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THE BUILT ENVIRONMENT AND PEDESTRIAN SAFETY IN THE PHILADELPHIA REGION

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Background

This document presents findings and summarizes ongoing work related to the Mobility21 project "THE BUILT ENVIRONMENT AND PEDESTRIAN SAFETY IN THE PHILADELPHIA REGION." This project is a continuation of an effort that was supported by the University the T-Set University Transportation Center. Although this is the final project report, the final section of this report briefly summarizes three ongoing studies that stem from this report.

Introduction

Traffic collisions are one of the leading causes of death, physical injury, and property damage worldwide. With over 10 traffic fatalities per hundred thousand residents in the United States, the transportation system is the leading cause of death for persons aged 5-to-24 and is one of the top ten causes of death for all but the elderly and very young (Centers for Disease Control and Prevention 2017). There is substantial variation in traffic safety records across cities, states, and regions. Phoenix and Dallas' streets are around three times as deadly as Boston and San Francisco's. The safest state, New York, had just 5.0 fatalities per hundred thousand residents in 2017 while the least safe, Mississippi, had 23.1(National Highway Traffic Safety Administration n.d.). Substantial variation in settlement patterns across cities and states may help to explain some of the variation in traffic safety records.

At first glance, densely populated states, counties, and cities have better traffic records than more sparsely populated ones. County-level traffic fatality rates (National Highway Traffic Safety Administration n.d.) decline systematically with population density. The median fatality rate in the least densely populated counties (0 to 0.2 people per acre) is four times higher than the median fatality rate in densest counties (3.2 to 108.5 people per acre). The average fatality rate is five times higher. Despite these general trends, Stevenson et al. (2016) in a recent special series by *The Lancet* estimated that increasing the density of six world cities would result in increased traffic fatalities as residents switched from driving to the more vulnerable modes of walking and bicycling. By contrast, Stevenson et al. (2016) predicted that increasing density would result in fewer deaths from pollution, diabetes, and cardiovascular disease.

This paper investigates relationships between neighborhoods' urban form, roadway characteristics, traffic collisions, and fatalities in the Philadelphia region. Particular attention is given to neighborhood population density, the most commonly used and discussed measure of urban form and a measure that is directly related to the most commonly used traffic safety statistic, fatalities per 100,000 people. A better understanding of whether denser neighborhoods correlate with higher or lower traffic fatalities could shed light on the likely public health effects of promoting compact cities. Better understanding of the factors that promote neighborhood traffic safety could also help households make more informed decisions about the tradeoffs between different types of neighborhoods.

Theoretical Overview

Population density is the simplest, most studied, and most referenced measure of urban form. Researchers, urbanists, and the general public frequently use population density as a catch-all term or empirical proxy for urban form. Higher population densities are associated with more cost-effective transit service (Guerra and Cervero 2011; Meyer, Kain, and Wohl 1965; Pushkarev and Zupan 1977), lower energy consumption (Glaeser and Kahn 2010; Newman and Kenworthy 1989), lower vehicle travel (Ewing and Cervero 2010; Stevens 2017), and more walking and biking (Saelens, Sallis, and Frank 2003).

Population density—and other aspects of the built environment—likely influence the probability and severity of traffic collisions. In dense environments, there are more frequent and more complicated interactions between multiple modes, particularly motor vehicles and pedestrians, potentially increasing the risk of injurious collisions, as simulated in *The Lancet* special issue (2016). Offsetting this, denser neighborhoods tend to have less vehicle travel (Ewing and Cervero 2010; Stevens 2017), potentially reducing the risk of collision, and slower vehicle speeds (Chatman 2008), which could reduce the severity of injury of a given collision. A pedestrian-involved collision, for example, may be substantially rarer in a low-density area, but also more likely fatal, since vehicle speed at the time of impact will likely be higher and drivers will likely be less aware of pedestrians. Though the precise relationship varies by study (Rosén, Stigson, and Sander 2011), pedestrians are five times more likely to survive a collision with a vehicle going 18 mph than 31mph (Rosén and Sander 2009).

Medical response times and the quality of hospital service may also vary with urban form. Blatt and Furman (1998) and Clark (2003) hypothesize that a collision might result in a serious injury in an urban area with many hospitals and experienced trauma centers but death in a suburban or rural setting with slower emergency response times and less prepared hospital staff.

Another reason to focus on population density is that it is directly related to total population, one of the most common controls for safety. Many researchers explicitly divide collisions by the number of residents in an area before estimating models (Cho, Rodriguez, and Khattak 2009; Ewing, Hamidi, and Grace 2016; Ewing, Schieber, and Zegeer 2003; Fischer, Sternfeld, and Melnick 2013). Others divide total collisions by land area (Fuentes and Hernandez 2013; Loukaitou-Sideris, Liggett, and Sung 2007), another key component of population density. These models, therefore, require careful interpretation for understanding the relationship between density and traffic safety. For example, predicting crashes per acre as a function of population per acre in a linear model, as in Loukaitou-Sideris et al. (2007), is mathematically equivalent to predicting crashes as a function of population.

Previous Work

The literature is inconclusive, even contradictory regarding the relationship between population density, traffic collisions, and traffic fatalities. Of the studies reviewed for this paper, 14 found statistically significant positive correlations between population density and traffic collision or collision severity (Cho, Rodriguez, and Khattak 2009; Clifton and Kreamer-Fults 2007; Ladrón de Guevara, Washington, and Oh 2004; LaScala, Gerber, and Grunewald 2000; Lee, Zegras, and Ben-Joseph 2014; Lovegrove and Sayed 2006; Quistberg et al. 2015; Siddiqui, Abdel-Aty, and Choi 2012; Ukkusuri et al. 2012; Wang and Kockelman 2013; Wedagama, Bird, and Metcalfe 2006; Wier et al. 2009; Moudon et al. 2011). Nine found statistically significant inverse correlations (Blatt and Furman 1998; Clark 2003; Dumbaugh and Rae 2009; Ewing, Hamidi, and Grace 2016; Ewing, Schieber, and Zegeer 2003; Fischer, Sternfeld, and Melnick 2013; Graham and Glaister 2003; Lucy 2003; Harvey and Aultman-Hall 2015). And three studies presented mixed results (Miranda-Moreno, Morency, and El-Geneidy 2011; Morency et al. 2012; Nunn and Newby 2015). For example, Miranda-Morena et al. (2011) found that higher density correlated with more pedestrian collisions but even more pedestrian activity and thus a lower pedestrian collision rate. Others, such as Marshall and Garrick (2011), drop population density from their final models due to statistical insignificance.

Inconsistency in the theoretical and statistical treatment of population density may contribute to the wide range of findings. Safety researchers use population density as a measure of urban form (Dumbaugh and Rae 2009; Ewing, Hamidi, and Grace 2016; Ewing, Schieber, and Zegeer 2003; Fischer, Sternfeld, and Melnick 2013; Graham and Glaister 2003; Lucy 2003; Ukkusuri et al. 2012; Wang and Kockelman 2013; Yu and Xu 2018), a proxy for or predictor of exposure (Cho, Rodriguez, and Khattak 2009; Clifton and Kreamer-Fults 2007; Delmelle, Thill, and Ha 2012; Fuentes and Hernandez 2013; Ladrón de Guevara, Washington, and Oh 2004; Loukaitou-Sideris, Liggett, and Sung 2007; Miranda-Moreno, Morency, and El-Geneidy 2011; Moudon et al. 2008; Quistberg et al. 2015; Siddiqui, Abdel-Aty, and Choi 2012; Wier et al.

2009; Yu and Zhu 2016), or simply a good predictor variable (Blatt and Furman 1998; Clark 2003; LaScala, Gerber, and Grunewald 2000; Lovegrove and Sayed 2006). Only two papers reviewed explicitly present and model a theoretically clear relationship between density and traffic collisions. For example, Ewing, Hamidi, and Grace (2016) use structural equation models that allow metropolitan development patterns to correlate with crashes and fatalities through an intervening relationship with total vehicle travel. Similarly, Miranda-Moreno, Morency, and El-Geneidy (2011) test for correlations between neighborhood built environments and pedestrian crashes through intervening variables, such as pedestrian volumes and traffic speeds.

The type and severity of collisions likely also influence findings. Most studies of fatalities or fatalities per capita find an inverse correlation with population density (Blatt and Furman 1998; Clark 2003; Ewing, Hamidi, and Grace 2016; Ewing, Schieber, and Zegeer 2003; Graham and Glaister 2003; Lucy 2003; Harvey and Aultman-Hall 2015; Nunn and Newby 2015), while most studies of pedestrian-involved collisions find a positive correlation (Ladrón de Guevara, Washington, and Oh 2004; LaScala, Gerber, and Grunewald 2000; Quistberg et al. 2015; Siddiqui, Abdel-Aty, and Choi 2012; Ukkusuri et al. 2012; Wang and Kockelman 2013; Wedagama, Bird, and Metcalfe 2006; Miranda-Moreno, Morency, and El-Geneidy 2011; Morency et al. 2012). Findings about the relationship between population density and total vehicle collisions, pedestrian fatalities, and the severity of pedestrian injuries from collisions are more split.

Data and Methods

Study Design and Research Context

This paper estimates relationships between population density, traffic collisions, severe injuries, and fatalities that occurred on road segments and intersections in Philadelphia and four surrounding suburban counties using five years of traffic collision data (2010 to 2014) from the Pennsylvania Department of Transportation (PennDOT) (2017). Reported models include six outcome measures: total reported collisions, total serious injuries, total traffic fatalities, pedestrian-involved collisions, serious pedestrian injuries, and pedestrian fatalities on each road segment or intersection. For each outcome, we estimated six models with different control variables that population density likely influences but are also associated with traffic safety, such as neighborhood socio-demographics, total vehicle travel, total pedestrian exposure, street design, and posted speed limits. Thus, we consider the relationship between population density and traffic collisions, independent of and dependent on a fixed level of exposure, existing road networks, and other land use patterns and socio-demographic characteristics.

Philadelphia has a population of over 1.5 million residents with a densely populated urban core but also low-density residential neighborhoods, particularly in the northeast and northwest. The surrounding Pennsylvania counties—Bucks, Chester, Delaware, and Montgomery—have another 2.5 million residents. Philadelphia has the fewest roadway miles per capita, the most grid-like road network, and the lowest share of highways and arterials, but also the highest concentration of car travel across the counties. Philadelphia has roughly proportional traffic fatality rates (6.01 per 100,000 residents) to the surrounding counties (6.02 average per 100,000).

Data Summary and Sources

Table 1 presents the mean, standard deviation, minimum, and maximum of each data variable in the study. Socio-demographic and land use variables (labeled with asterisks in the table) such as population density, land use diversity, and street link-to-node ratio are measured on the Census tract level, whereas roadway characteristics such as length and speed limit are measured on the road segment level. The mean values for the tract level variables equal the mean value for Census tracts weighted by the number of segments/intersections in each Census tract. Overall, there are approximately 250,000 street segments and intersections across 998 Census tracts in the study area.

TABLE 1 Summary of the minimum, maximum, average values, and standard deviations for explanatory variables and traffic collisions (n = 247,997)

Statistic	Mean	St. Dev.	Min.	Max.
Total collisions	0.69	2.72	0	190
Severe injuries	0.02	0.15	0	6
Fatal collisions	0.01	0.08	0	5
Pedestrian-involved collisions	0.05	0.32	0	17
Severe pedestrian injuries	0.003	0.05	0	3
Pedestrian fatalities	0.001	0.04	0	4
Population per acre*	10.27	13.83	0	102.40
Jobs per acre*	4.24	22.80	0	838.86
Land use diversity index*	0.54	0.19	0.01	0.98
Public school enrollments*	657	942	0	8,182
Proportion of black residents*	16.11	25.84	0	99.74
Proportion of families in poverty*	8.50	11.04	0	64.93
Proportion of residents over 64*	14.91	6.96	0	100
Pedestrian exposure: trips starting or ending in Census tract*	3,641	7,210	8	192,569
Street link-to-node ratio*	1.72	0.22	0.79	4.77
Average annual daily traffic (AADT)	2,746	9,835.80	0	210,456
Posted speed limits				
None available	0.11			
15 mph	0.03			
25 mph	0.63			
35 mph	0.20			
45 mph	0.01			
55 mph	0.01			
65 mph	0.03			
Roadway segment length (in feet)	334	537	0	8,308
Length of limited access highways (in feet)	12	136	0	6,368
Length of secondary highways (in feet)	11	106	0	6,775
Length of major arterials (in feet)	49	243	0	7,146
Length of secondary highways (in feet): one way	2	53	0	3,460
Length of major arterials (in feet): one way	4	69	0	3,744
AADT missing dummy (0/1)	0.13			
Intersection dummy (0/1)	0.34			
Philadelphia dummy (0/1)	0.24			

* Variable varies by Census tract. Others vary by segment/intersection.

Collisions, Injuries, and Fatalities
Geocoded crash statistics are from PennDOT and include information on the types of vehicles involved in a crash, the severity of injuries resulting from the crash, and the total number of fatalities and injuries (Pennsylvania Department of Transportation 2017). Due to inconsistencies in the reporting of crash locations over time, we exclude data prior to 2010. PennDOT defines crashes and fatalities as follows:

- Reportable Crash: A crash resulting in a death within 30 days of the crash; or injury in any degree, to any person involved; or crashes resulting in damage to any vehicle serious enough to require towing.
- Serious Injury: A serious injury is any injury other than fatal which results in one or more of the injuries defined by PennDOT, including broken or distorted extremity, significant burns, paralysis, etc.
- Fatal Crash: A crash in which one or more of the involved persons died within 30 days of the crash and the death(s) are attributable to the crash.

We match collisions that occurred from 2010 to 2014 to street segments and intersections. Collisions are assigned to their nearest street segments. Additionally, we assign collisions that are geo-located within a 50-foot radius of an intersection to that intersection. Street segments and intersections are assigned to Census tracts within which their centers fall. We provide a map of the density of traffic collisions, point locations of fatalities, major highways, water features, and study boundaries in Appendix A.

Population Characteristics
We match annual crashes to 5-year (2010 to 2014) Census tract-level average socio-demographic values from the 5-year American Community Survey for 2010 through 2014 (US Census Bureau n.d.). Poverty rates, racial characteristics, and age all correlate with population density and may also correlate with unobserved factors associated with collisions, such as vehicle quality, trip rates, policing, survival rates given a collision, and driver behavior. For example, two recent studies have found drivers less likely to yield to black pedestrians than to white ones (Coughenour et al. 2017; Goddard, Kahn, and Adkins 2015). Previous work has frequently found associations between traffic safety and a variety of neighborhood demographic and socioeconomic variables (Jermprapai and Srinivasan 2014; Yu and Xu 2017; Marshall and Garrick 2011; Wier et al. 2009; Yu 2014; Delmelle, Thill, and Ha 2012; Clifton and Kreamer-Fults 2007; LaScala, Gerber, and Grunewald 2000; Ukkusuri et al. 2012).

Urban Form Measures
We divide Census-reported population and job estimates (US Census Bureau and Center for Economic Studies n.d.) by land area to calculate population and job density. These estimates exclude large parks and bodies of water, but include roadways and other land uses like commercial and industrial buildings. In order to include separate coefficients for population density in Philadelphia and suburban counties, we also include a dummy variable for segments and intersections in Philadelphia. An estimate of the total expected collisions on a Philadelphia street should include the model constant and the coefficient for the Philadelphia dummy variable.

Land use diversity is estimated by applying a commonly used entropy index (Bordoloi et al. 2013) to five urban land uses from the Delaware Valley Regional Planning Commission's (2015) Land Use shape files. We exclude non-urban land uses (military, mining, etc.) before combining the remaining urban land uses into residential, commercial, industrial, institutional, and other (transportation, utility, and recreation) categories. A score of zero indicates homogenous land uses in a Census tract; a score of one indicates a perfect mix of land uses. Intersections and segments in neighborhoods with a mix of land uses are more likely to have more complicated interactions between multiple users, such as industrial trucks and pedestrians. Areas with a mix of shops, residences, and institutions like hospitals and universities are also more likely to have more pedestrians and transit users. Although the entropy index lacks a clear theoretical relationship to crashes, the measure is commonly used in studies of travel behavior (Ewing and Cervero 2010) and traffic safety (Lee, Zegras, and Ben-Joseph 2014; Chen and Shen 2016; Hwang, Joh, and Woo 2017; Wang and Kockelman 2013).

The link-to-node ratio (street segments to intersections)—estimated in ArcGIS using Esri's 2015 North American Street Map data (Esri n.d.)—provides an approximation of connectivity or how gridded the street network is. A relatively low score of one implies a road network that is primarily comprised of single streets with limited intersections and a non-gridded pattern. A relatively high score of two implies a gridded network. School enrollments are from the National Center for Education Statistics' (n.d.) geographic database of school locations and enrollments for the 2016-2017 academic year. Data include public school enrollments in prekindergarten through twelfth grade, but exclude private school enrollments, which were reported at the county level. Previous work has found associations between traffic safety outcomes and measures of form, including land use mix, job density, commercial activities, and the location of schools (Day et al. 2007; Miles-Doan and Thompson 1999; Dumbaugh and Rae 2009; Dumbaugh and Zhang 2013; Marshall and Garrick 2011; Ukkusuri et al. 2012; Wang and Kockelman 2013; Clifton and Kreamer-Fults 2007; Yu and Xu 2018; Yu and Zhu 2016).

Exposure Variables

Estimates of Annual Average Daily Traffic (AADT) on state and local roadways are from PennDOT's 2016 Highway Performance Monitoring System (HPMS) data and provide the best available estimate of total traffic volume in the Philadelphia region. Thirteen percent of segments do not have AADT counts. These segments are also more likely to have missing speed limit data and more likely to be local roadways as opposed to highways or major arterials. We use the highest AADT among streets approaching an intersection to represent the AADT at an intersection.

Pedestrian exposure data are from the Delaware Valley Regional Planning Commission's regional travel model. This regional travel model relies on the 2012 household travel survey (Delaware Valley Regional Planning Commission n.d.) to estimate the total number of attractions and productions by mode. The variable included in our final models is the sum of total pedestrian trip starts and ends, including the starts and ends of transit trips accessed by foot. This provides the best available and consistent estimate of pedestrian exposure throughout the Philadelphia region.

Roadway Characteristics

Total segment length by road class are from Esri's 2015 North American Street Map data (Esri n.d.) and the US Census TIGER Lines roadway classifications. For each segment, we include the total segment length and the length of limited access freeway, secondary highway, and major arterial segments. In general, we expect longer street segments and more substantial road types, like major arterials, to have more collisions. Driveways, pedestrian walkways, and trails were not kept in the final dataset. Additionally, we classify roadways into total lengths of one-way secondary highways and major arterials. One-way streets have been associated with increased collisions across places and over time (Dumbaugh and Rae 2009; Riggs and Gilderbloom 2016). The final parameter estimates are marginal and additive in nature. For example, the correlation between a traffic collision and one foot of one-way major arterial, is equal to the sum of the parameters for a foot of total roadway, a foot of major arterial, and a foot of one-way major arterial.

We also use posted speed limits from Esri's Street Map data. In the final models, we leave 25 mph roads (63% of all entries) and low frequency speed limits—20 mph (13 out of 247,997 observations) and 50 mph (2 observations)—in the omitted category. Putting the low frequency speed limits in different categories does not affect the model results in any meaningful way, but tends to make the meaning of the parameter less clear without looking at the data summary table to see how infrequently the category occurs. Speed limits serve as both a potential policy variable in terms of the set speed-limit, but also as our best available proxy for travel speeds throughout the day. In general, we expect higher speed limits to be associated with more crashes and fatalities. Pedestrian-involved crashes, however, may be less likely on limited access highways and freeways, if pedestrians do not travel on these roadways. We do not include road class dummy variables in the models because these are so strongly correlated with posted speed limits.

Variable Transformations

We transform variables with long-tailed distributions, including population density, by taking the natural log of the variable. In the case of variables with zeros, such as roadway length, we add one in order to avoid taking the natural log of zero. These transformed variables produce parameter estimates with simple interpretations as elasticities and better model fits. Additionally, we standardize the land use diversity index to center it at zero with a standard deviation of one.

Model Specifications

The final parameters are fit estimated with multilevel negative binomial models with the lme4 package (Bates et al. 2015) in R (R Core Team 2018). We use this multilevel modeling framework for three main reasons. First, when estimating the effects of predictors, multilevel models take group-level variation into account. In this study, multilevel model allows us to examine correlations that vary by Census tract as well as by segment/intersection. Second, the multilevel framework allows us to account for correlations within each Census tract. These correlations include repeated observations of the same Census tract, as well as unobserved spatial correlations across segments/intersections within a Census tract. Third, the number of observations within each census tract varies widely. Several Census tracts have fewer than 30 observations while the average is approximately 250. Multilevel model mitigates issues caused by small samples by using all the data to perform inferences for Census tracts with only a few observations (Gelman and Hill 2007). In all the models, we include random intercepts by Census tract.

For each crash type, we estimate six models with increasingly more controls. Annotation below Figure 1 explains the variables included within each level of control. In the following section, we present the outputs of models with only demographic controls and the full set of controls. We then summarize how the relationship between population density and the six traffic safety outcomes varies with the inclusion of additional controls. We provide outputs for all 36 models (6 crash outcomes with 6 sets of controls) in Appendix B. We also estimated models of crashes by Census tract, which produce overall findings similar to those presented below. Lastly, due to the low numbers of pedestrian fatalities, we also estimated pedestrian models using zero-inflated negative binomial models and binomial models. These produce results that do not vary substantially from the negative binomial models, which we prefer to report for simplicity and consistency across the various crash models.

Findings

Table 2 presents the parameter estimates for total crashes, total serious injuries, and total fatalities from the demographic and full control models. Table 3 presents the same but for pedestrian-involved crashes, serious injuries, and fatalities. Parameter estimates for log-transformed predictor variables, such as population density, have direct interpretations as elasticities. For example, a 1% increase in population density in a Philadelphia Census tract corresponds with a 0.13% reduction in traffic fatalities when including all controls (Table 2, Model 6). The non-transformed variables have indirect interpretations as incidence ratio rates. For example, a one-unit change in the street link-to-node ratio corresponds with an incidence ratio rate of 0.76 (the exponent of -0.27), a roughly 24% (0.76-1) reduction in the predicted incidence of the total number of crashes (Table 2, Model 2). Speed limits should be interpreted in relationship to the omitted category. For example, a 45 mph roadway has an expected 4.44 (the exponent of 1.49) times more fatalities than a 25 mph roadway.

The standardized land use diversity index has a similar interpretation, but in relationship to a one standard deviation change in the index. For example, a segment in a neighborhood with one-standard deviation higher land use diversity index (roughly 19 percentage points) has 1.23 (the exponent of 0.21) higher expected rate of traffic fatalities (Table 2, Model 6).

TABLE 2 Random intercept multilevel negative binomial models of total crashes, serious injuries, and fatalities by segment/intersection in the Philadelphia region

	Total crashes		Serious injuries		Total fatalities	
	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6
	Estimate (standard error)					
Population density (log) in Philadelphia	-0.20***	-0.10***	-0.26***	-0.10***	-0.36***	-0.13***
	(0.02)	(0.02)	(0.03)	(0.03)	(0.04)	(0.04)
Population density (log) in suburbs	-0.04	-0.06**	-0.22***	-0.08*	-0.23***	0.01
	(0.02)	(0.02)	(0.03)	(0.04)	(0.04)	(0.06)
Proportion of black residents (log)	0.06**	0.07***	0.07*	0.08**	0.09	0.07
	(0.02)	(0.02)	(0.03)	(0.03)	(0.05)	(0.04)
Proportion of families in poverty (log)	0.09***	0.08***	0.23***	0.19***	0.20**	0.12*
	(0.03)	(0.02)	(0.04)	(0.04)	(0.06)	(0.06)
Proportion of residents over 64 (log)	0.02	-0.08**	-0.05	-0.19***	0.13	-0.03
	(0.04)	(0.03)	(0.06)	(0.05)	(0.09)	(0.08)
Jobs per acre (log)		0.06**		-0.05		-0.08
		(0.02)		(0.04)		(0.05)
Land use diversity		0.03		0.05		0.21***
		(0.02)		(0.03)		(0.05)
Public school enrollments (log)		-0.002		-0.002		0.002
		(0.004)		(0.01)		(0.01)
Street link-to-node ratio		-0.27***		-0.05		-0.34
		(0.07)		(0.13)		(0.20)

Pedestrian exposure (log)		0.11***		0.08		-0.03
		(0.02)		(0.05)		(0.07)
Average annual daily traffic (log)		0.35***		0.32***		0.31***
		(0.003)		(0.01)		(0.02)
Posted speed limit (25 mph and low frequency omitted)						
None available		0.04		0.08		0.44**
		(0.02)		(0.10)		(0.14)
35 mph		0.96***		0.77***		0.70***
		(0.01)		(0.05)		(0.09)
45 mph		1.14***		1.05***		1.49***
		(0.06)		(0.18)		(0.24)
55 & 65 mph		1.08***		0.89***		0.86***
		(0.03)		(0.09)		(0.15)
Roadway segment length (in feet) (log)		1.03***		1.09***		1.11***
		(0.01)		(0.03)		(0.05)
Length (in feet) of limited access highways (log)		0.15***		0.05**		0.04
		(0.01)		(0.02)		(0.03)
Length (in feet) of secondary highways (log)		0.15***		0.09***		0.11***
		(0.01)		(0.02)		(0.02)
Length (in feet) of major arterials (log)		0.04***		0.03**		0.06**
		(0.003)		(0.01)		(0.02)
Length (in feet) of secondary highways: one way (log)		-0.02		0.0002		0.06
		(0.01)		(0.03)		(0.03)
Length (in feet) of major arterials: one way (log)		0.04***		0.02		0.02
		(0.01)		(0.02)		(0.04)
AADT missing dummy		0.01		-0.20		-0.03
		(0.04)		(0.21)		(0.32)
Intersection dummy		6.75***		7.00***		6.94***
		(0.05)		(0.21)		(0.34)
Philadelphia dummy	0.68***	0.35***	0.67***	0.58***	1.03***	1.15***
	(0.08)	(0.07)	(0.10)	(0.12)	(0.14)	(0.16)
Constant	-0.86***	-10.37***	-4.55***	-14.30***	-6.22***	-14.62***
	(0.12)	(0.23)	(0.18)	(0.47)	(0.27)	(0.71)
AIC	445,826	384,114	36,535	32,052	14,619	12,829
BIC	445,920	384,395	36,629	32,334	14,713	13,110

Significance levels: < 0.001 ***, < 0.01 **, < 0.05 *
Variables in italic are measured on Census tract level as opposed to segment/intersection level

Safety for All Road Users

Higher population density generally corresponds with fewer crashes, injuries, and fatalities in Philadelphia and surrounding suburban counties, although the estimated relationships are less than proportional (i.e., inelastic). This relationship is statistically stronger and more consistent in Philadelphia than in the suburbs. For example, in Philadelphia a 1% increase in population density corresponds with 0.20% (Table 2, Model 1) to 0.10% (Model 2) fewer collisions and 0.36% (Model 5) and 0.13% (Model 6) fewer fatalities. In the suburbs, the same increase in population density is associate with 0.04% (Model 1) to 0.06% (Model 2) fewer collisions and 0.23% (Model 5) and 0.01% (Model 6) fewer fatalities. Moreover, these relationships are not always statistically different from zero with 95% confidence. Including the full set of road controls generally weakens the relationship between population density and traffic crashes, injuries, and fatalities. This is particularly apparent for serious injuries and fatalities. We discuss these findings in greater detail in the following section, which focuses on the statistical and theoretical relationships between population density, crashes, and injuries using all six sets of model controls for each crash and injury type.

In addition to population density, we find statistically significant relationships between crashes and neighborhood socio-economics, the built environment, land use, traffic exposure, and street characteristics. In general, poorer neighborhoods have worse safety outcomes. Across crash outcomes and model specifications, a 1% increase in poverty corresponds with a 0.08% to 0.23% more collisions or injuries. Accounting for poverty rates, race also appears to play a role in traffic safety outcomes. A 1% increase in the percentage of black residents in a Census tract corresponds with a 0.06% to 0.09% in crashes, serious injuries, and fatalities. That the strength and significance of these relationships generally holds across model specifications suggests that the relationship is not due to differences in road or built environment conditions, but other factors such as behavior, vehicle quality, or traffic enforcement. The share of older residents in a neighborhood is associated with fewer crashes and serious injuries when including roadway and other controls.

In terms of land use, a one standard deviation increase in the land use diversity index corresponds with a 1.23 higher incidence of traffic fatalities. There is a weaker and statistically insignificant relationship with total crashes and serious injuries. Job density is significantly positively correlated with total collisions with an elasticity of 0.06. Its relationships with serious injuries and fatalities are negative but statistically insignificant. In terms of street connectivity, a more gridded network, represented by link-to-node ratio, correlates with fewer collisions, serious injuries, and fatalities. However, this effect is only statistically significant for total crashes. Parameter estimate for link-to-node ratio (-0.27) in Model 2 suggests that as a non-gridded network (a ratio of 1) becomes a gridded one (a ratio of 2), the expected occurrence of crashes decreases by 24%. We did not find statistically significant relationships between school enrollments and any of the three crash outcomes. This is a somewhat unexpected finding and may relate to enrollments being counted at too aggregate of a geography.

Of all the variables, the amount and type of roadway have the strongest and clearest relationships with the number of collisions, serious injuries, and fatalities on a given street segment or intersection. Each percent increase in total roadway is associated with more than a percent increase in total collisions, serious injuries, and fatalities. Increases in highway and arterial length appear to be even more dangerous. For example, including controls for speed limit and overall traffic follow, a 1% increase in the length of a secondary highway is associated with 1.18% more collisions, 1.18% more serious injuries, and 1.22% more fatalities. The safety difference between a 25 mph and faster roadway types is also stark. Across our sample and model specifications, a roadway with a 35 mph limit has 2.6 times more collisions, 2.2 times more serious injuries, and 2 times more fatalities than one with a 25 mph speed limit. A 45 mph speed limit road has 4.4 times more fatalities than a 25 mph one. It is unclear how much these differences in outcome across speed limits relate to unmeasured exposure, actual traffic speeds, or roadway design. Nevertheless, the findings support the overall generalization that a more conservative road network with fewer, narrower, and slower streets will be substantially safer than a network with more, bigger, and faster streets. Even with the same AADT, a 300-hundred-foot urban arterial with a 45mph speed limit has approximately 10 times more expected traffic fatalities than a 150-foot local road with a 25 mph speed limit. Unsurprising, intersections are also substantially more dangerous than typical road segments and account for a disproportionate amount of collisions and fatalities.

Higher numbers of cars and pedestrians are also associated with more collisions, serious injuries, and fatalities. For example, a doubling in AADT corresponds with approximately 35% more crashes, 32% more serious injuries, and 31% more fatalities. Pedestrian exposure, as measured at the Census tract level, is less strongly or consistently associated with traffic crashes. A doubling of the number of pedestrian trip starts and ends (productions and attractions) in a segment/intersection's Census tract is associated with 11% more crashes and is not statistically significantly associated with total serious injuries or fatalities. We discuss this at greater length in the following subsection.

Pedestrian Safety

Higher population densities are generally associated with higher numbers of pedestrian-involved collisions and injuries in the suburbs, but fewer in Philadelphia. A 1% increase in suburban population density corresponds with 0.62% (Table 3, Model 1) to 0.47% (Model 2) more pedestrian-involved crashes, 0.48% (Model 3) to 0.46% (Model 4) more serious pedestrian injuries, and 0.20% (Model 5) to 0.26% (Model 6) pedestrian fatalities. In Philadelphia, higher density neighborhoods tend to have segments/intersections with fewer fatalities but no difference in pedestrian-involved crashes or serious injuries. In short, there appears to be substantial variation in the relationship between population density and traffic safety by geography. Moreover, this suggests that the lower probability of collisions and injuries associated with higher population density presented in Table 2 tend to benefit people in cars, not pedestrians. We discuss this and the relationships between population density, traffic safety, and the model controls more generally in the following section.

TABLE 3 Random intercept multilevel negative binomial models of pedestrian involved crashes, pedestrian serious injuries, and pedestrian fatalities by segment/intersection in the Philadelphia region

	Pedestrian crashes		Serious pedestrian injuries		Pedestrian fatalities	
	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6
	Estimate (standard error)					
Population density (log) in Philadelphia	-0.01	-0.02	-0.07	0.02	-0.27***	-0.11
	(0.03)	(0.02)	(0.05)	(0.06)	(0.06)	(0.06)
Population density (log) in suburbs	0.62***	0.47***	0.48***	0.46***	0.20*	0.26*
	(0.04)	(0.04)	(0.08)	(0.09)	(0.10)	(0.13)
Proportion of black residents (log)	0.12***	0.13***	0.06	0.05	0.11	0.12
	(0.03)	(0.02)	(0.05)	(0.05)	(0.08)	(0.08)
Proportion of families in poverty (log)	0.20***	0.22***	0.26***	0.24**	0.22	0.17
	(0.04)	(0.03)	(0.08)	(0.08)	(0.11)	(0.11)
Proportion of residents over 64 (log)	-0.21***	-0.19***	-0.02	-0.02	0.10	0.01
	(0.05)	(0.04)	(0.11)	(0.11)	(0.14)	(0.14)
Jobs per acre (log)		0.11***		-0.02		0.13
		(0.03)		(0.07)		(0.10)
Land use diversity		0.04		0.13*		0.16
		(0.03)		(0.06)		(0.09)
Public school enrollments (log)		-0.01		-0.02		0.02
		(0.01)		(0.01)		(0.02)
Street link-to-node ratio		-0.67***		-0.74**		-0.44
		(0.11)		(0.27)		(0.37)
Pedestrian exposure (log)		0.24***		0.25**		-0.11
		(0.04)		(0.09)		(0.12)

Average annual daily traffic (log)		0.26***		0.31***		0.31***
		(0.01)		(0.03)		(0.04)
Posted speed limit (25 mph and low frequency omitted)						
None available		0.01		-0.09		0.44
		(0.06)		(0.22)		(0.26)
35 mph		0.69***		0.73***		0.65***
		(0.03)		(0.10)		(0.16)
45 mph		1.06***		0.30		0.71
		(0.15)		(0.60)		(0.63)
55 & 65 mph		0.49***		0.87***		0.66*
		(0.08)		(0.21)		(0.30)
Roadway segment length (in feet)		0.87***		0.83***		0.79***
		(0.02)		(0.07)		(0.10)
Length (in feet) of limited access highways (log)		-0.12***		-0.11*		0.02
		(0.02)		(0.05)		(0.06)
Length (in feet) of secondary highways (log)		0.13***		0.09**		0.21***
		(0.01)		(0.03)		(0.04)
Length (in feet) of major arterials (log)		0.07***		0.06*		0.11**
		(0.01)		(0.03)		(0.04)
Length (in feet) of secondary highways: one way (log)		-0.03		0.04		0.04
		(0.02)		(0.05)		(0.06)
Length (in feet) of major arterials: one way (log)		-0.01		0.02		0.06
		(0.02)		(0.05)		(0.07)
AADT missing dummy		0.11		0.09		0.37
		(0.14)		(0.54)		(0.65)
Intersection dummy		5.98***		5.24***		5.15***
		(0.14)		(0.45)		(0.63)
Philadelphia dummy	2.67***	1.99***	1.87***	1.29***	1.98***	1.76***
	(0.11)	(0.10)	(0.22)	(0.26)	(0.25)	(0.32)
Constant	-5.14***	-13.38***	-7.68***	-15.71***	-8.39***	-14.31***
	(0.17)	(0.36)	(0.37)	(0.98)	(0.48)	(1.33)
AIC	73,857	65,740	8,553	7,849	4,324	3,971
BIC	73,950	66,021	8,647	8,131	4,418	4,252

Significance levels: < 0.001 ***, < 0.01 **, < 0.05 *

Variables in italic are measured on Census tract level as opposed to segment/intersection level

Higher rates of poverty are associated with more pedestrian collisions and injuries than total collisions and injuries. In the fully specified models, a 1% increase the proportion of families living in poverty corresponds with a 0.22% (Model 2) more pedestrian-involved crashes, 0.24% more serious pedestrian injuries, and 0.17% more pedestrian fatalities. The percentage of black residents in a Census tract is also positively and significantly associated with pedestrian-involved crashes. The relationship with injuries and fatalities is positive but not statistically significant. A higher share of older residents is associated with fewer pedestrian-involved crashes but no statistically different relationship with serious injuries or fatalities.

Job density and land use diversity are either not statistically associated or positively associated with pedestrian crashes and injuries. A more connected and gridded street network, by contrast is generally negatively associated with pedestrian crashes, injuries, and fatalities. As in the models of total collisions, we did not find significant associations between school enrollments and the three types of pedestrian crashes presented in Table 3.

In terms of exposure, both higher amounts of AADT and pedestrian volumes are associated with more pedestrian collisions and fatalities. A doubling of AADT or pedestrian volumes corresponds with roughly 25% to 30% more pedestrian collisions and serious injuries. The relationship to pedestrian fatalities is inverted (-11%) but not statistically significant. Both the sign and the significance level may relate to the very low numbers of pedestrian fatalities from which to draw inferences. Only 282 segments/intersections in our sample had one or more pedestrian fatalities. Across multiple specification and models at different scales, however, we consistently find that pedestrian traffic is positively associated with pedestrian collisions and injuries, but not fatalities. More pedestrians do not necessarily correspond to more pedestrian deaths, as evidenced by Houston and New York having similar pedestrian fatality rates despite substantially different levels of pedestrian exposure.

As with total collisions, pedestrian-involved crashes, injuries, and fatalities are more strongly related with roadway type than neighborhood or exposure measures. For pedestrians as for all travelers, longer, faster, and more substantial roadways appear most dangerous, though there are some notable exceptions. For example, limited access highways are generally safer than other roadway types and roadways with 45 mph speed limits have the highest predicted number of crashes but lower predicted levels of injuries and fatalities than 35 mph roads. The high rates of predicted pedestrian collisions, injuries, and fatalities along roadways with 55 mph and 65 mph speed limits also suggest that the region could do a much better job separating pedestrian crossings and high-speed roads. A segment with highway speeds has 1.6 times the expected pedestrian collisions, 2.4 times the expected pedestrian serious injuries, and 1.9 times the expected pedestrian fatalities as a 25 mph road. Again, the data make it difficult to disentangle the relationship between road class and speed limits on safety outcomes. Accounting for exposure, both a 35 mph arterial and a 55 mph secondary highway are about 5 times more deadly for pedestrians than a 25 mph local road. Doubling the roadway length would increase the expected number of pedestrian fatalities another two to threefold.

Population Density and Traffic Safety

This section focuses on the theoretical and statistical relationships between population density, traffic crashes, serious injuries, and fatalities, based on the results of models of six collision and injury types using six consistent sets of statistical controls. Figure 1 presents the estimated elasticities of the different types of traffic collisions with respect to population density in Philadelphia and its suburbs. The controls in each of the models are summarized in the Figure notes, with the full model outputs provided in Appendix B. We structure this discussion around the three primary reasons that we focus on population density instead of stronger predictors of collisions like amounts of roadway, speed limits, and road types.

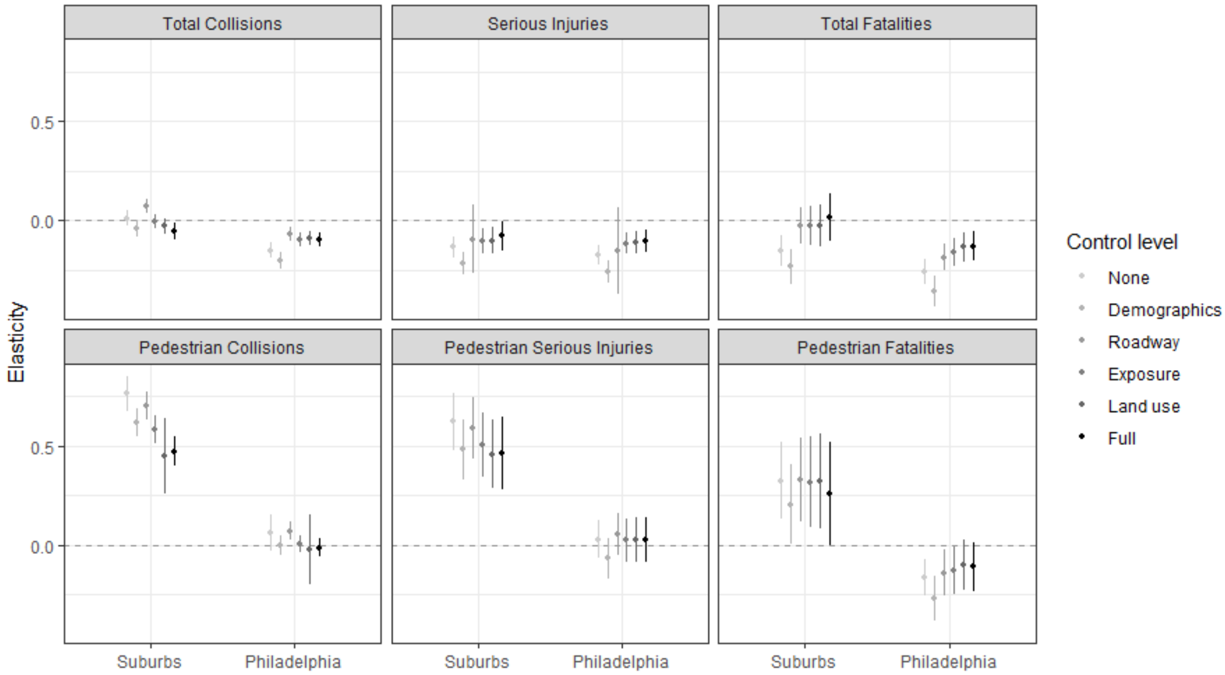

FIGURE 1 Population density and traffic safety. This figure presents the estimated mean elasticity and 95% confidence intervals between population density and six traffic outcomes across street segments and intersections in Philadelphia and suburban counties in Pennsylvania. Six different sets of controls are included and summarized here. (*None* includes the model constant, the Philadelphia dummy, population density in Philadelphia, and population density in suburbs. *Demographics* includes all variables in *None*, the proportion of black residents the proportion of families living in poverty, and the percent of residents over 64. *Roadway* includes all variables in *Demographics*, speed limits, roadway segment lengths by road class and directionality, one-way dummy variables, and an intersection dummy variable. *Exposure* includes all variables in *Roadway*, AADT, and pedestrian trip starts and ends. *Land use* include all variables in *Exposure*, land use diversity, public school enrollments, and to link-to-node ratios. *Full* includes all variables in *Land use* and jobs per acre.)

First, as described in our paper's introduction, there is substantial variation in empirical findings about the nature of the statistical relationship between traffic crashes and population density. By contrast, there is a general consensus that bigger, faster roads with more traffic tend to have more crashes, injuries, and fatalities than smaller, slower, roads with less traffic. Figure 1 suggests that differences in geography, crash type, and control variables likely contribute to the wide variation in findings. Even using consistent data from the same region, the relationship between population density, pedestrian collisions, and pedestrian fatalities varies substantially across county lines. In Philadelphia, a 1% increase in population density corresponds with about the same number of pedestrian-involved crashes, but 0.3% to 0.1% fewer pedestrian fatalities. In the suburban counties, the same increase corresponds with 0.5% to 0.7% more pedestrian collisions and 0.2% to 0.3% more pedestrian fatalities. Thus, differences in findings across the literature likely depend on crash type, geography, and model specification. These differences can influence not only the magnitude and statistical significance of the relationships, but also the sign. For example, population density is generally statistically positively correlated with pedestrian fatalities in the suburbs but negatively correlated in Philadelphia. Some specifications, such as the models of serious injuries with demographic and roadway controls, result in substantially larger standard errors than models with more or fewer controls.

Although care is required in generalizing from 36 model estimates, several additional trends emerge. In general, models with fewer controls have larger effect sizes (i.e., bigger elasticities.) This is especially the case for total traffic collisions, serious injuries, and fatalities (top plots in Figure 1). For example, with no controls or only demographic controls, a 1% increase in population density corresponds with around 0.4% fewer fatalities in Philadelphia and 0.2% fewer fatalities in the suburbs. With additional controls for roadway and the built environment, the same increase in population density corresponds with 0.1% fewer fatalities in Philadelphia and no difference in fatalities in the suburbs. This observation suggests that much of the relationship between population density and traffic safety can be explained through intervening variables like traffic volumes, roadway characteristics, and traffic speed (at least to the extent it is captured by posted speed limits). Nevertheless, across specifications and counties, higher population density tends to correspond with fewer total crashes, serious injuries, and fatalities. By contrast, higher population density corresponds with more pedestrian collisions, injuries, and deaths in the suburbs, but fewer pedestrian deaths in Philadelphia.

A second reason to focus on population density is that the causal nature of the relationship remains elusive. Perhaps, most importantly, it is unclear to what extent higher population densities cause slower speeds, lower speed limits, more grid-like street patterns, and more conservative road networks. In our sample, the densest quartile of Census tracts house 28% of the population, but contain only 6% of the total length of roadway. These roadways, moreover, are 12 times less likely to have a speed limit of 45 mph or greater than other roadways and were the location of just 6% of total fatalities. By presenting multiple models with a range of controls, our findings provide insight into the nature of the relationship between population density and traffic safety. One immediate implication is that, if population density affects traffic safety, much of this influence occurs through intermediary variables like speeds, road networks, and traffic exposure. To the extent that population density remains correlated with crashes in our fully specified models, this could relate to unobserved variables such as actual traffic speeds, pedestrian volumes, or distributions in speed and volumes by time of day. Regardless of the mechanisms, the elasticities presented in Figure 1 suggest that increased population density corresponds to better overall traffic safety records, but higher rates of pedestrian crashes and, at least in the suburbs, more pedestrian injuries and fatalities. Finally, at least in the long run, the biggest safety difference between compact cities and sprawling ones may simply be that compact cities tend to have less roadway and less driving. Within Philadelphia, denser Census tract tend to have slightly more residents (correlation of 0.1) and a lot less roadway (Pearson's correlation of -.6). By concentrating activities, however, pedestrian injuries and fatalities are also likely to concentrate. Twenty-six percent of pedestrian fatalities occurred in the densest quartile of tracts, compared to just 6% of total fatalities.

Third and finally, population density is a policy variable in its own right. Planners, policy-makers, and citizens regularly debate the merits of policies to constrain or promote population density or to concentrate growth in specific parts of metropolitan areas. The relationships presented in Table 2 and Table 3 suggest that changing population densities and concentrating growth in dense Census tracts are less effective tools for promoting traffic safety than directly influencing speeds or reducing roadway in a given neighborhood or along a given street. Moreover, urban form changes slowly over time, particularly in slow growing regions like Philadelphia. Nevertheless, our findings suggest that improved traffic safety is likely an additional benefit of urban densification. Perhaps as importantly, people choosing homes and apartments should know that there is substantial variation in the safety records of different neighborhoods. In Philadelphia at least, a densely populated urban neighborhood likely has a better traffic safety record than a quiet and sparsely populated one. One important exception appears to be pedestrian safety in suburban neighborhoods. Across specifications and controls, roads in denser suburban neighborhoods have more pedestrian collisions, serious injuries, and fatalities. It is unclear why this occurs but one possibility is that streets in denser suburban neighborhoods have more pedestrian exposure but no offsetting reductions in travel speeds or changes in driver behavior. In any case, policies to allow increased suburban densities may require greater attention to pedestrian safety. The results of Table 3 and previous studies suggest that reducing the quantity, speed, and size of suburban roadways would likely help.

Conclusion

Although traffic collisions are one of the leading causes of death in the US, traffic fatality rates vary substantially by state, city, and neighborhood. Urban form likely plays a role in the geographic differences in traffic safety outcomes. In the Philadelphia region, denser neighborhoods have substantially fewer roads than less densely populated ones. These roads also generally have fewer traffic fatalities, with and without controls for road type, road length, speed limit, exposure, and urban form. Although these relationships are associative rather than causal, they conform to the theory that population density reduces traffic fatalities and injuries by reducing the total amount of driving and the severity of an injury, given a collision.

Findings are more mixed for pedestrian crashes, which tend to increase with population density in the suburbs, but decrease with population density in the city. Pedestrian model results also vary substantially in models with and without controls for exposure, road networks, and other measures of urban form. These differences in findings across geographies and model specifications may help to explain some of the substantial variation in findings across studies examining the relationship between urban form and pedestrian safety. In any case, denser neighborhoods are indeed associated with generally safer streets in the Philadelphia region, but the association with pedestrian safety is mixed and uncertain. Future research could shed additional light on the mechanisms through which population density relates to traffic safety outcomes and how relationships between measures of urban form and traffic collisions vary from city to city, particularly in terms of pedestrian collisions. The relationship between population density and the amount and type of roadway in a given Census tract, city, or metropolitan area may be particularly important. Across our sample and specifications, for example, 300 feet of 45 mph arterial has 10 more expected fatalities and 4 times more expected pedestrian fatalities than a 150 feet of local roadway with a 25 mph speed limit.

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Project Outputs and Outcomes

Project publications

Guerra, Erick, Xiaoxia Dong, and Michelle Kondo (under revision.) Do denser neighborhoods have safer streets? The empirical relationship between population density and traffic collisions in the Philadelphia region.

Merlin, Louis, Erick Guerra, and Eric Dumbaugh (under review.) Crash Risk, Risk Exposure, and The Built Environment: A Conceptual Review.

Project-related publications

Kondo, Michelle C., Christopher Morrison, Erick Guerra, Elinore J. Kaufman, and Douglas J. Wiebe (2018). Where do bike lanes work best? A Bayesian spatial model of bicycle lanes and bicycle crashes. *Safety Science* 103 (March): 225–33.

Cervero, Robert, Erick Guerra, and Stefan Al (2017.) Beyond Mobility: Planning Cities for People and Places. Washington, DC: Island Press.

Project-related presentations

City of Philadelphia's Vision Zero Research Partnership Workshop. 2018. "What can we learn from the first automated-vehicle-involved traffic fatality?"

University of Pennsylvania Bicycle Committee. 2018. "Where do bike lanes work best?"

ACSP Conference, Denver, CO. 2017. "Does increasing neighborhood density mean safer streets?"

Penn Injury Science Center Research Meeting. 2017. "Does increasing neighborhood density mean safer streets?"

Project-related service

City of Philadelphia Policy Advisory and Data and Prioritization Committee for Strategic Transportation Plan

Students Supported Directly or Indirectly

PhD: Xiaoxia (Summer) Dong and Shengxiao (Alex) Li

Masters: Lucia Artavia, Juan Benitez, Jake Berman, Yue Guo, Ian Hester, Meiqing Li, Lufeng Lin, Diwen Shen, Alma Siulagi, Jia Yuan, Xinyi (Elynor) Zhou, and Chi (Zoe) Zhang.

Undergraduate: Ilan Gold and Jack Kearney

Project-related media links

http://www.philly.com/philly/opinion/commentary/bike-lanes-philadelphia-culture-war-transportation-cars-walking-20180518.html

https://whyy.org/episodes/making-philly-safer-for-cyclists/

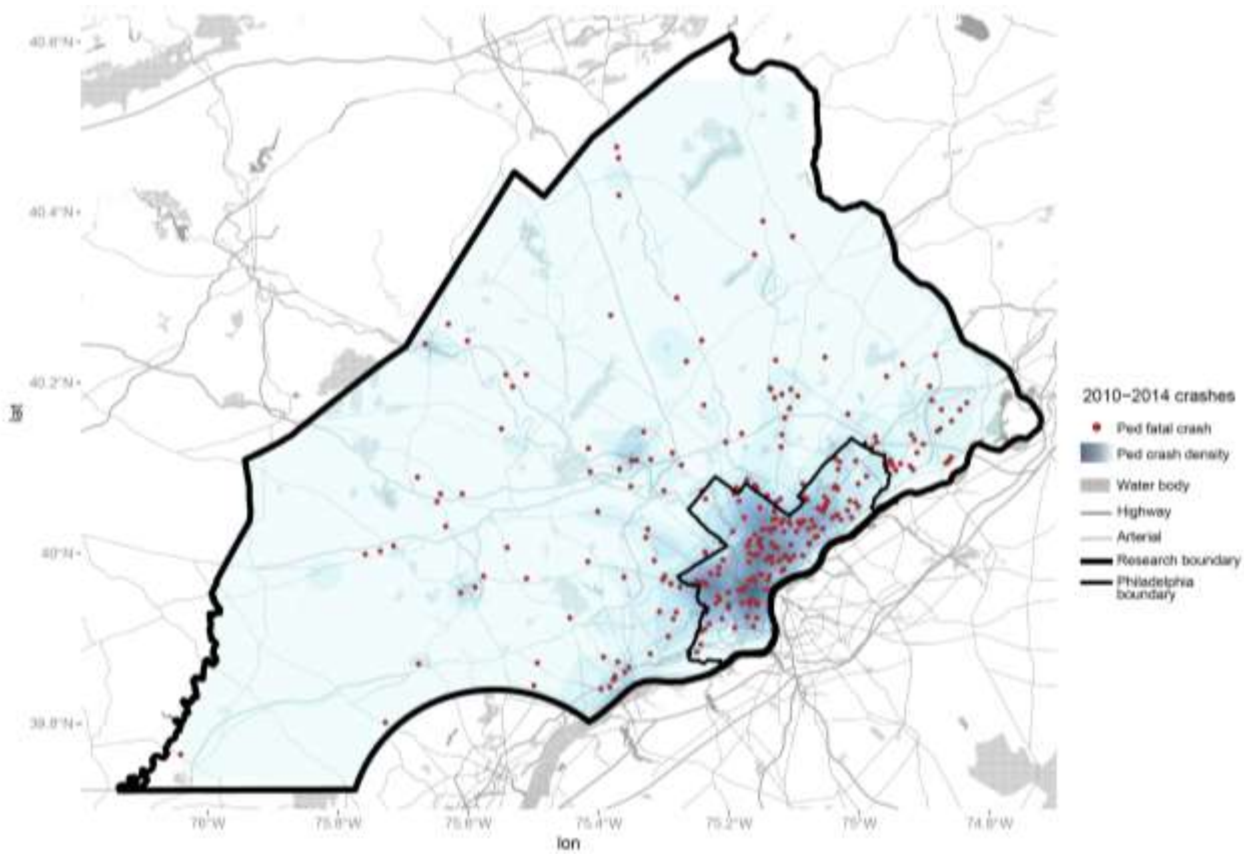
Ongoing and Next Steps

In addition to the report findings and dataset, we are continuing three projects that stem from and build on the work reported here. The first examines the relationship between predictors of pedestrian collisions and pedestrian injuries and fatalities by time of day. For example, measures like AADT do a good job of showing average vehicular exposure during the daytime, but not at night time. The second, compares the relationship between the built environment, traffic crashes, and fatalities throughout Pennsylvania. We are treating this study like a meta-analysis of statistical findings from all 67 PA counties, using consistent data and model specifications. The third project compares findings from two different statistical units of analysis: the Census tract and the segment/intersection.

Appendix A

Appendix A.1 Density of total crashes and fatal crashes in Philadelphia and suburban Pennsylvania counties from 2010 to 2014.

Appendix A.2 Density of pedestrian crashes and pedestrian fatalities in Philadelphia and suburban Pennsylvania counties from 2010 to 2014.



Appendix B

Appendix B.1 Random intercept multilevel negative binomial models of total crashes by segment/intersection in the Philadelphia region

	Control levels					
	None	Demographics	Roadway	Exposure	Land use	Full
	Estimate (standard error)					
Population density (log) in Philadelphia	-0.15***	-0.20***	-0.07***	-0.10***	-0.09***	-0.10***
	(0.02)	(0.02)	(0.02)	(0.02)	(0.02)	(0.02)
Population density (log) in suburbs	0.01	-0.04	0.08***	-0.004	-0.03	-0.06**
	(0.02)	(0.02)	(0.02)	(0.02)	(0.02)	(0.02)
Proportion of black residents (log)		0.06**	0.07***	0.07***	0.06***	0.07***
		(0.02)	(0.02)	(0.02)	(0.02)	(0.02)
Proportion of families in poverty (log)		0.09***	0.08***	0.08***	0.07**	0.08***
		(0.03)	(0.02)	(0.02)	(0.02)	(0.02)
Proportion of residents over 64 (log)		0.02	-0.08*	-0.08**	-0.09**	-0.08**
		(0.04)	(0.03)	(0.03)	(0.03)	(0.03)
Jobs per acre (log)						0.06**
						(0.02)
Land use diversity					0.06***	0.03
					(0.02)	(0.02)
Public school enrollments (log)					-0.005	-0.002
					(0.004)	(0.004)
Street link-to-node ratio					-0.29***	-0.27***
					(0.07)	(0.07)
Pedestrian exposure (log)				0.17***	0.16***	0.11***
				(0.02)	(0.02)	(0.02)
Average annual daily traffic (log)				0.35***	0.35***	0.35***
				(0.003)	(0.003)	(0.003)
Speed limit (25 mph and low frequency omitted)						
None available			0.11***	0.04	0.04	0.04
			(0.02)	(0.02)	(0.02)	(0.02)
35 mph			1.26***	0.97***	0.97***	0.96***
			(0.01)	(0.01)	(0.01)	(0.01)
45 mph			1.61***	1.14***	1.14***	1.14***
			(0.06)	(0.06)	(0.06)	(0.06)
55 & 65 mph			1.69***	1.09***	1.09***	1.08***
			(0.03)	(0.03)	(0.03)	(0.03)
Roadway segment length (in feet)			1.05***	1.03***	1.03***	1.03***
			(0.01)	(0.01)	(0.01)	(0.01)
Length (in feet) of limited access highways (log)			0.13***	0.15***	0.15***	0.15***
			(0.01)	(0.01)	(0.01)	(0.01)
Length (in feet) of secondary highways (log)			0.17***	0.15***	0.15***	0.15***
			(0.01)	(0.01)	(0.01)	(0.01)
Length (in feet) of major arterials (log)			0.04***	0.04***	0.04***	0.04***
			(0.004)	(0.003)	(0.003)	(0.003)
Length (in feet) of secondary highways: one way (log)			-0.06***	-0.02	-0.02	-0.02
			(0.01)	(0.01)	(0.01)	(0.01)
Length (in feet) of major arterials: one way (log)			0.04***	0.04***	0.04***	0.04***
			(0.01)	(0.01)	(0.01)	(0.01)
AADT missing dummy			-2.43***	0.01	0.01	0.01
			(0.03)	(0.04)	(0.04)	(0.04)
Intersection dummy			7.02***	6.74***	6.74***	6.75***

			(0.05)	(0.05)	0.05)	(0.05)
Philadelphia intercept	0.80***	0.68***	0.72***	0.45***	0.37***	0.35***
	(0.07)	(0.08)	(0.07)	(0.07)	(0.07)	(0.07)
Constant	-0.64***	-0.86***	-8.07***	-11.33***	-10.64***	-10.37***
	(0.03)	(0.12)	(0.12)	(0.17)	(0.22)	(0.23)
AIC	445,859	445,826	395,946	384,143	384,123	384,114
BIC	445,921	445,920	396,165	384,383	384,393	384,395

Significance levels: < 0.001 ***, < 0.01 **, < 0.05 *

Variables in italic are measured on Census tract level as opposed to segment/intersection level

Appendix B.2 Random intercept multilevel negative binomial models of serious injuries by segment/intersection in the Philadelphia region

	Control levels					
	None	Demographics	Roadway	Exposure	Land use	Full
	Estimate (standard error)					
Population density (log)	-0.17***	-0.26***	-0.15	-0.11***	-0.11***	-0.10***
in Philadelphia	(0.03)	(0.03)	(0.11)	(0.03)	(0.03)	(0.03)
Population density (log)	-0.13***	-0.22***	-0.09	-0.10**	-0.10**	-0.08*
in suburbs	(0.03)	(0.03)	(0.09)	(0.03)	(0.04)	(0.04)
Proportion of black		0.07*	0.12	0.09**	0.09**	0.08**
residents (log)		(0.03)	(0.09)	(0.03)	(0.03)	(0.03)
Proportion of families in		0.23***	0.22	0.21***	0.20***	0.19***
poverty (log)		(0.04)	(0.13)	(0.04)	(0.04)	(0.04)
Proportion of residents		-0.05	-0.13	-0.18***	-0.18***	-0.19***
over 64 (log)		(0.06)	(0.19)	(0.05)	(0.05)	(0.05)
Jobs per acre (log)						-0.05
						(0.04)
Land use diversity					0.03	0.05
					(0.03)	(0.03)
Public school enrollments					0.0005	-0.002
(log)					(0.01)	(0.01)
Street link-to-node ratio					-0.03	-0.05
					(0.13)	(0.13)
Pedestrian exposure (log)				0.06	0.05	0.08
				(0.03)	(0.04)	(0.05)
Average annual daily				0.32***	0.32***	0.32***
traffic (log)				(0.01)	(0.01)	(0.01)
Speed limit (25 mph and low frequency omitted)						
None available			-0.28	0.08	0.08	0.08
			(0.30)	(0.10)	(0.10)	(0.10)
35 mph			1.07***	0.77***	0.76***	0.77***
			(0.23)	(0.05)	(0.05)	(0.05)
45 mph			1.99	1.06***	1.06***	1.05***
			(1.06)	(0.18)	(0.18)	(0.18)
55 & 65 mph			1.68**	0.89***	0.89***	0.89***
			(0.52)	(0.09)	(0.09)	(0.09)
Roadway segment length			1.02***	1.09***	1.09***	1.09***
(in feet)			(0.11)	(0.03)	(0.03)	(0.03)
Length (in feet) of limited			0.10	0.05**	0.05**	0.05**
access highways (log)			(0.12)	(0.02)	(0.02)	(0.02)
Length (in feet) of			0.20*	0.09***	0.09***	0.09***
secondary highways (log)			(0.09)	(0.02)	(0.02)	(0.02)
Length (in feet) of major			0.07	0.03**	0.03**	0.03**
arterials (log)			(0.06)	(0.01)	(0.01)	(0.01)

Length (in feet) of secondary highways: one way (log)			0.04	0.0002	0.0002	0.0002
			(0.21)	(0.03)	(0.03)	(0.03)
Length (in feet) of major arterials: one way (log)			0.03	0.02	0.02	0.02
			(0.16)	(0.02)	(0.02)	(0.02)
AADT missing dummy			-2.50***	-0.21	-0.21	-0.20
			(0.35)	(0.21)	(0.21)	(0.21)
Intersection dummy			6.59***	7.01***	7.01***	7.00***
			(0.66)	(0.21)	(0.21)	(0.21)
Philadelphia intercept	0.90***	0.67***	0.70	0.55***	0.56***	0.58***
	(0.10)	(0.10)	(0.39)	(0.11)	(0.12)	(0.12)
Constant	-4.32***	-4.55***	-11.49***	-14.26***	-14.09***	-14.30***
	(0.04)	(0.18)	(0.90)	(0.37)	(0.44)	(0.47)
AIC	36,600	36,535	46,628	32,048	32,053	32,053
BIC	36,662	36,629	46,847	32,288	32,324	32,334

Significance levels: < 0.001 ***, < 0.01 **, < 0.05 *

Variables in italic are measured on Census tract level as opposed to segment/intersection level

Appendix B.3 Random intercept multilevel negative binomial models of total fatalities by segment/intersection in the Philadelphia region

	Control levels					
	None	Demographics	Roadway	Exposure	Land use	Full
	Estimate (standard error)					
Population density (log) in Philadelphia	-0.26***	-0.36***	-0.18***	-0.16***	-0.13***	-0.13***
	(0.03)	(0.04)	(0.04)	(0.04)	(0.04)	(0.04)
Population density (log) in suburbs	-0.15***	-0.23***	-0.03	-0.02	-0.03	0.01
	(0.04)	(0.04)	(0.05)	(0.05)	(0.05)	(0.06)
Proportion of black residents (log)		0.09	0.09*	0.10*	0.08.	0.07
		(0.05)	(0.04)	(0.04)	(0.04)	(0.04)
Proportion of families in poverty (log)		0.20**	0.20***	0.20***	0.14*	0.12*
		(0.06)	(0.06)	(0.06)	(0.06)	(0.06)
Proportion of residents over 64 (log)		0.13	0.02	-0.01	-0.02	-0.03
		(0.09)	(0.08)	(0.08)	(0.08)	(0.08)
Jobs per acre (log)						-0.08
						(0.05)
Land use diversity					0.17***	0.21***
					(0.04)	(0.05)
Public school enrollments (log)					0.005	0.002
					(0.01)	(0.01)
Street link-to-node ratio					-0.30	-0.34
					(0.20)	(0.20)
Pedestrian exposure (log)				-0.03	-0.10	-0.03
				(0.05)	(0.05)	(0.07)
Average annual daily traffic (log)				0.31***	0.31***	0.31***
				(0.02)	(0.02)	(0.02)
Speed limit (25 mph and low frequency omitted)						
None available			0.59***	0.45**	0.44**	0.44**
			(0.14)	(0.14)	(0.14)	(0.14)
35 mph			0.95***	0.70***	0.69***	0.70***
			(0.09)	(0.09)	(0.09)	(0.09)
45 mph			1.85***	1.49***	1.50***	1.49***
			(0.24)	(0.24)	(0.24)	(0.24)
55 & 65 mph			1.46***	0.88***	0.85***	0.86***
			(0.15)	(0.15)	(0.15)	(0.15)

Roadway segment length (in feet)			1.13***	1.11***	1.12***	1.11***
			(0.05)	(0.05)	(0.05)	(0.05)
Length (in feet) of limited access highways (log)			0.07**	0.04	0.04	0.04
			(0.03)	(0.03)	(0.03)	(0.03)
Length (in feet) of secondary highways (log)			0.14***	0.11***	0.11***	0.11***
			(0.02)	(0.02)	(0.02)	(0.02)
Length (in feet) of major arterials (log)			0.07***	0.06**	0.06**	0.06**
			(0.02)	(0.02)	(0.02)	(0.02)
Length (in feet) of secondary highways: one way (log)			0.06	0.06	0.06	0.06
			(0.04)	(0.03)	(0.03)	(0.03)
Length (in feet) of major arterials: one way (log)			0.05	0.02	0.02	0.02
			(0.04)	(0.04)	(0.04)	(0.04)
AADT missing dummy			-2.19***	-0.01	-0.04	-0.03
			(0.30)	(0.32)	(0.32)	(0.32)
Intersection dummy			7.26***	6.95***	6.97***	6.94***
			(0.34)	(0.34)	(0.34)	(0.34)
Philadelphia intercept	1.18***	1.03***	1.15***	1.09***	1.11***	1.15***
	(0.13)	(0.14)	(0.13)	(0.15)	(0.16)	(0.16)
Constant	-5.49***	-6.22***	-13.84***	-15.42***	-14.27***	-14.62***
	(0.06)	(0.27)	(0.44)	(0.57)	(0.67)	(0.71)
AIC	14,640	14,619	13,141	12,840	12,829	12,829
BIC	14,702	14,713	13,360	13,080	13,100	13,110

Significance levels: < 0.001 ***, < 0.01 **, < 0.05 *
Variables in italic are measured on Census tract level as opposed to segment/intersection level

Appendix B.4 Random intercept multilevel negative binomial models of pedestrian involved crashes by segment/intersection in the Philadelphia region

	Control levels					
	None	Demographics	Roadway	Exposure	Land use	Full
	Estimate (standard error)					
Population density (log) in Philadelphia	0.06	-0.01	0.07**	0.003	-0.02	-0.02
	(0.05)	(0.03)	(0.02)	(0.02)	(0.09)	(0.02)
Population density (log) in suburbs	0.76***	0.62***	0.70***	0.58***	0.45***	0.47***
	(0.05)	(0.04)	(0.03)	(0.03)	(0.10)	(0.04)
Proportion of black residents (log)		0.12***	0.12***	0.13***	0.16*	0.13***
		(0.03)	(0.02)	(0.02)	(0.07)	(0.02)
Proportion of families in poverty (log)		0.20***	0.22***	0.21***	0.19	0.22***
		(0.04)	(0.03)	(0.03)	(0.10)	(0.03)
Proportion of residents over 64 (log)		-0.21***	-0.24***	-0.21***	-0.25	-0.19***
		(0.05)	(0.05)	(0.04)	(0.16)	(0.04)
Jobs per acre (log)						0.11***
						(0.03)
Land use diversity					0.13	0.04
					(0.07)	(0.03)
Public school enrollments (log)					-0.02	-0.01
					(0.02)	(0.01)
Street link-to-node ratio					-0.45	-0.67***
					(0.36)	(0.11)
Pedestrian exposure (log)				0.33***	0.32***	0.24***
				(0.03)	(0.09)	(0.04)
Average annual daily traffic (log)				0.26***	0.28***	0.26***
				(0.01)	(0.05)	(0.01)
Speed limit (25 mph and low frequency omitted)						
None available			0.06	0.01	-0.34	0.01

			(0.06)	(0.06)	(0.23)	(0.06)
35 mph			0.89***	0.70***	0.82***	0.69***
			(0.03)	(0.03)	(0.18)	(0.03)
45 mph			1.36***	1.04***	1.12	1.06***
			(0.15)	(0.15)	(0.84)	(0.15)
55 & 65 mph			1.03***	0.50***	0.55	0.49***
			(0.08)	(0.08)	(0.42)	(0.08)
Roadway segment length			0.85***	0.87***	0.91***	0.87***
(in feet)			(0.02)	(0.02)	(0.08)	(0.02)
Length (in feet) of limited			-0.06**	-0.12***	-0.05	-0.12***
access highways (log)			(0.02)	(0.02)	(0.09)	(0.02)
Length (in feet) of			0.16***	0.13***	0.13	0.13***
secondary highways (log)			(0.01)	(0.01)	(0.07)	(0.01)
Length (in feet) of major			0.09***	0.07***	0.06	0.07***
arterials (log)			(0.01)	(0.01)	(0.04)	(0.01)
Length (in feet) of secondary highways: one			-0.05*	-0.03	0.02	-0.03
way (log)			(0.02)	(0.02)	(0.16)	(0.02)
Length (in feet) of major			0.01	-0.01	-0.01	-0.01
arterials: one way (log)			(0.02)	(0.02)	(0.12)	(0.02)
AADT missing dummy			-1.68***	0.10	0.01	0.11
			(0.13)	(0.14)	(0.40)	(0.14)
Intersection dummy			6.07***	5.97***	5.83***	5.98***
			(0.14)	(0.14)	(0.50)	(0.14)
Philadelphia intercept	3.15***	2.67***	2.73***	2.24***	2.18***	1.99***
	(0.17)	(0.11)	(0.10)	(0.10)	(0.34)	(0.10)
Constant	-5.27***	-5.14***	-11.19***	-15.23***	-14.32***	-13.38***
	(0.07)	(0.17)	(0.22)	(0.30)	(1.20)	(0.36)
AIC	99,091	73,857	67,104	65,804	111,996	65,740
BIC	99,154	73,950	67,322	66,044	112,267	66,021

Significance levels: < 0.001 ***, < 0.01 **, < 0.05 *
Variables in italic are measured on Census tract level as opposed to segment/intersection level

Appendix B.5 Random intercept multilevel negative binomial models of serious pedestrian injuries by segment/intersection in the Philadelphia region

	Control levels					
	None	Demographics	Roadway	Exposure	Land use	Full
	Estimate (standard error)					
Population density (log)	0.03	-0.07	0.05	0.02	0.02	0.02
in Philadelphia	(0.05)	(0.05)	(0.06)	(0.06)	(0.06)	(0.06)
Population density (log)	0.62***	0.48***	0.59***	0.50***	0.46***	0.46***
in suburbs	(0.07)	(0.08)	(0.08)	(0.08)	(0.09)	(0.09)
Proportion of black		0.06	0.06	0.06	0.05	0.05
residents (log)		(0.05)	(0.05)	(0.05)	(0.05)	(0.05)
Proportion of families in		0.26***	0.27***	0.28***	0.25**	0.24**
poverty (log)		(0.08)	(0.07)	(0.08)	(0.08)	(0.08)
Proportion of residents		-0.02	-0.04	-0.03	-0.02	-0.02
over 64 (log)		(0.11)	(0.11)	(0.11)	(0.11)	(0.11)
Jobs per acre (log)						-0.02
						(0.07)
Land use diversity					0.13*	0.13*
					(0.06)	(0.06)
Public school enrollments					-0.01	-0.02
(log)					(0.01)	(0.01)
Street link-to-node ratio					-0.73**	-0.74**
					(0.27)	(0.27)

Pedestrian exposure (log)				0.25***	0.24***	0.25**
				(0.07)	(0.07)	(0.09)
Average annual daily				0.31***	0.31***	0.31***
traffic (log)				(0.03)	(0.03)	(0.03)
Speed limit (25 mph and low frequency omitted)						
None available			-0.01	-0.08	-0.09	-0.09
			(0.22)	(0.22)	(0.22)	(0.22)
35 mph			0.94***	0.74***	0.73***	0.73***
			(0.10)	(0.10)	(0.10)	(0.10)
45 mph			0.68	0.30	0.30	0.30
			(0.60)	(0.60)	(0.60)	(0.60)
55 & 65 mph			1.53***	0.88***	0.87***	0.87***
			(0.21)	(0.21)	(0.21)	(0.21)
Roadway segment length			0.81***	0.83***	0.83***	0.83***
(in feet)			(0.07)	(0.07)	(0.07)	(0.07)
Length (in feet) of limited			-0.05	-0.11*	-0.11*	-0.11*
access highways (log)			(0.05)	(0.05)	(0.05)	(0.05)
Length (in feet) of			0.14***	0.09**	0.09**	0.09**
secondary highways (log)			(0.03)	(0.03)	(0.03)	(0.03)
Length (in feet) of major			0.09***	0.06*	0.06*	0.06*
arterials (log)			(0.03)	(0.03)	(0.03)	(0.03)
Length (in feet) of secondary highways: one			0.03	0.05	0.04	0.04
way (log)			(0.05)	(0.05)	(0.05)	(0.05)
Length (in feet) of major			0.03	0.02	0.01	0.02
arterials: one way (log)			(0.05)	(0.05)	(0.05)	(0.05)
AADT missing dummy			-2.03***	0.08	0.09	0.09
			(0.51)	(0.54)	(0.54)	(0.54)
Intersection dummy			5.37***	5.24***	5.25***	5.24***
			(0.45)	(0.45)	(0.45)	(0.45)
Philadelphia intercept	2.17***	1.87***	1.91***	1.46***	1.29***	1.29***
	(0.21)	(0.22)	(0.23)	(0.25)	(0.26)	(0.26)
Constant	-7.39***	-7.68***	-13.37***	-17.13***	-15.65***	-15.71***
	(0.13)	(0.37)	(0.61)	(0.81)	(0.93)	(0.98)
AIC	8,573	8,553	8,021	7,853	7,848	7,849
BIC	8,636	8,647	8,239	8,093	8,119	8,131

Significance levels: < 0.001 ***, < 0.01 **, < 0.05 *
Variables in italic are measured on Census tract level as opposed to segment/intersection level

Appendix B.6 Random intercept multilevel negative binomial models of pedestrian fatalities by segment/intersection in the Philadelphia region

	Control levels					
	None	Demographics	Roadway	Exposure	Land use	Full
	Estimate (standard error)					
Population density (log)	-0.16***	-0.27***	-0.14*	-0.13*	-0.10	-0.11
in Philadelphia	(0.05)	(0.06)	(0.06)	(0.06)	(0.06)	(0.06)
Population density (log)	0.32**	0.20*	0.33**	0.32**	0.32**	0.26*
in suburbs	(0.10)	(0.10)	(0.11)	(0.12)	(0.12)	(0.13)
Proportion of black		0.11	0.10	0.11	0.10	0.12
residents (log)		(0.08)	(0.08)	(0.08)	(0.08)	(0.08)
Proportion of families in		0.22	0.24*	0.23*	0.14	0.17
poverty (log)		(0.11)	(0.11)	(0.11)	(0.11)	(0.11)
Proportion of residents		0.10	0.03	0.004	0.01	0.01
over 64 (log)		(0.14)	(0.14)	(0.14)	(0.14)	(0.14)
Jobs per acre (log)						0.13

						(0.10)
Land use diversity					0.22**	0.16
					(0.08)	(0.09)
Public school enrollments					0.01	0.02
(log)					(0.02)	(0.02)
Street link-to-node ratio					-0.52	-0.44
					(0.37)	(0.37)
Pedestrian exposure (log)				0.07	-0.004	-0.11
				(0.09)	(0.10)	(0.12)
Average annual daily				0.31***	0.31***	0.31***
traffic (log)				(0.04)	(0.04)	(0.04)
Speed limit (25 mph and						
low frequency omitted)						
None available			0.56*	0.46	0.45	0.44
			(0.26)	(0.26)	(0.26)	(0.26)
35 mph			0.88***	0.67***	0.65***	0.65***
			(0.15)	(0.16)	(0.16)	(0.16)
45 mph			0.95	0.68	0.70	0.71
			(0.63)	(0.63)	(0.63)	(0.63)
55 & 65 mph			1.20***	0.71*	0.67*	0.66*
			(0.30)	(0.30)	(0.30)	(0.30)
Roadway segment length			0.76***	0.78***	0.78***	0.79***
(in feet)			(0.10)	(0.10)	(0.10)	(0.10)
Length (in feet) of limited			0.09	0.02	0.02	0.02
access highways (log)			(0.06)	(0.06)	(0.06)	(0.06)
Length (in feet) of			0.25***	0.21***	0.21***	0.21***
secondary highways (log)			(0.04)	(0.04)	(0.04)	(0.04)
Length (in feet) of major			0.14***	0.11**	0.11**	0.11**
arterials (log)			(0.04)	(0.04)	(0.04)	(0.04)
Length (in feet) of						
secondary highways: one			0.04	0.04	0.04	0.04
way (log)			(0.06)	(0.06)	(0.06)	(0.06)
Length (in feet) of major			0.10	0.07	0.06	0.06
arterials: one way (log)			(0.06)	(0.07)	(0.07)	(0.07)
AADT missing dummy			-1.77**	0.40	0.38	0.37
			(0.59)	(0.65)	(0.65)	(0.65)
Intersection dummy			5.22***	5.09***	5.11***	5.15***
			(0.63)	(0.63)	(0.63)	(0.63)
Philadelphia intercept	2.22***	1.98***	1.98***	1.81***	1.81***	1.76***
	(0.23)	(0.25)	(0.26)	(0.30)	(0.32)	(0.32)
Constant	-7.75***	-8.39***	-13.87***	-16.35***	-14.85***	-14.31***
	(0.17)	(0.48)	(0.83)	(1.10)	(1.27)	(1.33)
AIC	4,330	4,324	4,048	3,974	3,971	3,971
BIC	4,392	4,418	4,267	4,214	4,242	4,252

Significance levels: < 0.001 ***, < 0.01 **, < 0.05 *
Variables in italic are measured on Census tract level as opposed to segment/intersection level