Road Safety in New York City After Vision Zero for Different Land Use Contexts

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ABSTRACT

Over the past decade, more than 45 cities have committed to Vision Zero in the United States. New York City is one of them that has made good progress in reducing car occupant fatalities but struggled to achieve similar declines in pedestrian and bicyclist fatalities. This study assesses road safety performance based on land use context at the census tract level. We use the combined density of population and jobs to categorize NYC census tracts and compare fatalities and fatality risk for different classes of road users in each group. Using aggregate crash data for 2004-2008 and 2014-2018, we track the changes before and after launch of Vison Zero in 2014. We identify a large and growing discrepancy in fatality rates between pedestrians, bicyclists, and car occupants at places with different land use features. Surprisingly, the low density group has the largest number of pedestrian fatalities compared to other density groups in 2014-2018. This is unexpected since low density areas are places where one would not expect to see large numbers of pedestrians. Fatalities per 1,000 road users and fatality risk for pedestrians and bicyclists decreased with the density of the land use. There were very little or no declines in pedestrian and bicyclist fatalities from before to after Vision Zero, expect in the highest density areas. It suggests the need for cities to better understand the relationship between land use context and traffic safety and to implement context appropriate strategies to effectively address traffic fatality issue.

Keywords: Meso-level Analysis, Categorical Analysis**,** Road Safety, Pedestrians, Vision Zero, Safe System Approach, New York City

INTRODUCTION

In February 2014, New York City (NYC) launched its "Vision Zero" initiative, a systems-based approach to safety with the ultimate goal of preventing any serious injuries and fatalities on city streets. Since then, NYC has implemented a series of actions to achieve that target, such as left turn traffic calming, protected bike lanes, and speed cameras. In 2020, total fatalities fell 10% and pedestrian fatalities fell 37% compared to the five-year averages from before the official adoption of Vision Zero (*1*). This is dramatically different from the trends in the USA as a whole where pedestrian fatalities have sky-rocketed since 2009. Specifically, pedestrian fatalities increased 46% from 2010 to 2019 while other fatalities increase 5% in the USA (*2*). However, there is one aspect in which the evolution in fatality rates in NYC tracks that of the USA – non-motorized road users are still burdened more with road fatalities rate than people in cars. As more than 40 cities have officially committed to the Vision Zero policy, the evidence from NYC can critically inform other jurisdictions.

One of the core principles of Vision Zero is to keep track of the process by employing data-driven approaches. Prior literature focuses on the effectiveness of vision zero countermeasures at the intersection level or the corridor level (*3*, *4*). However, there is very limited research that assesses safety outcomes of Vision Zero at an area-wide level and examine how safety improvements are unequally distributed across different contexts in the city. This paper seeks to answer the following questions using data at a census tract unit of analysis: 1) Do fatalities/fatality risk vary across types of places with different population and employment densities? 2) Do the changes in fatalities/fatality risk between before and after the adoption of Vision Zero differ across different types of places?

We use categorical analysis based on population and job density to distinguish between different types of census tracts in NYC and show the fatalities per estimated road users and fatality-casualty ratio for different classes of road users in each group. We also compare the changes of these road safety measures for different clusters by calculating the differences between before and after the adoption of Vision Zero in NYC. The answers to these questions are important because they identify potential disparities and inequities in road safety improvement. Moreover, this study will help provide future directions to evidence-based practices by signaling the types of places that were dangerous and/or getting worse but can be overlooked by policy makers if this type of meso-scale analysis is not conducted.

LITERATURE REVIEW

A number of studies evaluate the impact of land use on non-motorized users' safety, which includes population density and job density, land use diversity, and street design features. This section covers varied aspects of these studies including the unit of analysis, built environment variables, safety outcomes, and mode of transportation. This review helps illustrate how researchers select the above items for various study purposes and shows the intrinsic complexities and challenges in such studies.

Unit of Analysis

Various geographic units of analysis have been explored in transportation safety. Some studies focused on meso-level analysis, ranging from block groups (*5*, *6*), census tracts (*7*), zip codes level (*8*, *9*), and traffic analysis zones (*10*, *11*). Because land use data are more often aggregate at small administrative areas, meso-level analyses are more common in the research on the relationship between land use and road safety. Researchers also tried to define uniform grids as the scale of analysis and argued that this smaller-area analysis infuses higher-resolution data and also helps to account for boundary effects (*12*, *13*). However, this requires higher computing cost for built-environment and socio-economic variables, and the random process of generating grids in terms of both size of grid cells and their placement introduces uncertainty. Other studies have focused on micro-level analysis (e.g., intersection level and corridor comparison) (*14*, *15*) or macro-level analysis (nation or citywide study) (*16*). In terms of selecting units of analysis, Ukkusuri stated that census tract analysis (more disaggregate data) provides more consistent results than the analysis undertaken at the zip code level (*8*). Abdel-Aty et.al found that the significance of explanatory variables is not consistent among analyses at different geographic units of analysis although the signs of coefficients are consistent. They further suggested that a better zone system should be delineated for crash analysis since the existing ones are not delineated for safety planning (*17*).

Built Environment and Safety Outcomes

What variables researchers used to measure land use is another important perspective. The majority of studies used more than one measures. For example, Chen and Zhou used 18 land use variables to model the effects on pedestrian crash frequency in Seattle (*11*). Other researchers used one measure to represent land use features. One example is Marshall and Ferenchak's study that focused on road fatality disparities between urban and rural areas (*18*). In terms of variable types, researchers have studied the effects of population density, land use mix, street network features, sidewalk and bike lane, and comprehensive indices. Several studies have found a positive relationship between population density and crashes that resulted in pedestrian injuries (*14*), while other studies have found that higher population density tends to correspond with fewer pedestrian injuries and fatalities (*19*, *20*). Guerra et al. reported that the relationship varies from Philadelphia and its surrounding suburban counties (*19*). They found a negative association between population density and pedestrian fatality in Philadelphia but a positive association in its surrounding suburban counties. Although research findings have been mixed, it is broadly accepted that higher density development results in lower average speeds, thus decreasing the crash severity, as Ewing and Dumbaugh argued (*21*).

Existing studies have found that a higher proportion of commercial areas is positively associated with pedestrian and bicyclist involved injuries (*7*, *11*, *22*). More residential land use was negatively correlated with pedestrian crash frequency (*8*). However, the effect of mixed land use was unclear. Chen and Zhou found a positive relationship between land use mix and pedestrian crash frequency and risk for years 2009-2012 in Seattle (*11*). In contrast, Wang and Kockelman found a negative relationship between land use entropy (e.g., land use balance. Smaller value means less balanced land use patterns) and pedestrian crash for the years 2007-2009 in Austin (*23*).

The effects of street network features on pedestrians' and bicyclists' safety outcomes are mixed in the literature. For example, Yin and Zhang examined the impact of intersection density on pedestrian-involved injuries in Buffalo, NY and found that both three-way intersection and four-way intersection density were positively correlated with pedestrian injuries (*14*). However, Marshall and Garrick found that higher intersection density was significantly associated with fewer crashes across all severity levels when conducting analysis on street level characteristics in 24 California cities (*6*). Results on pedestrian and bicyclist infrastructure seemed more consistent in previous studies. Researchers have found that sidewalk density is negatively correlated with the pedestrian crash frequency and risk (*11*, *23*). Studies showed that a higher percentage of bike lanes in a city was associated with a decrease in the expected number of fatal crashes, but the results were not significant for total crashes and severe crashes (*6*).

Modes of Transportation and Exposure

When evaluating the safety performance in different land use contexts, it's critical to control for proper exposure because distinct land uses tend to induce different travel behaviors (*24*). Researchers used different exposure and surrogates for exposure to reflect the amount of traveling by road users. Traffic count data (such as annual average daily traffic) is readily available therefore researchers have often estimated traffic volume (VMT) through extrapolation of the road length (*6*, *25*, *26*). However, as Marshall and Garrick suggested in their study (*6*), VMT only accounts for vehicle travel therefore it cannot be used as proxies for the total number of people in the area on foot, bike, or traveling by transit. Population and employment data are the other direct sources of exposure. Research that used population exposure regarded road safety as a public health issue (*8*, *16*). Time spent or number of trips for each mode of transportation are both desirable exposures for the comparison between different classes of road users. Nevertheless, these types of exposure data have very limited availability, especially for non-motorized users. Some scholars have been able to find some reliable estimates for the number of trips by pedestrians and bicyclists. For example, Chen and Zhou used a regional activity-based travel demand model to forecast the number of walking trips and the total number of trips and used these as exposures (*11*). Many studies have used commuting mode share to estimate the numbers of road users (*25*, *27*). The assumption is that areas with the higher rates of pedestrian, bicycle or car mode share likely have corresponding higher level of mobility. The assumption seems reasonable at the national or citywide scales. However, this exposure metric is very sensitive to the underlying geographic unit of analysis. At the census tract level, the car commuting rate seems to be unreliable in predicting the numbers of cars while pedestrian and bicycle commuting rates are more aligned with the number of trips. In addition, researchers have increasingly sought out more accurate proxies of non-motorized users counts from mobile data and crowdsourced data (*28*). Unfortunately, a number of studies have ignored the need for appropriate exposure measures, which generate less convincing conclusions (*29*).

As Handy stated (*30*), researchers often rely on citing other researchers' work using the same measures without even justifying the use and testing likely multicollinearity of the D variables (such as density, land use diversity, street design, destination accessibility, distance to transit, etc.). In this paper, we focus on population density because it is a reliable indicator of the built environment for the scale of our study. Road users' behaviors are largely determined by the immediate context, such as the interaction between motorists and pedestrians, traffic speed, and pedestrian crossing. Therefore, we wish to use density to characterize different types of land use in NYC and test the changes between pre and post in different land use contexts.

DATA AND CATEGORICAL ANALYSIS

NYC comprises of considerably diverse built environments across its five boroughs, and it has relatively complete data on road safety. The database used in the analysis was compiled from multiple sources.

Crash data were obtained and cross-referenced from Fatal Accident Reporting System (FARS) and NYC Open Data- Motor Vehicle Collisions (*31*, *32*). Most crash data entries have coordinates for latitude and longitude, and those that did not were geocoded if they included accurate street or intersection names. The crash-level data files and person-level data files were linked to get the exact number of fatalities for each crash. The data were then aggregated to the census tract level over two 5-year periods (years 2004-2008 and 2014-2018). In addition to the fatalities, the numbers of injuries were also available from 2014 to 2018 only.

To assess the land use characteristics, we derived population and employment data at each census tract from Smart Location Database versions 2.0 and 3.0, respectively for our before/after Vision Zero time periods (*33*). Originally, population data were from 2010 decennial Census and 2018 Census American Community Survey (ACS) 5-Year Estimate; employment data were from 2010 and 2017 Longitudinal Employer-Household Dynamics. To control for exposure, we used mode share data from ACS 5-year estimate commuting in 2010 and 2018 (*34*). The study used 2010 Census Tracts boundaries (clipped to shoreline) from the Department of City Planning (DCP) (*35*).

We screened the citywide census tract land use features, including population density, land use mix, road network density, and walkability score. As we discussed in the Literature Review section, many variables are correlated with each other. In our study, we focus on combined density of population and jobs because it is a reliable indicator of the built environment for the scale of our study as we argued in Literature Review section. Some census tracts with unique land use types were identified before the density classification. Census tracts that were excluded for density classification were analyzed separately. These included census tracts consisting mostly of airports (count for 2 census tracts), cemeteries (count for 12 census tracts), parks (count for 16 census tracts), areas with larger amounts (more than 50%) of highways (count for 16 census tracts), and others (jail, fort, or power station, count for 3 census tracts).

We categorized the remaining 2115 census tracts into four equal-sized groups based on the density in 2010. The combined density of population and jobs is calculated as follows:

$$density = \frac{population + jobs}{area\ of\ census\ tract\ (acres)} \tag{1}$$

There are four groups ranging from low density level (<45.5 count/acre), medium density level (45.2-78.8 count/acre), high density level (78.8-130 count/acre) and highest density level (>130 count/acre). Each group has 529 census tracts except the high density group which has 528 census tracts. A map is presented in the results section to show the spatial distribution of the various groups. To test if those different density groups differ in fatalities, we ran a two-way mixed analysis of variance (ANOVA) with the number of fatalities as dependent variable, the 5-year periods (before/after) as within-group factor, and density group as between-group factor. The test shows that there is significant ($p<0.05$ level) difference between density groups in terms of the numbers of fatalities.

In order to evaluate safety performance by classes of road users in each group, we developed several road risk indicators using estimates of exposure.

Equation (2) shows the fatality rate for each class of road user. The first metric was used to control the number of road users in each group of census tracts. A number of researchers adopted commute mode share as the readily available estimates for the actual number of bicyclists and pedestrians. For example, Marshall and Garrick developed the user-based exposure matrix to estimate of travelers using each mode of transportation at the city-level (*27*). We believe that the differences in the walk or bike share of trips roughly parallel differences in the numbers of pedestrian or bicycle trips, therefore making user-based exposure matrix an acceptable metric for non-motorized users at the scale of our study.

$$\begin{aligned} fatality\ rate &= \frac{fatalities}{estimated\ number\ of\ road\ users/1{,}000} \\ &= \frac{fatalities}{mode\ share * (population + jobs)/1{,}000} \end{aligned} \tag{2}$$

Raw number of fatalities or average number of fatalities may not be appropriate for the comparison between road users, but it provides valuable insights about how fatality number evolved after Vision Zero became city policy. Therefore, we introduce average number of fatalities to represent this, as defined in Equation (3).

$$Average\ number\ of\ fatalities\ = \frac{total\ number\ of\ fatalities}{number\ of\ census\ tracts\ in\ each\ group} \tag{3}$$

Equation (4) defines the percentage of census tracts with fatalities. This is another metric to examine how Vision Zero affected changes in fatalities, especially for the priority areas outlined in Vision Zero plan (*1*).

$$\begin{aligned} &percentage\ of\ census\ tracts\ with\ fatalities \\ &= \frac{number\ of\ census\ tracts\ with\ at\ least\ one\ fatalities\ during\ 5 - year\ period}{number\ of\ census\ tracts\ in\ each\ group} \end{aligned} \tag{4}$$

Equation (5) defines the risk of fatality as the ratio of fatalities to casualties. This metric is commonly used in studies of the relationship between impact speed and pedestrian fatality risk (*36*). We introduce this metric to represent the probability of dying if one is involved in an injurious crash and calculated the probabilities for different density groups. It is an important dimension to track the progress of Vision Zero initiative as mitigating crash severity is a vital principles of safe systems (*37*).

$$risk\ of\ fatality = \frac{number\ of\ fatalities}{number\ of\ casualties} = \frac{number\ of\ fatalities}{number\ of\ fatalities + number\ of\ injuries} \quad (5)$$

RESULTS

In this section, we calculate the above-mentioned metrics and show the results for NYC as a whole, each borough and each density group for 2004-2008 and 2014-2018. The statistics also show the difference in changes of fatality rate between the two periods for different classes of road users.

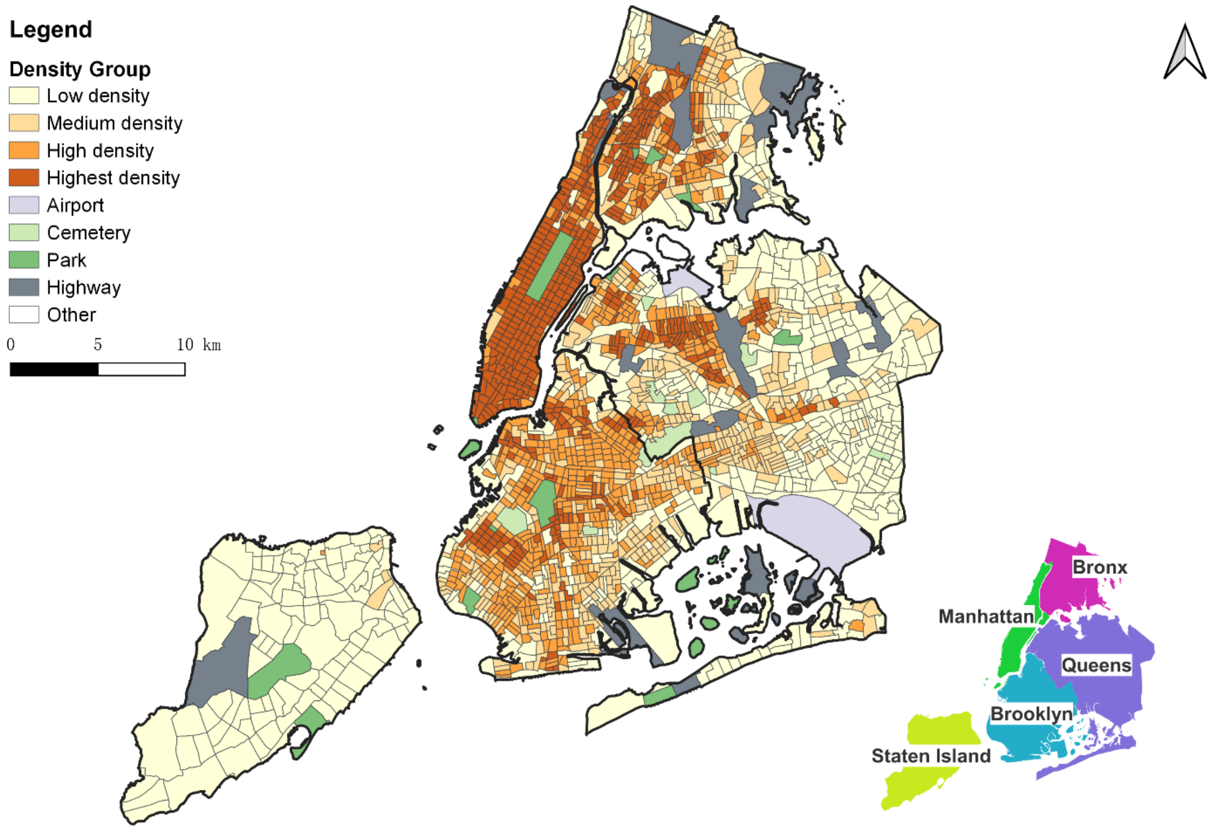
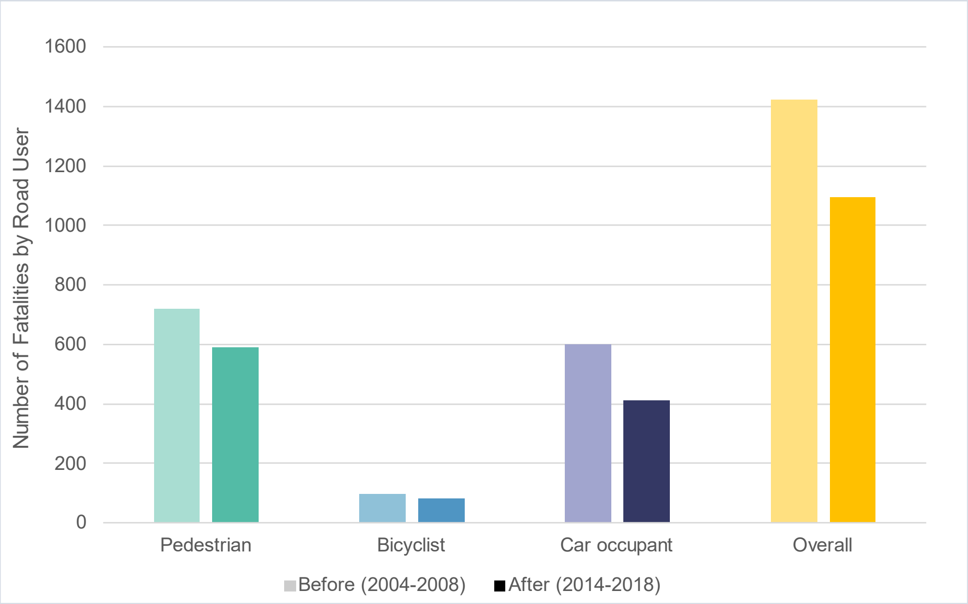


Figure 1 Map of census tract groups and boroughs in NYC based on density

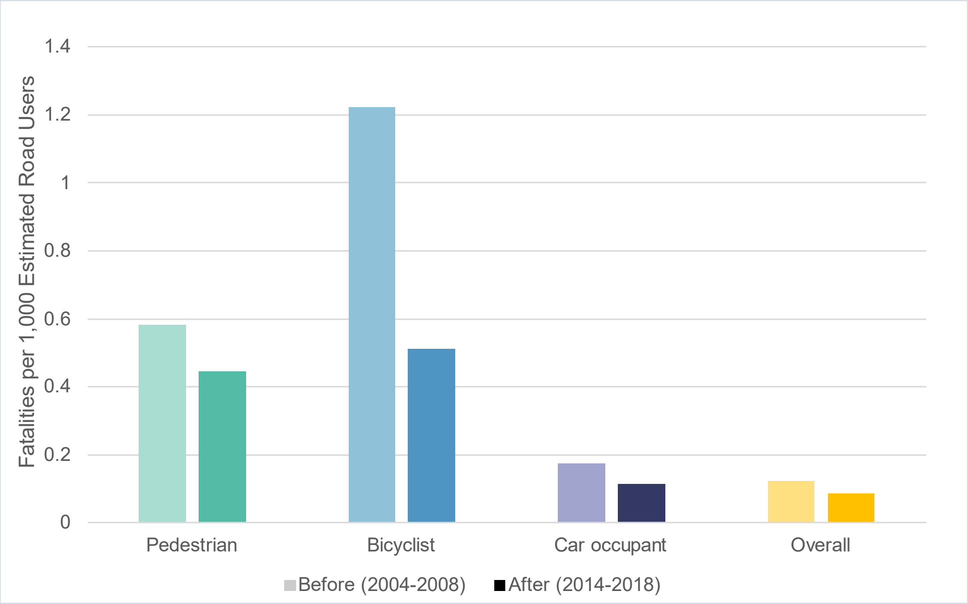
Figure 1 shows the map of density groups and special land use at the census tract level, along with the boundaries of five boroughs in NYC. The geographical distribution of density groups highlights the variability in land use type and some unique characteristics in each borough. Most census tracts in Manhattan fall in the highest density level and most Census Tracts in Staten Island are in the low density level. The Bronx, Queens and Brooklyn have a larger range of density groups with higher density Census Tracts concentrating in places such as downtown Brooklyn and surroundings, the Chinatowns, and West Bronx. Overall, the classification method using density as indicators for the land user seems to do a good job distinguishing between different types of land use contexts in NYC.

Citywide

The citywide trends of road fatalities show some remarkable achievements in pursuing zero death goals in NYC. **Figure 2a** shows that the numbers of fatalities for pedestrians, bicyclists, and car occupants all decreased from 2004-2008 to 2014-2018 after the official declaration of Vision Zero initiative. However, the various modes had very different rates of decrease. Car occupant fatalities fell by 32% while pedestrian fatalities and bicyclist fatalities fell by only 18% and 16% respectively. **Figure 2b** shows fatality rate for classes of road users based on the mode-share-based risk measure and overall fatalities per 1,000 New Yorkers. The reduction in the bicyclist fatality rate was 58%, which was noticeably larger than those of the pedestrians and car occupants and also outpaced the decline of bicyclist fatalities arguably because of the city's bicycle boom in the recent decades. The statistics from a NYC report confirmed this finding that bicyclist severe injuries and fatalities per ten million trips decreased by 69% from 2005 to 2018 (*38*). The modal shift towards bicycling was likely due to better protected bicycle lane networks and popular bike sharing programs in NYC. Meanwhile, the 23% reduction in pedestrian fatalities was less than the 34% reduction in car occupant fatalities. Overall, in 2014-2018 non-motorized users still had substantially greater fatality rates than car occupants did. This indicates that the disparities of road safety exist between different classes road users in NYC. In contrast, our previous study found that the fatality rates for pedestrians, bicyclists and vehicle occupants have all converged to identical low level in the Netherlands (*39*), which are dramatically different from the situation in NYC.



(a)



(b)

Figure 2 Comparison of (a) number of Fatalities and (b)fatalities per 1,000 estimated road users for different classes of road users in NYC

Borough

Overall, the number of fatalities is decreasing citywide, but we are interested in whether fatalities rates vary across geographically across our study area. Assessing the road safety by borough will provide some insights into this question. **Figure 3** shows the number of fatalities for classes of road users and total by borough. Total fatalities decreased in all boroughs over time. However, the declines were much smaller for pedestrians than for car occupants in all boroughs except for Manhattan where the declines were similar. Even more strikingly, pedestrians were the only class of road user for which we did not observe decreasing trends in all boroughs. Specifically, the numbers of pedestrian fatalities increased at Queens and Bronx by 10.3% and 1.1%, respectively. Bronx and Queens also have the smallest declines in term of total road fatalities, 5% and 10% respectively. Manhattan had the largest decline in pedestrian fatalities and the safest borough based on total fatalities per-capita, probably because in Manhattan much effort was put into reducing pedestrian and car fatalities through investment in safety improvement projects such as left turn traffic calming and leading pedestrian intervals (*40*). With more mixed density groups, Brooklyn nearly halved car occupant fatalities and decreased pedestrian fatalities by 24%, making it the second safest borough based on total fatalities per-capita. What is intriguing and will be explored in the next section is how the places with various density levels differ in safety outcomes in NYC.

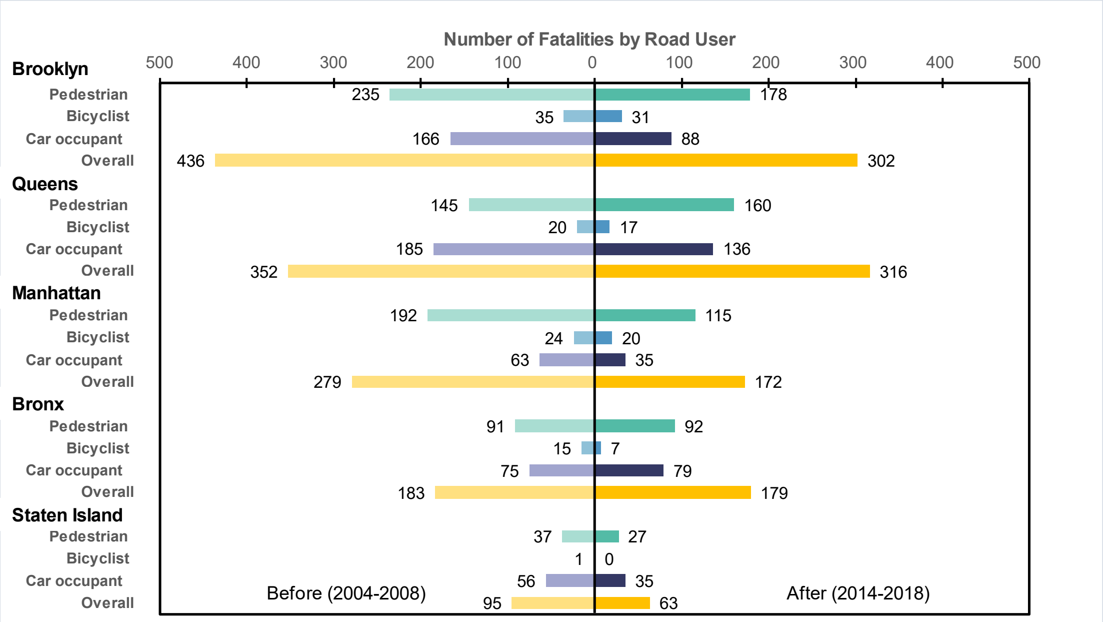


Figure 3 Comparison of number of Fatalities for different classes of road users in each borough

Census Tract-level Density Groups

Figure 4 shows the number of fatalities for pedestrians, bicyclists, car occupants, and total fatalities aggregated at different density groups. The numbers of total fatalities were higher in low density group than those in other three groups for both before and after Vision Zero. Regarding pedestrian fatalities, the highest density group had the largest number among all groups in 2004-2008. However, in 2014-2018, all group had similar numbers of pedestrian fatalities. Meanwhile, low density areas, which are not usually associated with intense pedestrian activities, had the largest number of pedestrian fatalities. As for bicyclists, fatality numbers tend to be larger in areas with higher density levels. The numbers of car occupant fatalities were substantially higher in areas with lower density levels than those in other density groups. And the numbers of car occupant fatalities generally increased with the density level.

Figure 5 reveals a huge and growing discrepancy in pedestrian, bicyclist, and overall fatality rates per 1,000 road users across different density areas. We did not include the car fatality rate here as we argued in method section that car mode share does not align with the number of car trips at census tract level. Fatality rates for pedestrian, bicyclist, and overall fatality rates decreased with density level. In other words, those non-motorized users had a significantly higher fatality rate in areas with lower density. Even in 2014-2018, pedestrian fatalities per 1,000 pedestrians in low density area were 16 times higher than that in highest density area, and 3 times higher than that in high density area. The difference for bicyclist pedestrian rates between density groups was smaller. Bicyclist fatalities per 1,000 bicyclists in low density area were more than 4 times higher than that in highest density area, and more than 2 times higher than that in high density area. The statistics show that both pedestrians and bicyclists were facing with more perilous situation in lower density areas of NYC.

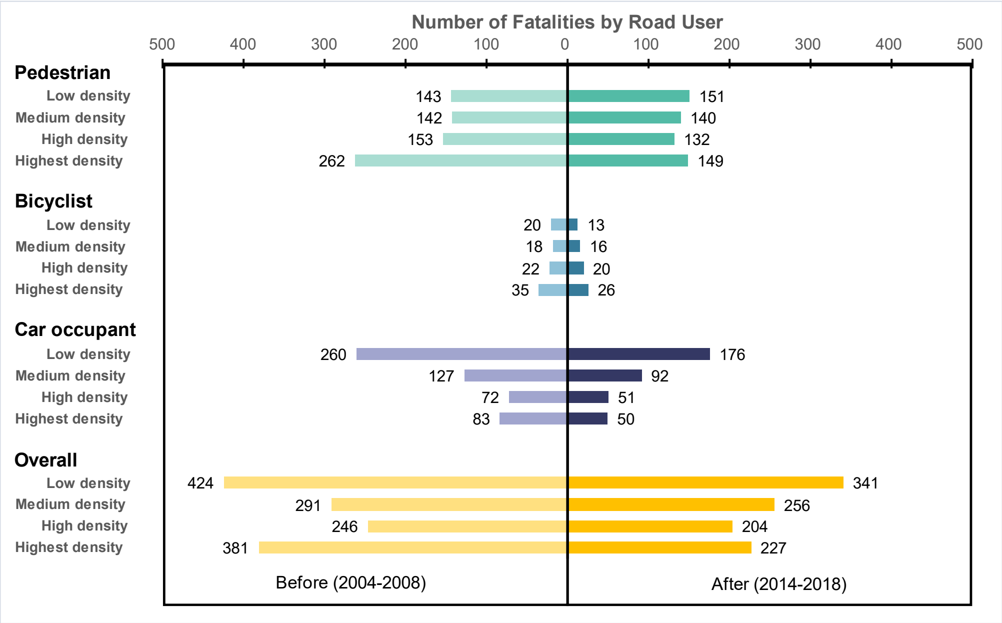


Figure 4 Comparison of fatalities for density group by class of road user

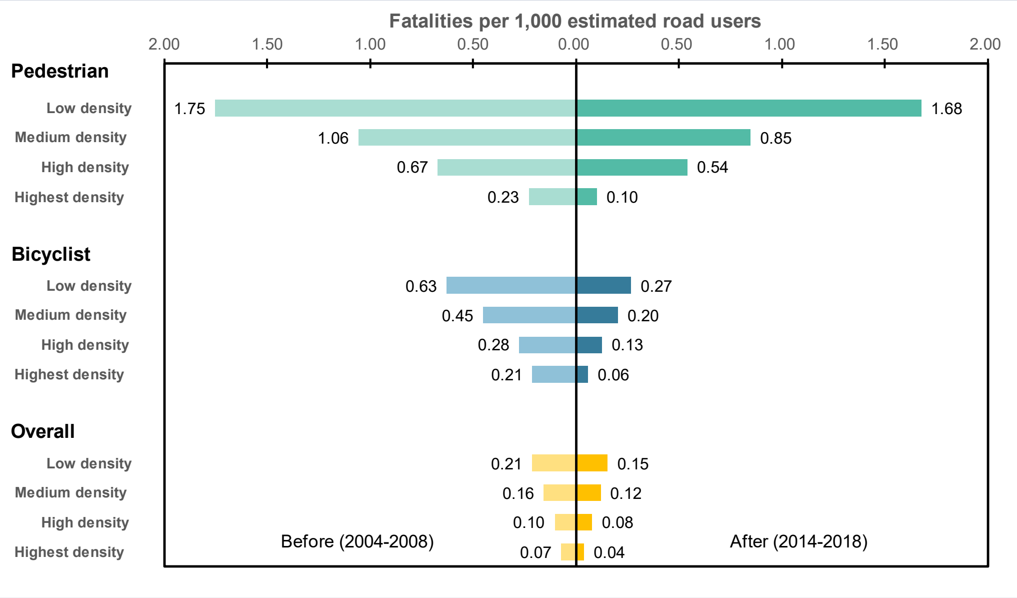


Figure 5 Comparison of fatalities per 1,000 estimated road users for density group by class of road user

Figure 6 and **Figure 7** track the changes of average number of fatalities and fatalities per 1,000 estimated road users between 2004-2008 and 2012-2018. Low-density areas strikingly saw little or no decrease in average pedestrian fatalities and fatality rates in the after period. Average number of pedestrian fatalities rose by 6% in low density group over time, as shown in **Figure 6**. This indicates that the environments for walking in low density areas had not improved. Both low density and highest density areas show large declines in average number of bicyclist fatalities. The declines in average number of car occupant fatalities and overall fatalities were similar across different density groups even though highest density group had a slightly larger decline.

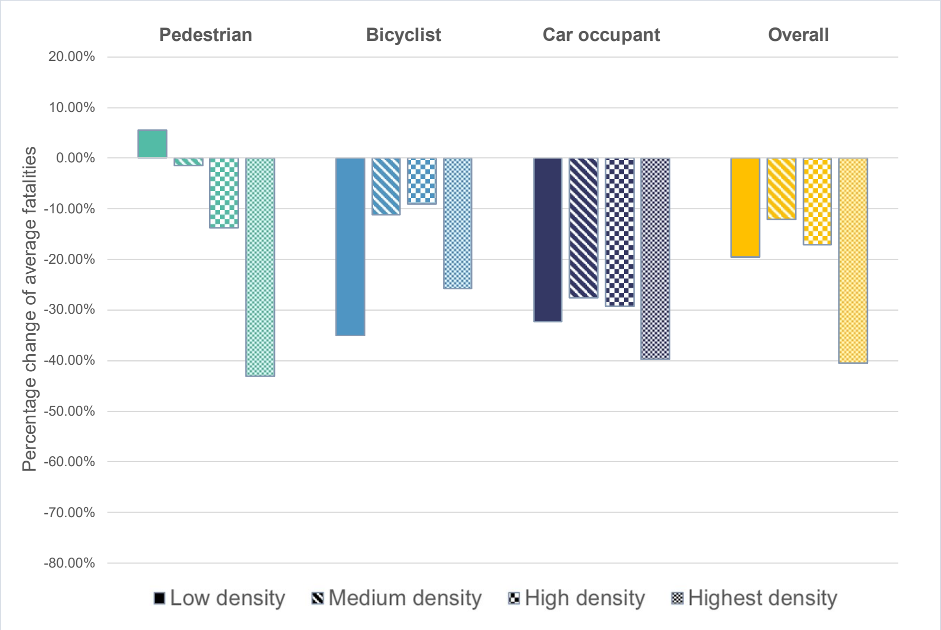


Figure 6 Percentage change of average fatalities per census tract for different classes of road users by density group (2004-2008 and 2014-2018)

The fatalities rate metric provides similar information, as shown in **Figure 7**. The decline in pedestrian fatalities per 1,000 estimated road users was 4% in low density area while the decline was 56% in highest density area. Highest density group also had the largest declines in bicyclist fatalities rate at 72% and overall fatalities rate at 44%.

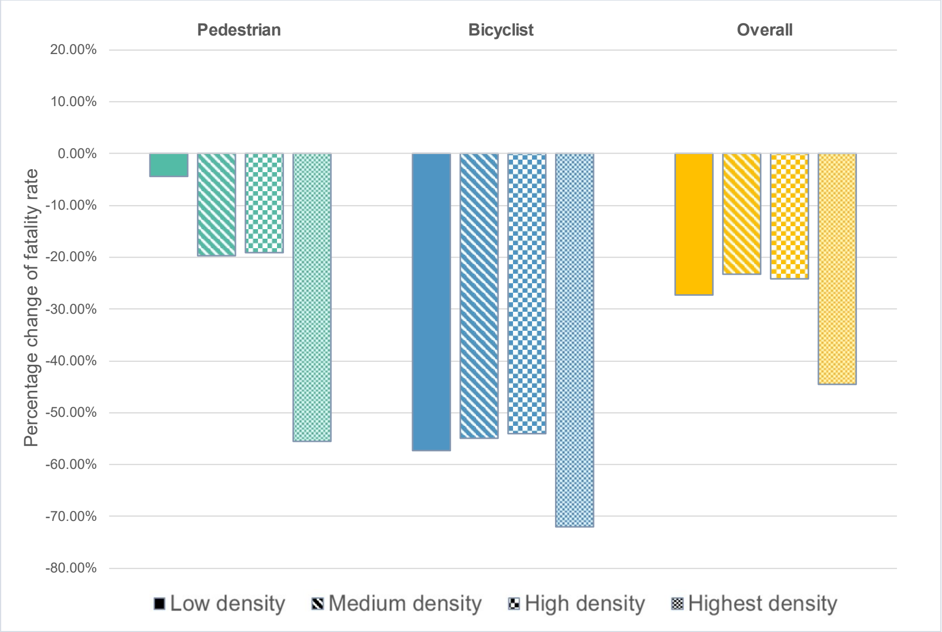
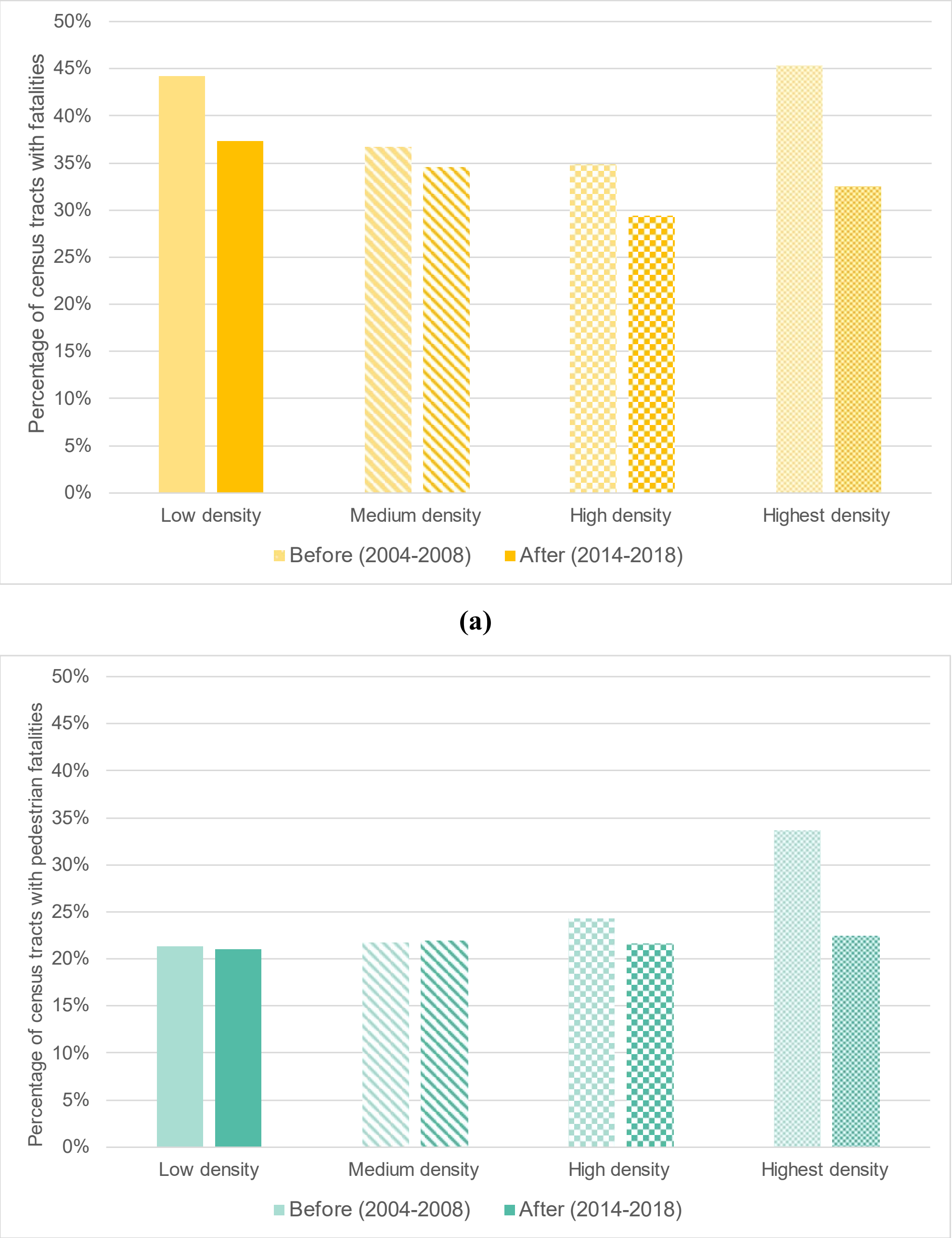


Figure 7 Percentage change of fatalities per 1,000 estimated road users for different classes of road users by density group (2004-2008 and 2014-2018)

Figure 8a and 8b show the percentage of census tracts with any fatalities and percentage of census tracts with pedestrian fatalities in 2004-2008 and 2014-2018, respectively. Although the census tracts with fatalities were not necessarily the same tracts, this plot implicitly shows how the vision zero managed to geographically concentrate traffic crash incidents. For all density groups, the percentage of census tracts with fatalities decreased over time. However, the decline was much larger in the highest density group than in other groups. Percentage of census tracts with fatalities changed by 12% in highest density area compared to 7% in low density area, 2% in medium density area, and 6% in high density area. The patterns were more pronounced for the percentage of census tracts with pedestrian fatalities. In 2004-2008, the highest density group had the largest percentage of census tracts with pedestrian fatalities. In 2014-2018, the highest density group had the similar level with other groups, resulting from 12% reduction. At the same time, there were not obvious declines in the other three density groups. These results coincided with the findings represented in **Figure 6** and **Figure 7**, which indicates a disparity in pedestrian safety across types of places with different density levels.



(a)

(b)

Figure 8 Percentage of Census Tracts with (a) Total Fatalities; (b) Pedestrian Fatalities by Density Group (2004-2008 and 2014-2018)

Figure 9 shows the risk of fatality when one person is involved in an injurious crash. Even though we do not have the crash data for all severities in 2004-2008, the risk of fatality in 2014-2018 is consistent with the general patterns from the previous results. The risk of fatality for all road users decreased with the density level. The probability of death as a pedestrian or bicyclist involved in an injurious crash was more than two times higher in low density areas than in the highest density area. The probability of death as a car occupant death in low density areas was twice as much as that in highest density areas. It is also noteworthy that the risk of fatality for pedestrians and bicyclists was much higher than that for car occupants wherever they are. The road crashes for unprotected road users occurred more frequently and were more deadly than for people in cars, which stands as a warning signal for NYC vision zero. In particular, the differences in fatality risk imply the persistence of the "vulnerable road users" concept in NYC. We will discuss what lessons this assessment could provide for future vision zero initiatives in more details in next section.

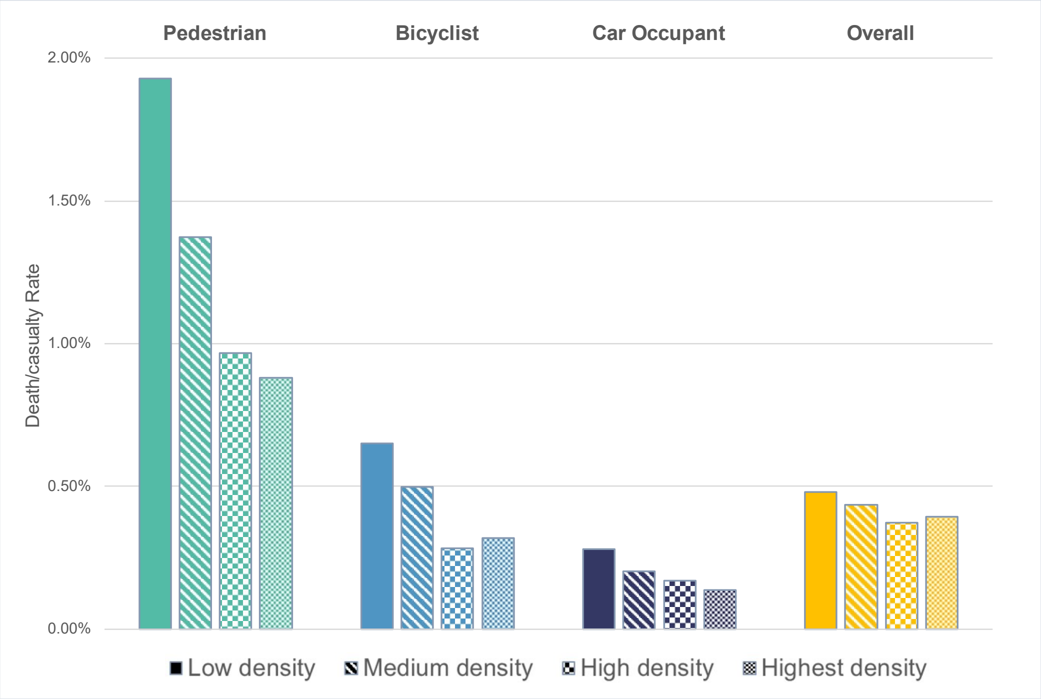


Figure 9 Death/casualty Rate for Different Classes of Road Users, 2014-2018

DISCUSSION

We observe that Vision Zero in NYC has been successful in terms of improving traffic safety at the city-wide level. That said, when the changes in road safety are examined from a geographic perspective, stark variations across the study area become apparent.

Low density areas were much more dangerous for all types of road users, particularly for non-motorized users. There were large and growing inequalities in fatality rates between pedestrians, bicyclists, and car occupants in these areas. Although the fatalities and fatality rate for car occupants decreased, there were very little or no decline for pedestrians and bicyclists, expect in the highest density areas. These results suggest that the Vision Zero impacts to date have resulted in very different outcomes for different types of user groups and for different types of land use context. Moreover, the risk of fatality for non-motorized users was significantly higher than that for car occupants no matter the context.

The results show that NYC has not eliminated the concept of "vulnerable road users". In other words, the non-motorized road users are faced with higher road fatality risks than people in cars. Conversely, earlier adopters of Safe Systems approach such as the Netherlands made enormous advances by reducing fatality rates to identical low level for all three classes of road users (*39*). Therefore, NYC needs more data-driven studies to better understand the reasons for this disparity in results even after the adoption of Vision Zero.

Another alarming finding is that there was a substantial number of pedestrian fatalities in low density areas and the number has kept rising over time. Places with lower population and job density were places where small number of pedestrians and consequently, pedestrian fatalities, are expected. However, our meso-level analysis highlighted the fact that pedestrians are at a great risk of dying and in large numbers on the roads in low density areas. More alarmingly, this seems to be a growing problem. People walking or bicycling at lower density areas, even without access to a car should be as safe as people at higher density areas for Vision Zero to be achieved.

Those findings through the comparison between the before and after Vision Zero data points provide some possible solutions. Fatal crashes for pedestrians and bicyclists are occurring at surprisingly high rates in low density areas. This is likely due to the higher vehicle speed, and slower trauma response in low density areas (*41*). Vision zero initiatives put much effort on speed management, and it seems to be very effective. For example, NYC installed 1,259 speed cameras from 2014 to 2020 and this contributed to 14% decline of injuries on school speed zone corridors with cameras (*42*). Speed cameras and automated traffic enforcement were recently proven to operate at all time of the day. An expansion of the speed camera program may be useful in decreasing traffic speed at low density areas. More importantly, engineering solutions focusing on street retrofitting should be invested to calm the traffic. NYC has adopted some measures such as turning traffic calming, enhanced crossings, speed humps, etc. However, these implementations were more focused on denser areas (*43*). In order to better protect all road users in lower density areas, NYC should implement more slow zones and living streets, where appropriate. It can help create a sense of place for people instead of being conduit for moving traffic. In areas where these measures are not feasible or appropriate more efforts will be needed to separate and protect pedestrians and bicyclists from fast moving traffic. In any case, we must build on the research from this paper to better understand the specific nature of these low-density areas in order to develop effective countermeasures.

There is also a desperate need of better infrastructure for pedestrians and bicyclists. Over the past decade, people increasingly chose to walk, bike, or use other micro-mobilities for their daily travel in NYC. Since research has proven the association between infrastructure and reduced crash risk for pedestrians and bicyclists (*6*, *11*), more infrastructure is needed to keep up with the modal shift. This point is also illustrated by the trends found in the Results section. Safety improvement projects for bicyclists were extensively implemented since 2014. Taking advice from Sweden Vision Zero and the Dutch Sustainable Safety, NYC built offset crossing at intersections, 135-miles protected bike lanes, along with marked bike lanes. The positive outcomes for bicyclist safety were immense. According to our finding, bicyclist fatality rate fell by 58% from 2004-2008 to 2014-2018. And the number of bicycle trips increased by 150% from 2006 to 2015 (*44*).

Transportation planners and engineers should focus on promoting accessibility rather than just mobility for the sake of road safety. People who stand by accessibility planning believe that it reduces the need for driving and keeps destinations within relatively short distances in a decent and pleasant way (*45*). Therefore, good accessibility creates safer situation generally by reducing the total amount of vehicle trips, i.e., decreasing exposure in traffic and footprint for the environment. In our study zones, the lower density areas tend to be single familiar houses with lower land use mix, thus requiring longer times of exposure on road. It is noteworthy that combining access with mobility on the same facilities causes lots of hazards, such as building commercial areas on a fast-moving road. This type of facilities that is notoriously ubiquitous in the USA (often called "stroad") is discouraged by the safe system principles (*37*).

CONCLUSIONS

Several studies have explored potential factors leading to the increase in pedestrian fatalities in the USA during the last decade. NYC is tackling this road safety issue, as one of the first cities that adopted the concept of Vision Zero in the USA. As we have highlighted, the NYC approach has garnered significant success with significant reduction in fatalities for all classes have road users. In particular, pedestrian and bicyclist fatalities have decreased in the era of zero vision in NYC. This is an important achievement given the fact that in many other places in the USA, pedestrian fatalities have increased substantially. Nonetheless, our research highlights the fact that there are large and growing discrepancies in fatality rates between pedestrians and bicyclists, on the one hand, and car occupants, on the other.

The analytical approach used in this study is based on using land use variables as grouping factors. We use population and job density to characterize different types of land use in NYC as density is a reliable indicator of the built environment for the scale of our study. By using this categorization method, we identify the differences in fatality risks and test the changes between pre and post Vision Zero in different land use contexts. This relatively uncommon approach to analyze traffic fatalities allows us to identify some surprising aspects of the traffic fatality distribution in different land use contexts in NYC. Specifically, we are able to show that areas of the city with lower density level have a surprisingly high number of pedestrian fatalities. We characterize this result as surprising because on first blush one would not expect a high number of pedestrians in these areas. This line of thinking is borne out by the fact that Vision Zero initiatives have largely been implemented in other areas of the city, away from these low-density zones.

Overall, the results of this analysis suggest that even though the city is having some success in reducing traffic fatalities, the safety of people in vehicles is improving at a significantly faster rate than that of people on foot or on bikes. As such, it is incumbent on the city to rethink its strategy of reducing pedestrian and bicyclist fatalities. One important aspect of this rethinking is highlighted by our results showing that not only is there an unexpectedly large number of fatalities in low density land use context, but areas with this type of land use in the city is where pedestrian fatalities have not decreased. Our study draws attention to the need to study this type of context in details and to develop context appropriate safety measures.

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AUTHOR CONTRIBUTIONS

The authors confirm contribution to the paper as follows: study conception and design: N. Garrick, C. Atkinson; data collection: G. Shi, Y. Song; analysis and interpretation of results: G. Shi, Y. Song, N. Garrick, C. Atkinson; draft manuscript preparation: G. Shi, Y. Song, N. Garrick, C. Atkinson. All authors reviewed the results and approved the final version of the manuscript.

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