Spatial Analysis of Child Pedestrian and Bicycle Crashes

Development of Safety Performance Function for Areas Adjacent to Schools

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Pedestrian and bicycle safety for school-aged children is a particular concern as traffic crashes continue to be a leading cause of death for children 5 to 14 years old. For this concern to be addressed, Safe Routes to School (SRTS) programs have been implemented in communities across the country, with one of the primary objectives being to provide safe and convenient routes for children to walk or bike to school. Unfortunately, SRTS programs allocate limited funding for such projects. Consequently, it is imperative that programs are implemented at locations where they are likely to have the greatest impact. The primary focus of this study was to develop a safety performance function (SPF) for use in prioritizing candidate schools for SRTS programs. Traffic crashes over a 5-year analysis period were examined and linked to data that included the school enrollment, the socioeconomic and demographic data for each school district, and the functional class of the roadway on which each school was located. Schools on local roads were found to experience more crashes than those located on other, higher-class road facilities. Crashes also varied with average family size, number of parents per household, population density, and median family income. Crashes were less frequent in school districts that exhibited greater ethnic diversity. The SPF developed as a part of this research can be used for prioritization of candidate schools as well as to assess the efficacy of SRTS programs on a longitudinal basis and thus provide a valuable tool for school administrators and others involved in child pedestrian and bicycle safety.

Each year, more than 4,000 pedestrians and nearly 700 bicyclists are fatally injured in traffic crashes throughout the United States (*1, 2*). Although pedestrian and bicycle traffic comprises a very small proportion of all travel nationwide, these fatalities account for 15% of the national total. Pedestrian and bicycle safety is a particular concern among school-aged children because pedestrian fatalities account for 19% to 23% of all traffic fatalities among children ages 0 to 15, while 10% of all bicyclist fatalities involved children in this youngest age group (*1, 2*). Child pedestrian and bicyclist activity tends to be highest during the periods before and after school, periods that also tend to coincide with high levels of traffic volume, increasing the potential risk for child pedestrian crashes (*3*).

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Safety concerns present one of several factors that explain the relatively low rate of children who currently walk or bike to school (*4, 5*). Prior research has shown various demographic, attitudinal, psychosocial, and environmental factors to influence parents' decisions as to whether to allow children to walk or bike to school. Among the most influential factors are land use and geographic factors, income, parental attitudes and schedules, and traffic- and crime-related fears (*6, 7*). Children with less independent mobility, fewer traveling companions, and those less likely to engage in conversations about safety have been found more likely to be driven to school (*8*). Parental intervention and influence may increase rates of active travel to school (ATS) for both pedestrian and bicyclists (*9, 10*). In support of increased ATS, a national study of state laws showed that legislation requiring minimum busing distances, hazardous route exemptions, crossing guards, speed zones, and other traffic control measures all influenced ATS policies (*11*). Within the scope of planning and engineering, the proximity of homes to a school, the level of traffic exposure in the surrounding neighborhood, and the connectivity of the roadway network around the school have all been shown to be significant determinants of children walking or bicycling to school (*12–14*).

To address some of the aforementioned issues, Safe Routes to School (SRTS) programs have been implemented in communities across the country, with one of the primary objectives being to provide safe and convenient routes for children to walk or bike to school. The SRTS program funds a variety of projects, including infrastructure improvements (e.g., sidewalk and bike lane installation), educational programs, and on-site safety audits.

Unfortunately, SRTS programs allocate limited funding for such projects. Consequently, it is imperative that programs are implemented at locations where they are likely to have the greatest impact. To this end, the National Center for Safe Routes to School presented a practical process for identifying and prioritizing schools for SRTS programs (*15*). This methodology provided a balance between what is known about preventing child pedestrian injuries and what can realistically be accomplished without having to perform comprehensive field reviews of each site. Primary emphases for prioritization are centered on three major factors: crash history, public and school officials' concerns, and current or potential pedestrian use. While this framework presents a promising starting point, its application is somewhat limited because of the relative infrequency of child pedestrian and bicycle crashes near schools and the inherent subjectivity involved in the more qualitative assessments.

The objective of this research was to develop a safety performance function (SPF) for K–8 schools that could be used as part of a data-driven approach to assist communities in identifying or prioritizing candidate schools for SRTS funding. Furthermore, this SPF can also be used to conduct longitudinal assessments of the effectiveness of SRTS programs in reducing child pedestrian and bicycle crashes, filling an important gap in the research literature (*16*).

LITERATURE REVIEW

The research literature includes a few studies that have examined crashes involving school-aged pedestrian or bicyclists, as well as a more extensive volume of recent research that has examined pedestrian- and bicycle-involved crashes more broadly.

Studies of Pedestrian and Bicycle Crashes Involving Children

A 1997 study in England involved the development of a procedure to identify the number crashes occurring during the commute to and from school (*17*). Schools were ranked on the basis of the number of crashes occurring within a 250-m radius from 8:00 to 9:00 a.m. and from 3:30 to 4:30 p.m. Crash statistics were subsequently linked to self-reported travel data. The resultant crash rates were compared between two school locations, though no significant differences were identified.

Exploratory spatial analysis was used to map the distribution of crashes involving child pedestrians less than 10 years of age in Lille, France (*18*). The results showed that crashes tended to be concentrated in a select number of areas rather than randomly localized across space. Furthermore, the proportion of crashes tended to decrease at distances further from schools.

A more recent study in Baltimore, Maryland, examined pedestrian-involved crashes in the vicinity of public schools (*19*). Separate models were estimated to examine crash frequency and severity. The results showed that both measures tended to decrease at locations where driveways or turning bays were present near the school entrance. Conversely, both frequency and severity increased when recreational facilities were present on the site. Each of these factors is likely to be capturing the effects of varying exposure, as are several of the other significant variables identified in the study, which included transit access, commercial access, and population density.

Spatial and temporal analyses of child pedestrian crashes in Santiago, Chile, were conducted to identify critical areas that exhibited high crash concentrations and frequencies for periods of 5 or more years during the period from 2000 to 2008 (*20*). Seven critical areas were identified and these areas tended to be located in districts with lower-middle socioeconomic statuses. Crashes tended to be clustered by time of day and no trends were evident with respect to the children's ages, which ranged from 5 to 18 years old.

General Spatial Analyses of Pedestrian- and Bicycle-Involved Crashes

Beyond studies focused on schools and young children, there has been considerable recent research to assess the crash risks of pedestrians and bicyclists. A study in Hamilton, Ontario, Canada, mapped commuter cyclist collision risk per distance traveled (*21*). The authors recommended this method be used as a basis for transportation policy as opposed to more traditional analyses focused on rates per capita.

A spatial epidemiologic approach was used to study the relative risk factors of bicycle and pedestrian crashes at the neighborhood level in Buffalo, New York (*22*). Among the factors considered in the evaluation were roadway functional classes, as well as socioeconomic and demographic variables. Results show neighborhood-level characteristics, such as ethnicity, education level, and land use type, to significantly influence the frequency of pedestrian and bicycle crashes.

A study in four Florida counties examined trends in crash frequency with respect to trip productions and attractions within traffic analysis zones while controlling for the effects of road characteristics (*23*). The results showed that pedestrians and bicyclists tended to be overrepresented in intersection crashes. Crashes involving pedestrians and bicyclists also tended to increase with trip productions and trip attractions on a zonal level, while crashes were underrepresented on roads with a 35-mph speed limit.

A New York City study involved the development of a random parameter negative binomial model to examine factors influencing the frequency of pedestrian crashes at the census tract level (*24*). Crashes tended to be higher in African-American and Hispanic neighborhoods, as well as in areas with lower levels of education. Areas with more schools or more concentrated commercial or industrial development were also prone to more crashes.

A study in Ciudad Juárez, Mexico, used linear regression to examine the density of pedestrian crash data at the census tract level (*25*). Pedestrian crashes were more likely in areas with greater population and employment density, higher levels of commercial and retail land use, and larger proportions of persons age 65 and older.

Collectively, the extant research literature summarized here shows that a variety of analytical techniques can be utilized to assess pedestrian and bicycle crashes in a spatial context. Regardless of the approach, several common factors emerge as important, particularly information about the transportation infrastructure, as well as socioeconomic and demographic characteristics.

METHODOLOGY

Available safety resources are optimally invested at those locations that present the greatest opportunity to reduce the frequency of traffic crashes, injuries, and fatalities. Traditionally, such locations were identified on the basis of historical crash counts. However, given the random and rare nature of traffic crashes, such data may not necessarily lead to the identification of the locations with the highest potential for crashes in the future. This is particularly true for pedestrian- and bicycle-involved crashes, which tend to occur much less frequently on a site-specific basis in comparison with motor vehicle crashes.

In light of these facts, the *Highway Safety Manual* suggests that historical crash counts be supplemented with crash estimates provided by SPFs (*26*). SPFs allow for the prediction of the expected number of crashes at a given location based on site-specific information, such as exposure (e.g., traffic volumes), roadway geometry, and other relevant factors that are correlated with crash counts. The primary focus of this study was to develop an SPF for use in the Michigan SRTS program.

Data Collection and Summary

To develop the SPFs, details of those schools eligible for SRTS funding were obtained from the State of Michigan's Center for Educational Performance and Information, which is responsible for the collection and analysis of performance data for Michigan's K–12 public schools and students (*27*). Data were collected for a total of 2,404 schools that included any students in grades kindergarten through eighth grade. Each school was geocoded in a geographic information system database for use in the subsequent spatial analysis.

The spatial analysis involved using the coordinates for each school to create a 1-mi buffer. Data were then obtained for all crashes involving bicycles and child pedestrians ages 5 to 14 (kindergarten through eighth grade) within the buffer surrounding each of the schools. These data were obtained from the Michigan State Police (MSP) crash database, a condensed version of which can be accessed from the MSP Office of Highway Safety Planning's Michigan Traffic Crash Facts Data Query Tool (*28*). Given the limited number of crashes experienced on an annual basis at even the schools with the highest crash frequencies, 5 years of data were obtained (from 2007 to 2011). A total of 7,781 crashes occurred at the eligible schools over the 5-year analysis period. Figure 1 provides both a probability density function and cumulative distribution function, which illustrate the percentage of schools that experienced specific crash frequencies during the analysis period. The data appear to be well approximated by a Poisson or negative binomial distribution, with roughly 50% of the schools experiencing zero crashes during the analysis period.

The school and crash data were then combined with demographic and socioeconomic information obtained from the United States Census Bureau (*29*). These data were obtained at the school district level and matched with each of the K–8 schools included in the study. The data included as a part of the analysis were average family size (number of persons in the household related to the householder); average number of parents in each household; total district population by age, race, and sex; and median income. Various combinations of these and other socioeconomic characteristics were examined as part of the modeling process.

Finally, the National Functional Class (NFC) code (*30*) was obtained for the primary roadway on which each school was located based on its official address. This information was obtained from the Michigan Department of Transportation roadway database (*31*). Table 1 provides summary statistics for those factors that were found to be significant as a part of the analysis.

Statistical Methods

Once the analysis data set was created, an SPF was estimated to examine the relationships between the factors listed in Table 1 and

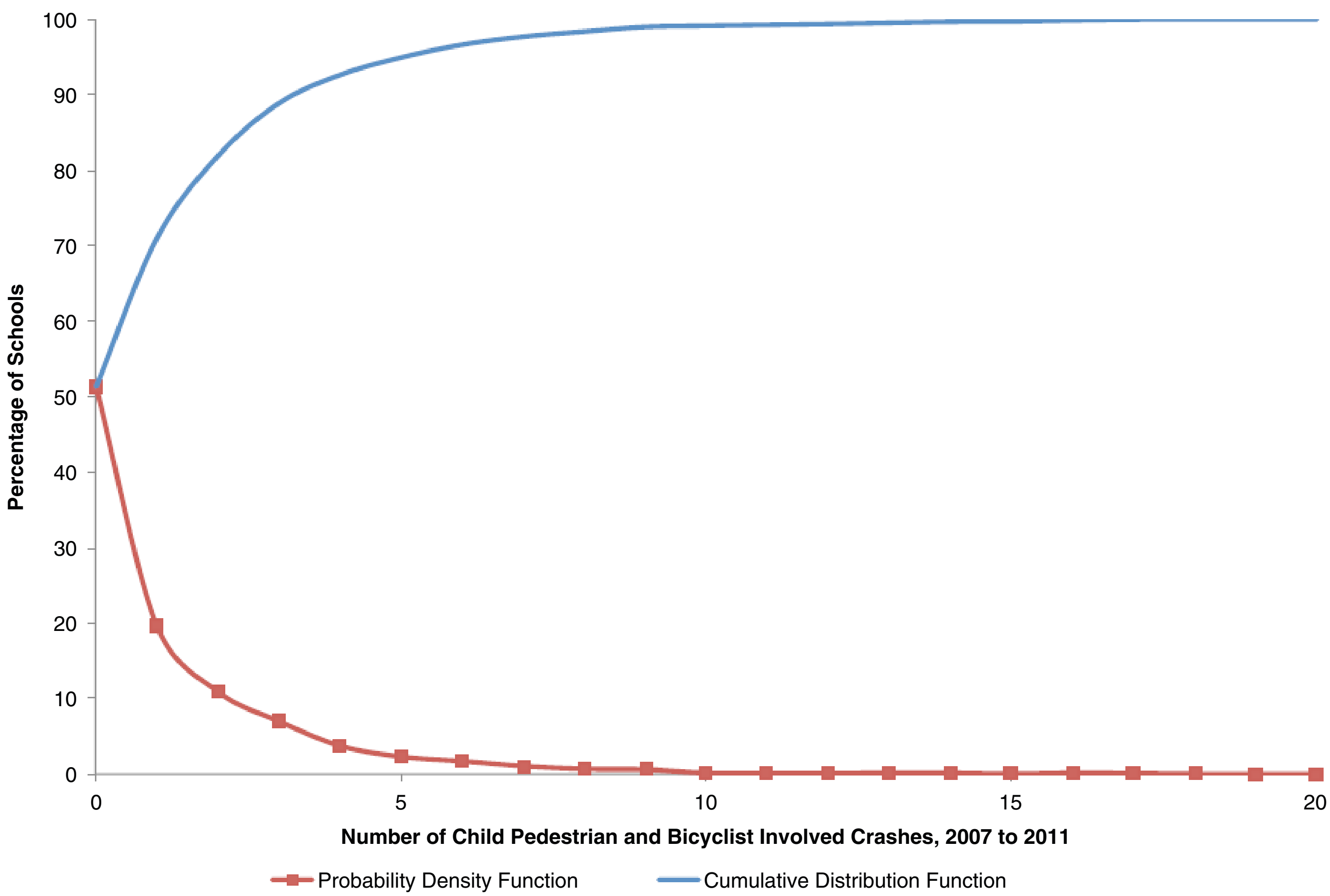

FIGURE 1 Probability density and cumulative distribution functions of crashes involving child pedestrian and bicyclist within 1 mi of a school, 2007 to 2011.

TABLE 1 Summary Statistics

Variable	Mean	SD	Maximum	Minimum
Child pedestrian–bicycle crash data				
Crashes from 2007 to 2011	1.31	2.17	0	18
Census data				
Average family size	3.05	0.18	2.34	3.98
Children ages 5 to 14	10,543	23,349	25	102,261
Average parents per household	1.72	0.13	1.25	1.89
Median family income ($)	54,626	19,420	9,906	163,366
Population density (1,000 per mi^2)	1.60	1.86	0.002	10.76
Proportion of nonwhite households	0.19	0.23	0.02	0.97
Roadway functional class				
Local roads (proportion)	0.51	0.50	0	1
Collectors (proportion)	0.23	0.42	0	1
Arterials (proportion)	0.26	0.44	0	1
School data				
Students enrolled	397	203	10	1,298

NOTE: SD = standard deviation.

the frequency of child pedestrian and bicycle crashes near each school during the 5-year analysis period.

Consistent with contemporary research (*32*) and the recommended methodology from the *Highway Safety Manual* (*26*), the SPF takes the form of a negative binomial regression model. The negative binomial specification provides the probability $P(n_i)$ of school i experiencing a total of n_i child pedestrian- or bicycle-involved crashes over the 5-year analysis period:

$$P(n_i) = \frac{\Gamma(\theta + n_i)}{\Gamma(\theta) n_i!} u_i^{\theta} (1 - u_i)^{n_i} \tag{1}$$

where

$u_i = \theta/(\theta + \lambda_i)$,
$\theta = 1/\alpha$,
$\Gamma(\cdot)$ = gamma function, and
λ_i = mean number of crashes at given location.

The variable λ_i is a linear function of covariates:

$$\lambda_i = \exp(\beta X_i + \varepsilon_i) \tag{2}$$

where

X_i = vector of data describing the traffic, socioeconomic, demographic, and enrollment characteristics of school i;
β = vector of estimable parameters; and
$\exp(\varepsilon_i)$ = gamma-distributed error term with mean one and variance α.

The resultant mean variance relationship is given by

$$\text{var}[n_i] = E(n_i)[1 + \alpha E(n_i)] \tag{3}$$

If α is significantly different from zero, the data are overdispersed or underdispersed. If α is equal to zero, then the negative binomial reduces to the Poisson distribution. Estimation of λ_i can be conducted through standard maximum likelihood procedures (*32*).

Given the nature by which crashes occur, as well as the available data, it is reasonable to expect unobserved heterogeneity because of the presence of unobserved factors (e.g., pedestrian and vehicular volumes, detailed roadway geometry, etc.). For this heterogeneity to be accounted for, the constant term is allowed to vary as

$$\beta_i = \beta + \omega_i \tag{4}$$

where ω_i is a randomly distributed term. For the constant, this term is assumed to be normally distributed with mean zero and variance σ^2. The probabilities are now conditional based on the probability distribution of ω_i. A simulation-based maximum likelihood method is used to estimate the model parameters, further details of which can be found elsewhere (*33, 34*). In the research literature, this model formulation is also referred to as a random effects model.

RESULTS AND DISCUSSION

This random effects negative binomial model is presented in Table 2, which includes parameter estimates, standard errors, *P*-values, and marginal effects. Marginal effects represent the effect on the expected frequency, λ_i, that is associated with a one-unit change in each independent variable. Marginal effects are calculated as follows:

$$\text{ME}_{x_{ik}}^{\lambda_i} = \frac{\partial \lambda_i}{\partial x_{ik}} = \beta_k \exp(\beta X_i) \tag{5}$$

where

x_{ik} = value of the kth independent variable for school i,
β_k = estimated parameter for the kth independent variable, and
λ_i = expected crash count for school i.

Marginal effects are calculated for each observation and then averaged across the entire sample.

In examining the model results, they are generally found to be consistent with a priori expectations. First, the standard deviation of

TABLE 2 Random Effects Negative Binomial Model Results

Parameter	Estimate	Standard Error	*P*-Value	Marginal Effect
Constant	0.933	0.654	.153	na
Standard deviation	0.635	0.021	<.001	na
Log (child population ages 5–14)	0.228	0.020	<.001	0.168
Log (K–8 enrollment)	0.066	0.014	<.001	0.049
School located on local roadway	0.172	0.038	<.001	0.126
Average family size	0.326	0.127	.010	0.239
Population density (persons/mi^2)	0.292	0.013	<.001	0.215
Median family income ($1,000)	–0.017	0.001	<.001	–0.012
Average parents per household	–2.214	0.403	<.001	–1.630
Proportion of nonwhite households	–1.644	0.217	<.001	–1.210
α (overdispersion parameter)	20.183	7.365	.006	na

NOTE: na = not applicable; K = kindergarten.

the constant term was found to be significantly different from zero, which is evidence of unobserved heterogeneity (and random effects) that is attributable to some important factors for which data were not available. Second, the overdispersion parameter was also significantly larger than zero, indicating that the negative binomial model outperformed the more restrictive Poisson model (a finding that was confirmed by comparing the log-likelihood values for the two models).

With respect to the variables of interest, crashes were found to increase with the population of children ages 5 to 14 (corresponding to grades kindergarten through eighth grade), as well as with the number of students enrolled in each school. In lieu of actual count data that indicate the number of children who walk or bike to school, these variables are likely capturing the effects of such exposure. This finding is consistent with prior work that has shown similar trends with respect to student enrollment and population (*19*).

Also consistent with prior research (*8*), the location of the school also affected the expected number of crashes. Schools that were located on local roads (as per the NFC code) experienced more crashes than schools that were located on higher-class collector or arterial roads. This finding could be reflective of less regulated travel behavior by both student commuters and motor vehicle drivers in the area adjacent to the school. Field observation conducted as a part of prior research in Michigan (*35, 36*) showed erratic behavior by parents who were picking up or dropping off their children at school, as well as by the children themselves who would frequently dart in and out of traffic, particularly on lower-volume local roads. This finding could also be attributable to underdevelopment of pedestrian and bicycle facilities along local roadways that may discourage safe crossing behavior (*13*). Finally, this factor could also be capturing the effects of increased exposure as schools located on local roads may be located within a subdivision. As a result, the proportion of children walking or biking to and from school may be much higher than that of a school located on a major roadway, where it may be more likely that children would be picked up by parents or bused to and from school.

Turning to the socioeconomic and demographic factors, crashes were found to increase in school districts with larger average family sizes. Children in larger households may be more apt to walk or bike to school because of limitations in the number of available vehicles. Similar dynamics may explain why crashes decrease in areas with more two-parent households. Two-parent households are more easily able to facilitate automobile transportation for children as shown by previous studies (*8, 12*). A two-parent household would also make it easier for one of the parents to walk or bike to school with his or her children. This finding may also capture some effects of greater parental interaction and oversight within such households.

Pedestrian and bicycle crashes were also found to increase in school districts with greater population density, which is likely to reflect differences in travel patterns as denser, more urbanized areas are likely to have higher proportions of children walking or biking to school. Such areas are also likely to be subject to higher traffic volumes, further elevating the risks of crash involvement. Crash frequency was negatively correlated with median family income. Higher income has generally been associated with higher levels of education and higher-income areas are also more likely to have greater availability of automobiles for use in transportation children to and from school.

It is interesting that more diverse school districts (as measured by the proportion of nonwhite families) were found to experience fewer crashes than less diverse districts. However, the reasons for this correlation are not easily explained and further research is warranted to better understand the underlying causes of this result.

CONCLUSIONS

This study provides an important contribution to the state of the art in the development of a safety performance function for use in SRTS programs. The SPF could be calibrated to other jurisdictions using the procedures outlined in the *Highway Safety Manual* (*26*). The method can also be easily applied in other jurisdictions using data that are available from the United States Census Bureau and state transportation agencies. Such SPFs can be used for various functions, including two that are of particular relevance for SRTS:

- Prioritizing candidate locations for subsequent investment decisions. Locations that are in need of safety improvements can be identified by comparing observed and expected safety performance. Schools that have experienced significantly more pedestrian or bicycle crashes than expected may be indicative of underlying safety issues. Alternatively, schools that have experienced fewer crashes than expected may reflect either safe campuses or luck because of the random and rare nature of crashes.

• Conducting longitudinal evaluations of the effectiveness of prior investments. Historically, evaluations of SRTS programs have focused on whether the number of children walking and bicycling to school has increased (*16*). Safety performance functions will allow for a quantitative assessment of how well existing programs meet the complementary objective of enhancing the safety for children who walk and bike to school.

As a result of this research, decision makers will be able to more efficiently prioritize schools for safety improvements or other SRTS programs. In addition to providing this tool, the study results support prior research, which has associated a variety of socioeconomic, demographic, and other school-specific factors with child pedestrian and bicycle crashes (*12–14*).

Specific findings include the following:

• Crashes increased with the number of children enrolled at a given school and with the population of children ages 5 to 14 in the accompanying school district;

• Schools located on local roadways experience higher crash frequencies than schools located on other, higher-class facilities; and

• Crashes also varied with average family size, number of parents per household, population density, and median family income. Crashes were less frequent in school districts that exhibited greater ethnic diversity.

This research can be expanded by conducting more in-depth investigations that consider additional factors, such as pedestrian and motor vehicle volumes, travel speeds, and infrastructure characteristics.

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