modes KA		
	Before	After	Change	Before	After	Change
Alcohol/Drug Involved	5.1%	5.0%	-0.1%	17.6%	23.8%	6.2%
Disregarded Traffic Signal	8.6%	9.9%	1.3%	7.8%	14.3%	6.4%
Driver Inattention	**29.5%**	**31.1%**	**1.6%**	**13.7%**	**9.5%**	**-4.2%**
Excessive Speed*	6.5%	6.5%	-0.1%	**17.6%**	**0.0%**	**-17.6%**
Failed to Yield Right of Way	**15.0%**	**10.4%**	**-4.6%**	**15.7%**	**0.0%**	**-15.7%**
Following Too Closely	11.7%	13.2%	1.5%	2.0%	14.3%	12.3%
Improper Lane Change	2.8%	2.7%	-0.1%	2.0%	0.0%	-2.0%
Improper Overtaking	1.1%	1.2%	0.1%	2.0%	0.0%	-2.0%
Made Improper Turn	3.4%	3.8%	0.4%	0.0%	0.0%	0.0%
None	**3.8%**	**2.7%**	**-1.0%**	0.0%	0.0%	0.0%
Other Improper Driving	2.8%	3.7%	0.8%	5.9%	4.8%	-1.1%
Pedestrian Error	1.9%	2.5%	0.5%	15.7%	28.6%	12.9%
Other	7.6%	7.4%	-0.2%	0.0%	4.8%	4.8%
TOTAL KNOWN	100.0%	100.0%	0.0%	100.0%	100.0%	0.0%

is not available and it does not take into account how the built environment may influence pedestrian behavior. Since such a high proportion of pedestrian crashes were classified with this contributing factor both before and after the implementation of the BRT, the category did not show any meaningful changes associated with the BRT implementation.

4. Results

4.1. Contributing factor

4.1.1. All crashes

The most frequently cited contributing factors in the before period for all reported motor vehicle crashes were “Driver Inattention” (29.5 % of all crashes) and “Failed to Yield Right of Way” (15.0 %) (Table 3). The largest statistically significant reductions in crashes between the before and after periods came from reductions in “Failed to Yield Right of Way” (−43.5 %), “Alcohol/Drug Involved” (−20.3 %), and “Excessive Speed” (−19.1 %) crashes (Table 2 and Fig. 2). The most frequently cited contributing factors in the after period for all reported motor vehicle crashes were “Driver Inattention” (31.1 %) and “Following Too Closely” (13.2 %) (Table 3).

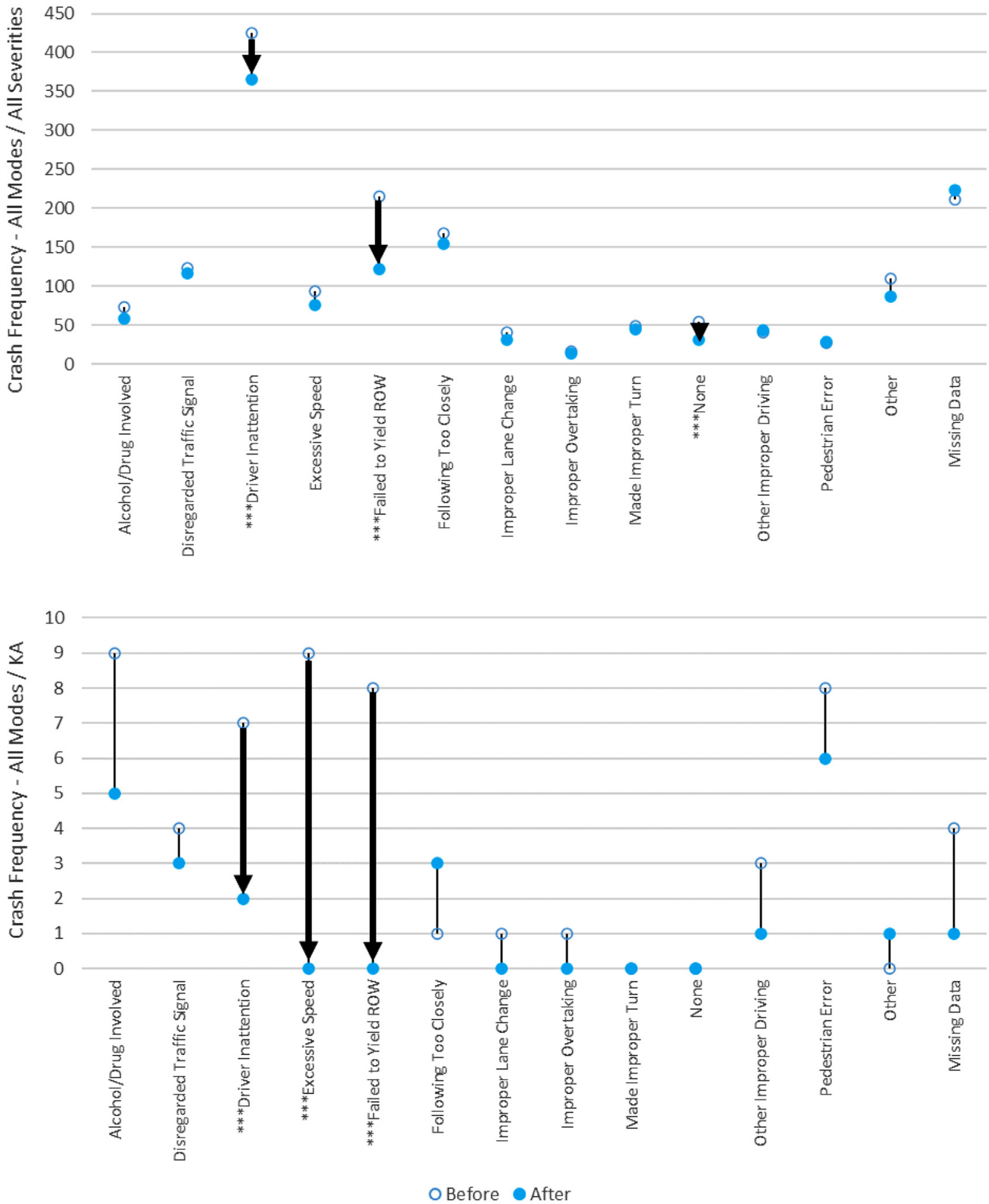

Fig. 2. Entire BRT corridor contributing factor frequencies for all modes and all severities (top) and KA crashes (bottom) (statistically significant decreases at 95 % confidence based on one-tailed *t*-tests are highlighted with bold arrows and asterisks).

The most frequently cited contributing factors in the before period for KA crashes were “Alcohol/Drug Involved” (17.6 % of KA crashes) and “Excessive Speed” (17.6 % of KA crashes) (Table 3). The largest statistically significant reductions in KA crashes came from “Failed to Yield Right of Way” (−100.0 %) and “Excessive Speed” (−100.0 %), (Table 2). The most frequently cited contributing factors in the after period for KA crashes were “Pedestrian Error” (28.6 %) and “Alcohol/Drug Involved” (23.8 %) (Table 3).

Based on the contributing factor analysis, there is evidence that excessive speeding was reduced on the BRT corridor. The total number of collisions attributed to “Excessive Speed” was reduced by 19.1 %, which was statistically significant at 90 % confidence.

Table 4
Entire BRT corridor crash type frequencies for all modes (statistically significant decreases based on one-tailed *t*-tests are shaded in green).

Crash Type	All Modes All Severities					All Modes KA				
	Before	After	Change	% Change	p	Before	After	Change	% Change	p
Fixed Object	**68**	**39**	**-29**	**-42.6%**	**0.002**	**5**	**0**	**-5**	**-100.0%**	**0.008**
Other Vehicle	**1,257**	**794**	**-463**	**-36.8%**	**<0.001**	**27**	**8**	**-19**	**-70.4%**	**<0.001**
From Opp. Direct.	**288**	**46**	**-242**	**-84.0%**	**<0.001**	1	0	-1	-100.0%	0.162
Left Turn	**201**	**131**	**-70**	**-34.8%**	**<0.001**	**8**	**1**	**-7**	**-87.5%**	**0.009**
Rear End	349	350	1	0.3%	0.486	7	3	-4	-57.1%	0.074
Right Turn	**76**	**37**	**-39**	**-51.3%**	**0.002**	1	0	-1	-100.0%	0.162
Sideswipe	**202**	**163**	**-39**	**-19.3%**	**0.011**	8	4	-4	-50.0%	0.086
Parked Vehicle*	**46**	**6**	**-40**	**-87.0%**	**<0.001**	1	0	-1	-100.0%	0.162
Pedalcyclist**	30	29	-1	-3.3%	0.450	4	1	-3	-75.0%	0.123
Pedestrian	61	60	-1	-1.6%	0.465	16	12	-4	-25.0%	0.189
Other	10	16	6	60.0%	0.107	2	1	-1	-50.0%	0.280
TOTAL KNOWN	**1,472**	**944**	**-528**	**-35.9%**	**<0.001**	**55**	**22**	**-33**	**-60.0%**	**<0.001**
Invalid Code	**89**	**12**	**-77**	**-86.5%**	**<0.001**	0	0	0	0.0%	N/A
Left Blank	**90**	**443**	**353**	**392.2%**	**<0.001**	0	0	0	0.0%	N/A

And while “Excessive Speed” contributed to the most KA crashes in the before period at nine KA crashes, that number was reduced to zero in the after period. This reduction in “Excessive Speed” KA crashes represented 30.0 % of the total reduction in KA crashes.

We are not confident in making any judgements on the role of turning restrictions based on the contributing factor data. “Made Improper Turn” was only 3.4 % of total crashes and 0.0 % of KA in the before period. We would assume that “Failed to Yield Right of Way”, which saw significant reductions in overall crashes and KA crashes, would consist of some turning movement crashes. However, we cannot be sure given the relatively broad categorization, and we will therefore wait until the crash type analysis to make any conclusions on turning movements.

Another important factor in improved safety was a reduction in “Alcohol/Drug Involved” crashes. There were substantial reductions in this category for both total crashes and KA crashes. It would be interesting to determine whether there were reduced levels of driving while intoxicated between the before and after periods (we would imagine that would not be the case, at least not 20.3 % fewer driving while intoxicated cases), or whether this reduction simply represents intoxicated road users being less likely to experience a reportable crash.

While contributing factors such as “Excessive Speeding”, “Failed to Yield Right of Way”, and “Driver Inattention” seem to have improved significantly, there is evidence that other contributing factors may have gotten worse with the implementation of BRT. “Pedestrian Error” saw an increase of one crash which aligns with the fact that pedestrian crashes did increase, possibly because of increased pedestrian exposure (Table 2). The only contributing factor that saw an increase in KA crashes was “Following Too Closely” which saw an increase of two KA crashes. This may be expected if reductions in the number of travel lanes led to more vehicle platooning. “Disregarded Traffic Signal” also performed relatively poorly with only small decreases, possibly because of added complexity to the signalized intersections along the corridor.

4.1.2. Pedestrian

Total pedestrian crashes increased from 58 to 60 (3.4 % increase) and KA pedestrian crashes increased from 33 to 38 (15.2 % increase). The only statistically significant change in contributing factors for pedestrian crashes was an increase in “Other Improper Driving” which increased by three crashes and does not provide much insight us about the possible relationship with the BRT infrastructure. 70.7 % of the pedestrian crashes in the before period were contributed to either “Pedestrian Error” or “Alcohol/Drug Involvement”, which again does not provide much insight into the possible mechanisms of the BRT infrastructure changes. We therefore perform a more complete pedestrian safety analysis when analyzing crash types.

4.2. Crash type

4.2.1. All crashes

There was a substantial increase in crash types coded as “Left Blank” and a substantial decrease in “Invalid Code” in the after period for crashes involving all modes and all severities (Table 4). These coding errors make interpretation of crash type results difficult for crashes involving all modes all severities. However, this was only the case for the analyses of all modes and all severities. For KA crashes, there were no “Invalid Code” or “Left Blank” values in either the before or after periods. For pedestrian crashes, there was only one “Invalid Code” or “Left Blank” crash, which occurred in the before period (Table 6).

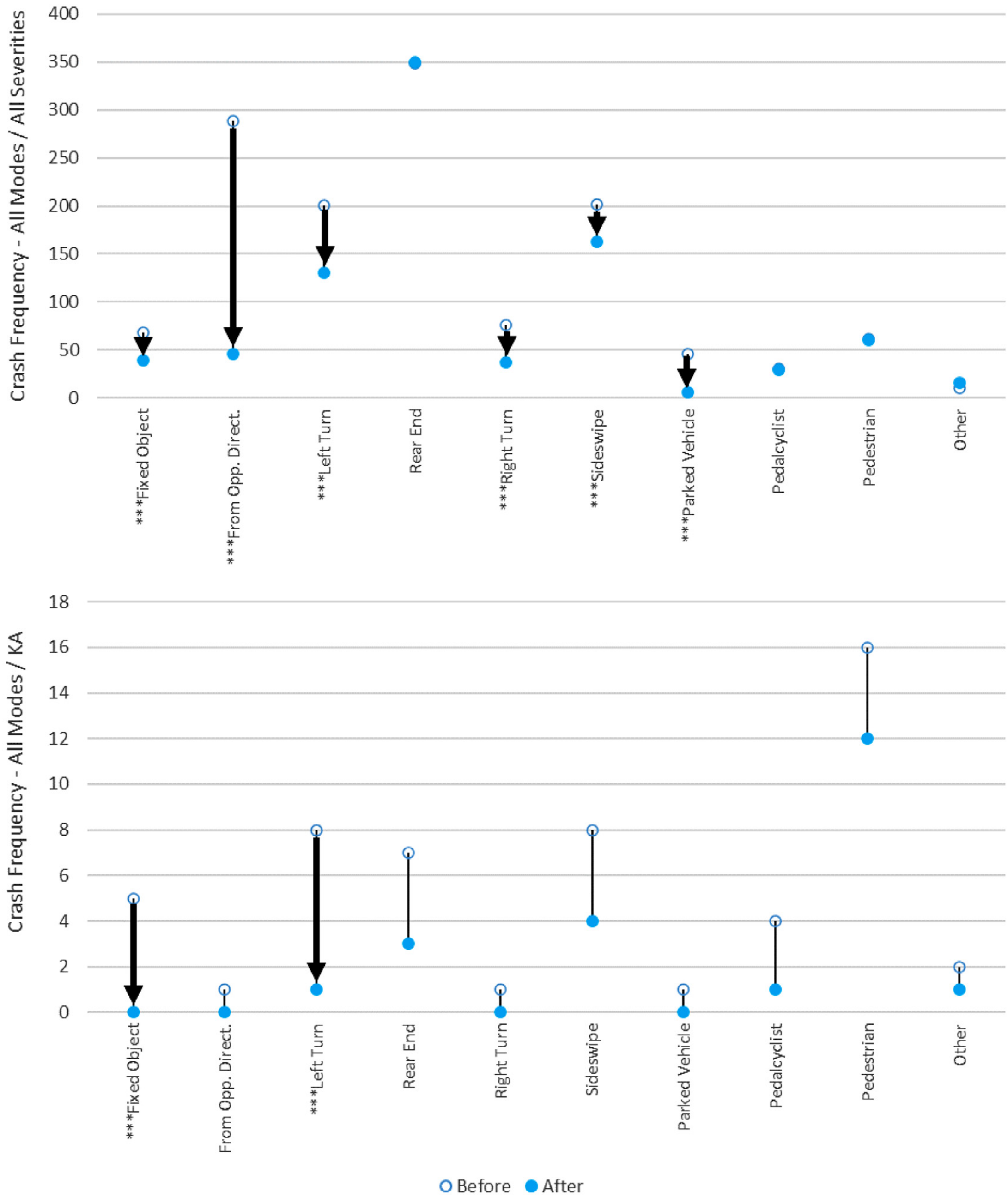

Fig. 3. Entire BRT corridor crash type frequencies for all modes and all severities (top) and KA crashes (bottom) (statistically significant decreases at 95 % confidence based on one-tailed *t*-tests are highlighted with bold arrows and asterisks.

The largest decrease in KA crashes occurred with “Left Turn” crashes which went from eight cases in the before period to just one in the after period (87.5 % decrease) and represented 21.2 % of the total reduction in KA crashes (Table 4 and Fig. 3). “Left Turn” crashes decreased 34.8 % overall.

“Fixed Object” crashes experienced the second largest KA decrease (a reduction of five crashes), representing 15.2 % of the total reduction in KA crashes (Table 4 and Fig. 3). While there was no direct measure of vehicle speed in the crash type analysis, this may provide further evidence of reduced involvement of excessive vehicle speeds if we assume that “Fixed Object” KA crashes oftentimes involve vehicle leaving the roadway while travelling at excessive speeds.

“Left Turn” and “Fixed Object” crashes also represented the largest proportional decreases in KA crashes (−10.0 % and −9.1 %, respectively) (Table 5).

Table 5
Entire BRT corridor crash type proportions (for known crashes) for all modes (statistically significant decreases based on one-tailed *t*-tests are shaded in green).

Crash Type	All Modes All Severities			All Modes KA		
	Before	After	Change	Before	After	Change
Fixed Object	**4.6%**	**4.1%**	**-0.5%**	**9.1%**	**0.0%**	**-9.1%**
Other Vehicle	**85.4%**	**84.1%**	**-1.3%**	**49.1%**	**36.4%**	**-12.7%**
From Opp. Direct.	**19.6%**	**4.9%**	**-14.7%**	1.8%	0.0%	-1.8%
Left Turn	**13.7%**	**13.9%**	**0.2%**	**14.5%**	**4.5%**	**-10.0%**
Rear End	23.7%	37.1%	13.4%	12.7%	13.6%	0.9%
Right Turn	**5.2%**	**3.9%**	**-1.2%**	1.8%	0.0%	-1.8%
Sideswipe	**13.7%**	**17.3%**	**3.5%**	14.5%	18.2%	3.6%
Parked Vehicle*	**3.1%**	**0.6%**	**-2.5%**	1.8%	0.0%	-1.8%
Pedalcyclist**	2.0%	3.1%	1.0%	7.3%	4.5%	-2.7%
Pedestrian	4.1%	6.4%	2.2%	29.1%	54.5%	25.5%
Other	0.7%	1.7%	1.0%	3.6%	4.5%	0.9%
TOTAL KNOWN	100.0%	100.0%	0.0%	100.0%	100.0%	0.0%

Table 6
Entire BRT corridor crash type frequencies for pedestrian crashes (statistically significant decreases based on one-tailed *t*-tests are shaded in green).

Crash Type	Pedestrians All Severities					Pedestrians KAB				
	Before	After	Change	% Change	p	Before	After	Change	% Change	p
Vehicle Backing	1	2	1	100.0%	0.280	1	2	1	100.0%	0.280
Vehicle Going Straight	36	41	5	13.9%	0.311	20	26	6	30.0%	0.206
Vehicle Turning Left	7	3	-4	-57.1%	0.101	5	1	-4	-80.0%	0.070
Vehicle Turning Right	12	9	-3	-25.0%	0.213	5	4	-1	-20.0%	0.373
TOTAL KNOWN	56	55	-1	-1.8%	0.430	31	33	2	6.5%	0.407
Pedestrian Collision-All Others and Not Known	**1**	**5**	**4**	**400.0%**	**0.039**	**1**	**5**	**4**	**400.0%**	**0.039**
Invalid Code	1	0	-1	-100.0%	0.162	1	0	-1	-100.0%	0.162
Left Blank	0	0	0	0.0%	N/A	0	0	0	0.0%	N/A

While there was a relatively small decrease in the total number of "Sideswipe" crashes and there was actually an increase in "Rear End" crashes, the number of serious/fatal injuries for these categories still saw significant decreases (50.0 % and 57.1 % decreases, respectively; both statistically significant at 90 % confidence) (Table 4 and Fig. 3). This suggests that while the corridor may have gotten more complicated for drivers (resulting in slightly more rear-end crashes), the safety of the corridor in terms of reducing KA injuries was improved, likely because of lowered vehicle speeds.

There was also a significant decrease in "Parked Vehicle" crashes (Table 4 and Fig. 3). Although this category did not represent a large proportion of total crashes or serious/fatal crashes, it is worth noting that the BRT implementation resulted in significant reductions for this crash type.

4.2.2. Pedestrian

The only statistically significant change in pedestrian crash types was a reduction in "Vehicle Turning Left" pedestrian KA crashes, which were reduced from five crashes in the before period to one in the after period (80.0 % decrease) (Table 6 and Fig. 4). However, "Vehicle Turning Left" pedestrian KA crashes represented a low proportion of the pedestrian KA crashes (Table 7). Most pedestrian collisions and pedestrian KA collisions consisted of "Vehicle Going Straight" collisions. Unfortunately, the number of pedestrians struck by vehicles going straight increased in the after period. This may have been a result of lane reductions and/or slower motor vehicles leading to more pedestrians risking unprotected midblock crossings.

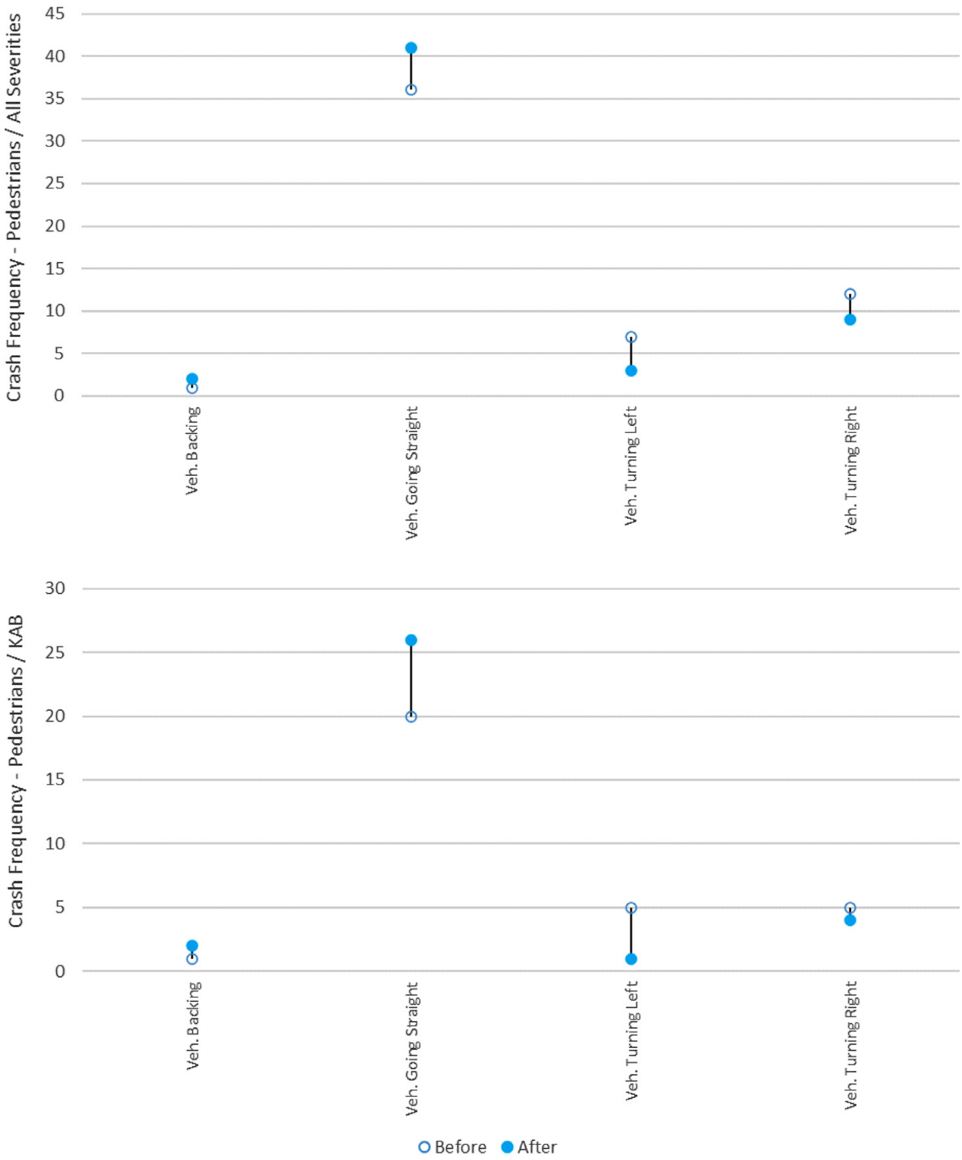

Fig. 4. Entire BRT corridor crash type frequencies for pedestrian crashes of all severities (top) and KAB crashes (bottom) (statistically significant decreases at 95 % confidence based on one-tailed *t*-tests are highlighted with bold arrows and asterisks).

Table 7
Entire BRT corridor crash type proportions (for known crashes) for pedestrian crashes (statistically significant decreases based on one-tailed *t*-tests are shaded in green).

Crash Type	Pedestrians All Severities			Pedestrians KAB		
	Before	After	Change	Before	After	Change
Vehicle Backing	1.8%	3.6%	1.9%	3.2%	6.1%	2.8%
Vehicle Going Straight	64.3%	74.5%	10.3%	64.5%	78.8%	14.3%
Vehicle Turning Left	12.5%	5.5%	-7.0%	16.1%	3.0%	-13.1%
Vehicle Turning Right	21.4%	16.4%	-5.1%	16.1%	12.1%	-4.0%
TOTAL KNOWN	100.0%	100.0%	0.0%	100.0%	100.0%	0.0%

5. Conclusions

We found that ART improved traffic safety outcomes, with fewer total crashes and KA crashes after ART construction, but with increases in pedestrian crashes and pedestrian KA crashes. Our analysis suggests that overall crash reductions were most strongly driven by decreases in excessive vehicle speed, and especially so for KA crashes. There were also significant reductions in left-turn crashes, particularly those resulting in overall KA injuries.

Although results for pedestrians were more variable, there was also a strong and significant decrease in left-turn crashes that resulted in pedestrian KA injuries. However, pedestrian crashes involving vehicles going straight increased, likely because of increased pedestrian crashes as pedestrians crossed the road at midblock locations.

Overall, while traffic crashes and fatalities are concentrated on a few major roads for many North American cities, conventional traffic calming measures are not feasible on these high-traffic arterial roads. By making these major corridors more multimodal through BRT and associated improvements, we can decrease crashes and fatalities while simultaneously increasing accessibility for those who cannot drive.

There are several practical applications of this research for urban planners and traffic managers. One key takeaway is that future BRT implementation should integrate pedestrian safety treatments throughout the design. Pedestrian crashes and pedestrian KAB crashes both increased along ART after completion of the BRT system. We suspect that pedestrian exposure likely increased after completion of ART, likely because many users access the system by walking (although this is still an anecdotal hypothesis as we did not have data to substantiate). More detailed pedestrian behavior data is needed to continue future research on this topic, but it may be that pedestrians were more likely to cross midblock after ART construction because they were accessing the BRT stations in the center of the roadway or because the bus-only lanes and the median turning restrictions provided de facto refuges for midblock pedestrian crossings. While the exact reasons behind the overall increase in pedestrian crashes are still unclear, the fact that there was an increase clearly warrants intervention to ensure pedestrian safety. Enhanced pedestrian crossing treatments such as pedestrian hybrid beacons (PHB) or rectangular rapid flashing beacons (RRFB) are recommended at regular intervals to serve pedestrians using the BRT system or attempting to cross the BRT system. Based on ART observations, such crossing treatments are likely most effective in terms of pedestrian compliance when the overall number of general vehicle travel lanes has been minimized.

If a city wishes to leverage their BRT system to improve general traffic safety outcomes along their corridor, reductions in general vehicle travel lanes should be considered. Such lane reductions provide more space for transit while reducing vehicle operating speeds through the increased platooning of vehicles. Furthermore, raised medians should be integrated into the design as ubiquitously as possible as the findings from ART show significant decreases in left-turn collisions both overall and for pedestrians.

It is worth noting the limitations of the police-reported crash data used for these analyses. Police are reliant on their observations after a crash occurs and what the involved persons tell them, which may lead to inaccuracies in identifying factors that led to the crash. Furthermore, only one contributing factor was reported for each crash in the dataset. Since it is possible that there was more than one contributing factor for a crash (e.g., both “Alcohol/Drug Involved” and “Excessive Speed” could be involved), this reporting methodology could lead to further inaccuracies. However, we found no evidence that there were any changes in reporting protocol during the study period. We therefore do not believe that any such reporting issues that may have existed would have changed significantly between the before and after periods and therefore would not impact the main conclusions of this paper.

Even if contributing factors were marked correctly for every crash, the existing categories may not be helpful to our understanding of the safety impacts of the BRT system. For example, although the categories “Failed to Yield Right of Way” and “Other Improper Driving” were cited in significant numbers of crashes, these categories do not provide significant insight into the crash characteristics and what role the infrastructure changes may have played. Future research could examine individual crash reports and study the narrative sections to analyze crashes in more detail.

It is also important to note that injury severity is often misdiagnosed by responding police officers and crashes resulting in minor injuries or less often go unreported, and especially so for pedestrian crash victims (Ferenchak and Osofsky, 2022; Ferenchak et al., 2024). If minor injuries are more likely to go unreported than serious or fatal injuries and ART caused a shift to more minor injuries, the benefits in overall crash reductions noted in this paper may be overestimated. However, crashes resulting in more severe injuries (such as KA or KAB crashes reported in this paper) are more likely to be reported and are therefore less likely to be impacted by the issue noted above. Future work on BRT corridors might collect video data or other similar data that can allow researchers to identify all traffic conflicts (including even near misses) so as not to rely just on crashes reported to police.

It is also important to note that crash data only illuminates some pedestrian safety issues. Other roads may be so dangerous for pedestrians that there is little pedestrian activity at those locations and therefore few crashes to investigate (Ferenchak and Marshall, 2019b; Ferenchak and Marshall, 2020; Ferenchak and Katirai, 2017). The analysis in this work only investigates safety issues that precipitated into crashes. Future work might further benefit from analyses of near misses or subjective perceptions of safety.

Future studies could separately analyze midblock segments and intersections to garner further information about where safety improved or worsened. We hypothesize that BRT infrastructure simplifies midblock segments due to turning restrictions and lane reductions but complicates intersections due to the additional modes of traffic and possibly more turning conflicts. We might be able to detect important differences by examining them separately.

This study examined two 19-month periods before and after the construction of ART, during which there were no BRT buses operating on the new infrastructure. Future research should incorporate longer before and after periods, which would solve several problems. Increasing the study period would increase the sample size, offering more data to be examined. This would also show more of the long-term impacts of the BRT system. A longer "after" period could also include operation of the BRT buses, since ART didn't begin full operations until December 2019.

The key takeaway of this research is a positive one: BRT may both enhance public transportation operations while simultaneously improving traffic safety for other users of the roadway, particularly through reductions in excessive speed and left-turn crashes. BRT is still relatively new in many contexts, but as more cities implement this type of transit, they may expect to see improvements in safety for other modes of transportation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Nicholas N. Ferenchak: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Brady A. Woods:** Writing – review & editing, Writing – original draft, Visualization, Formal analysis.

Acknowledgements

The work presented in this paper was conducted with support from University of New Mexico , Transportation Consortium of South-Central States (TranSET) [grant number 22SAUNM18], and the Center for Pedestrian and Bicyclist Safety (CPBS) [grant number 23UNM01]. TranSET and CPBS are University Transportation Centers funded by the U.S. Department of Transportation. The contents of this paper reflect the views of the authors, who are responsible for the facts and accuracy of the information presented. TranSET and CPBS were not involved in study design, analysis, or writing of the paper.

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