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ABSTRACT

The San Francisco pedestrian volume modeling process refined the methodology used to develop previous intersection-based models and incorporated variables that were tailored to estimate walking activity in the local urban context. The methodology included two main steps. First, manual and automated pedestrian counts were taken at a sample of 50 study intersections with a variety of characteristics. A series of factor adjustments were applied to produce an annual pedestrian crossing estimate at each intersection. Second, log-linear regression modeling was used to identify statistically-significant relationships between the annual pedestrian volume estimate and land use, transportation system, local environment, and socioeconomic characteristics near each intersection. Twelve alternative models were considered, and the preferred model had a good overall fit (adjusted-R^2 = 0.804). As identified in other communities, pedestrian volumes were positively associated with the number of households and the number of jobs near each intersection. Uniquely, this San Francisco model also found significantly higher pedestrian volumes at intersections in high-activity zones with metered on-street parking, in areas with fewer hills, near university campuses, and controlled by traffic signals. The model was based on a relatively small sample of intersections, so the number of significant factors was limited to six. Results are being used by public agencies in San Francisco to better understand pedestrian crossing risk and to inform citywide pedestrian safety policy and investment.

INTRODUCTION

Pedestrian volume estimates are important for applications such as safety analysis, project prioritization, facility design, physical activity monitoring, and development impact assessment (*1,2,3*). Estimates are also useful since collecting counts at all locations in a large community is impractical. For example, San Francisco has more than 8,100 street intersections, and a data collector counting at one intersection per day without breaks for weekends or holidays would take more than two decades to cover the entire city. Therefore, planners, engineers, public health professionals, and urban designers need methods to estimate pedestrian activity levels throughout a jurisdiction. Statistical models can be used for this purpose.

Study Purpose

This paper provides an overview of previous pedestrian volume models and highlights innovative data collection techniques used to develop the San Francisco Pedestrian Volume Model. It also highlights variables that were important for estimating walking activity in the unique urban context of San Francisco. Finally, local applications of the model are summarized.

PREVIOUS PEDESTRIAN VOLUME MODELS

Several modeling approaches have been used to estimate pedestrian volumes in the roadway environment. Conventional, four-step travel models have been modified to include pedestrian mode choice (*4,5*). However, these models are typically applied to traffic analysis zones, a geographic scale that is too large to capture fine-grained differences in pedestrian activity at individual intersections. One study overcame this limitation by estimating pedestrian trip generation, trip distribution, and route assignment between block-sized pedestrian analysis zones in central Baltimore (*6*). However, the model requires significant computing time to apply.

Other models estimate pedestrian volumes at specific locations directly from characteristics of the surrounding area. For example, roadway network attributes, such as connectivity and sight lines have been combined with land use variables to estimate pedestrian flows in Oakland (*7*) and Boston (*8*). Several direct demand models use land use data from street block faces or the area around an intersection to estimate pedestrian volumes. Street block face data have been used to model volumes in New York, NY (*9*) and Milwaukee, WI (*10*). Intersection-based models have been developed in Charlotte, NC (*11*); Alameda County, CA (*12*); San Francisco, CA (*13*); San Diego County, CA (*14*); Santa Monica, CA (*15*); and Montreal, Quebec (*16*) (TABLE 1). These models predict the total number of pedestrian crossings on all legs of an intersection or the total number of pedestrians arriving at an intersection during a particular time period. Most use either a linear or log-linear model structure, and they can be applied using a simple spreadsheet. Note that these models are distinct from other pedestrian demand indices developed from professional judgment and community input. Indices often suggest locations where pedestrian activity is relatively higher or lower than average, but they rarely produce estimates of actual pedestrian volumes.

The most common predictive variables in existing intersection-based pedestrian models include some form of population density, employment density, and transit accessibility (TABLE 1). However, different models weigh these factors differently. Therefore, they may produce different pedestrian volume estimates when applied outside of the context where they were developed. This suggests that the unique characteristics of individual communities should be addressed when estimating pedestrian volumes.

TABLE 1 Examples of Previous Pedestrian Intersection Volume Models

General information		Pedestrian count information					Statistically-significant predictive variables				Model information		
Model Location	**Developed by**	**Intersections Used for Model**	**Pedestrian Count Description**	**Type of Count Sites**	**Count Period(s) Used for Model**	**Weather During Counts**	**Land Use**	**Transportation System**	**Socioeconomic Characteristics**	**Other**	**Model Output**	**Model Type**	**Validation Testing**
Charlotte, NC	UNC Charlotte (Pulugurtha & Repaka 2008)	176	Pedestrians counted each time they arrived at the intersection from any direction	Signalized intersections	7 am-7 pm	Clear weather conditions	• Pop. within 0.25 mi. • Jobs within 0.25 mi. • Mixed land use within 0.25 mi. • Urban residential area within 0.25 mi.	• Number of bus stops within 0.25 mi.			Total pedestrians approaching intersections from 7 am to 7 pm (shorter periods also modeled)	Linear	None reported
Alameda County, CA	UC Berkeley SafeTREC (Schneider, Arnold, & Ragland 2009)	50	Pedestrians counted every time they crossed a leg of the intersection (pedestrians within 50 feet of the crosswalk were counted)	Signalized and unsignalized intersections	Tu, W, or Th: 12-2 pm or 3-5 pm; Sa: 9-11 am, 12-2 pm, or 3-5 pm	All weather conditions; weather adjustment factors were calculated from automated counters	• Population within 0.5 mi. • Employment within 0.25 mi. • Commercial properties within 0.25 mi.	• BART (regional transit) station within 0.1 mi.			Total pedestrian crossings at intersections during a typical week	Linear	46 historic counts used for validation (30 additional intersections were counted for validation in 2009)
San Francisco, CA	San Francisco State (Liu & Griswold 2009)	63	Pedestrians counted each time they crossed a leg of the intersection (no distance to crosswalk specified)	Signalized and unsignalized intersections	Weekdays 2:30-6:30 pm	Not reported	• Population density (net) within 0.5 mi. • Employment density (net) within 0.25 mi. • Patch richness density within 0.063 mi. • Residential land use within 0.063 mi.	• MUNI (light-rail transit) stop density within 0.38 mi. • Presence of bike lane at intersection		• Mean slope within 0.063 mi.	Total pedestrian crossings at intersections from 2:30-6:30 pm on typical weekday	Linear	None reported
Santa Monica, CA	Fehr & Peers (Haynes *et al*. 2010)	92	Pedestrians counted each time they crossed a leg of the intersection (no distance to crosswalk specified)	Signalized and unsignalized intersections	Weekdays 5-6 pm	Not reported	• Employment density within 0.33 mi. • Within a commercially-zoned area	• Afternoon bus frequency • Average speed limit on the intersection approaches		• Distance from Ocean	Total pedestrian crossings at intersections from 5-6 pm on typical weekday	Linear	Approximately 107 additional intersections were counted for validation
San Diego, CA	Alta Planning + Design (Jones *et al.* 2010)	80	Pedestrians counted each time they arrived at the intersection from any direction	Signalized and unsignalized intersections (includes some trail/roadway intersections)	Weekdays 7-9 am	Nice weather	• Population density within 0.25 mi. • Employment density within 0.5 mi. • Presence of retail within 0.5 mi.	• Greater than 6,000 transit ridership at bus stops within 0.25 mi. • 4 or more Class I bike paths within 0.25 mi.	• More than 100 households without vehicles within 0.5 mi.		Total pedestrians approaching intersections from 7 am to 9 am	Log-linear	None reported
Montreal, Quebec	McGill University (Miranda-Moreno & Fernandes 2011)	1018	Pedestrians counted each time they crossed a leg of the intersection (no distance to crosswalk specified)	Signalized intersections	Weekdays 6-9 am, 11 am-1 pm, and 3:30-6:30 pm	Most counts during nice weather; weather variables were analyzed	• Population within 400 m • Commercial space within 50 m • Open space within 150 m • Schools within 400 m	• Subway within 150 m • Bus station within 150 m • % Major arterials within 400 m • Street segments within 400 m • 4-way intersection		• Distance to downtown • Daily high temperature >32°C	Total pedestrian crossings at intersections over 8 count hours (shorter periods also modeled)	Log-linear (also used Negative binomial)	Counts at 20% of the intersections were compared to a model based on 80% of the intersections for validation

SAN FRANCISCO PEDESTRIAN MODEL DEVELOPMENT

The San Francisco Pedestrian Volume Model was developed in two main steps. First, annual pedestrian crossing volumes were estimated from manual and automated counts at 50 study intersections. Second, possible explanatory factors were measured and compared to the counts using statistical models.

Intersection Selection

San Francisco, CA (Census 2010 population of 805,000) has more than 8,100 roadway intersections (*17,18*). Fifty study intersections were selected to represent the range of urban characteristics across the city (FIGURE 1). Intersections were selected in two stages. The first 28 intersections were included in a pedestrian counting program that began in 2009. These intersections included high-crash locations, regional count locations, locations near planned or completed projects, locations near key transit hubs, and other intersections to provide geographic representation throughout San Francisco. The final 22 intersections were selected in 2010 to increase the diversity of locations across a number of factors to support model development.

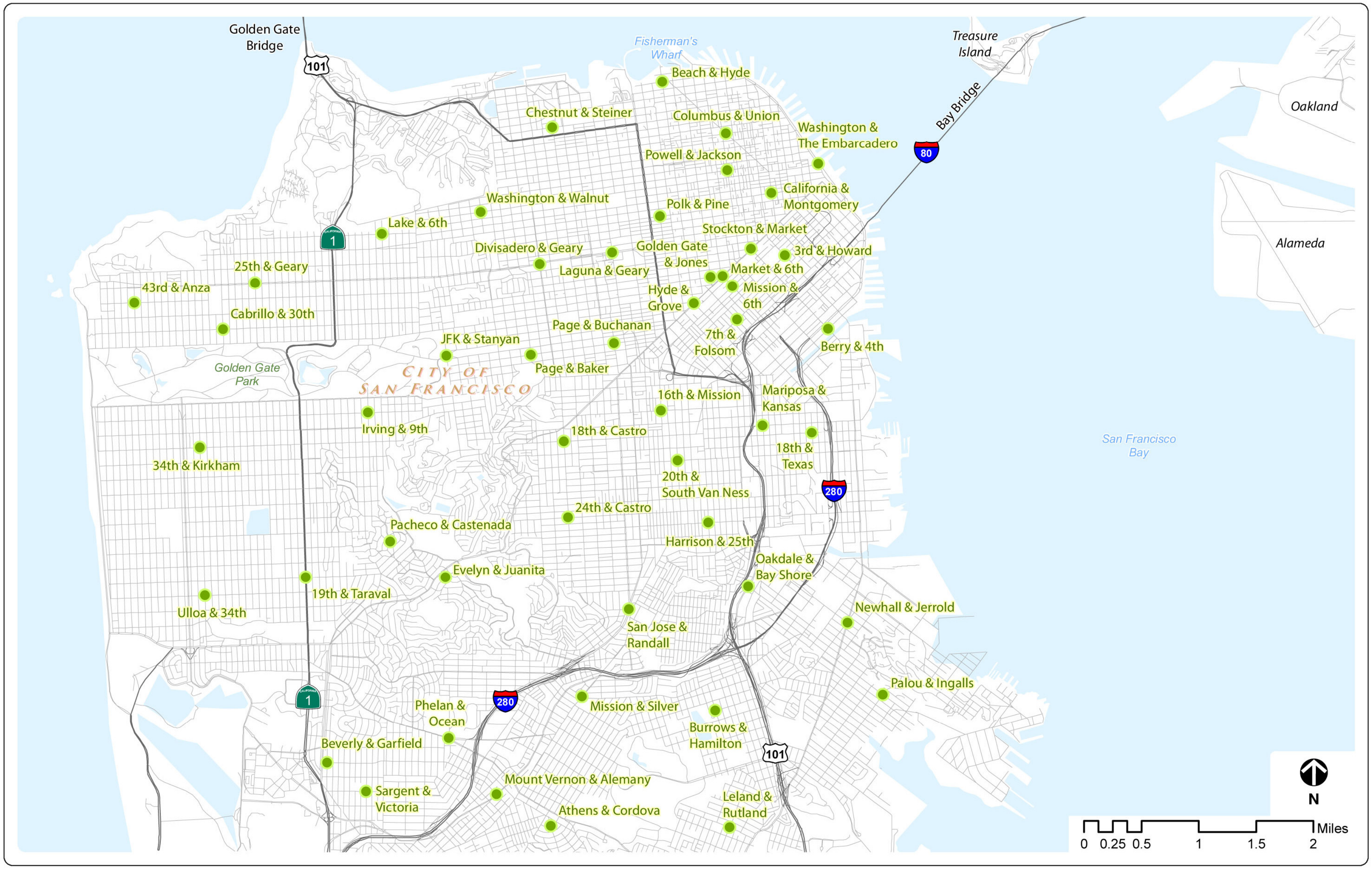
The 50 study intersections had a wide variety of characteristics, including:

- 10 intersections had fewer than 2,500 residents within 0.25 miles (402 m); 10 intersections had more than 7,500 residents within 0.25 miles (402 m).
- 16 intersections had fewer than 1,000 jobs within 0.25 miles (402 m); 12 intersections had more than 5,000 jobs within 0.25 miles (402 m).
- 22 intersections were in neighborhoods where more than 80% of households own a motor vehicle; 12 intersections were in neighborhoods where fewer than 50% of households own a motor vehicle.
- 16 intersections had a steepest approach leg with a slope of less than 5%; 11 intersections had a steepest approach leg with a slope of more than 10%.
- 37 intersections had a maximum approach leg posted speed limit of 25 miles per hour (40 kilometers per hour).
- 22 intersections were on arterial roadways.
- 29 intersections were signalized.
- 23 intersections were in zones with metered on-street parking.
- 4 intersections were within 0.25 miles (402 m) of a major university campus.

Pedestrian Intersection Count Data

The San Francisco Municipal Transportation Agency (SFMTA) collected manual pedestrian volume counts at approximately half of the study intersections in September 2009 and half in July and August 2010. Manual counts included all pedestrians who crossed each leg of the intersection during a two-hour period. Pedestrians were counted as long as they crossed within 50 feet (15 m) of the intersection (this included pedestrians crossing in and outside of marked crosswalks). One study intersection was a three-leg intersection, and pedestrians using the "sidewalk leg" were included in the count so that total four-leg volume could be compared across all intersections.

FIGURE 1 San Francisco Pedestrian Volume Model Study Intersections



(1 mile = 1.61 kilometers)

Automated counters were rotated among 25 of the study intersections between March and September 2010 to document typical weekly pedestrian activity patterns. The sensors were installed on a pole at waist height and pointed across the sidewalk so that pedestrians were counted each time they crossed the infrared beam. The study methodology assumed the sidewalk pedestrian volume pattern near the intersection was similar to the adjacent intersection crossings. The automated counter collected continuous, hourly pedestrian counts for three to four weeks at each intersection.

Background information about the methodology for collecting pedestrian intersection crossing counts and using automated counters to extrapolate two-hour counts to longer time periods is provided in previous references (*12,19,20*). The sections below describe specific techniques used to improve annual pedestrian intersection count estimates in San Francisco.

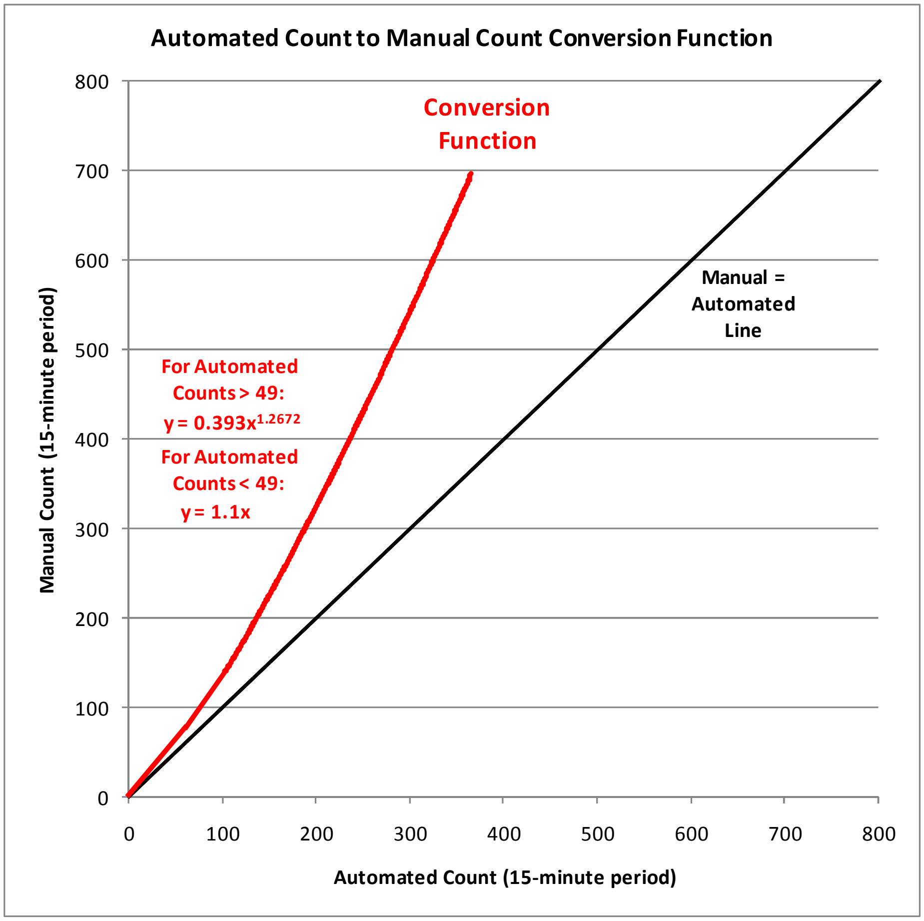
Estimation of Annual Pedestrian Crossing Volumes

Automated counter, temporal, and weather adjustment factors were used to extrapolate an annual pedestrian volume estimate from the two-hour counts at the 50 study intersections.

Automated Counter Adjustment Factor

The automated counter adjustment factor accounted for the tendency for the sensor to undercount pedestrians walking side-by-side. SFMTA took 19 15-minute-period manual validation counts at several automated counter locations during summer 2010 to test the amount of undercounting that occurred at different pedestrian volume levels. The counts were supplemented by 32 15-minute period validation counts from Alameda County in 2008. Results showed that undercounting was relatively modest at low-volume locations but more significant at higher-volume locations. The observations were the basis for a conversion function used to account for undercounting (FIGURE 2). The adjustment factor was applied before weekly volume patterns were calculated.

FIGURE 2 Automated Count to Manual Count Conversion Function



Notes:
1) This 15-minute period conversion function was adjusted for use with the 1-hour period data in San Francisco.
2) Undercounting is likely to depend on the width and design of the sidewalk in addition to the volume of pedestrians. However, this general conversion function was adequate to account for the main source of undercounting error in San Francisco.

Temporal Adjustment Factors

The adjusted automated counter data were used to identify the typical weekly volume pattern for the location near each intersection. These weekly pedestrian activity patterns were then used to extrapolate a typical weekly volume from the two-hour manual count. If each hour of the week had exactly the same number of pedestrians, each two-hour period would represent 1.19% (2 hours/168 hours) of the weekly volume; however, the automated counter data showed that the two-hour manual count periods at certain locations had more than twice this proportion of the weekly volume.

Further, several distinct pedestrian volume patterns emerged among the study intersections, so location-specific temporal adjustment factors were needed to increase the accuracy of weekly and annual volume estimates. To develop location-specific factors, the 50 study locations were classified into six general land use categories: 1) Central Business District, 2) High-Density, Mixed-Use, 3) Mid-Density, Mixed-Use, 4) Low-Density, Mixed-Use, 5) Residential, and 6) Tourist Area. Each of these land use types had a slightly different pedestrian volume pattern (e.g., the proportion of weekly pedestrian volume on a typical weekday between 4 p.m. and 6 p.m. ranged from 1.56% to 2.29%, depending on general land use category). Therefore, where automated count data were not available, the two-hour counts were multiplied by a land-use-specific temporal adjustment factor to estimate the typical weekly pedestrian volume.

Weather Adjustment Factors

The final adjustment factor accounted for differences in pedestrian volumes by weather. Historic weather data were not available for specific locations in San Francisco, so weather adjustments were based on the adjustment factors developed from 13 locations in Alameda County, just across the San Francisco Bay. Compared to pedestrian volumes under typical conditions, volumes were 10% lower when the temperature was below 50 °F (10 °C), 11% lower when it was cloudy, and 27% lower when it rained (*20*). Adjustments for temperatures above 80 °F (27 °C) were not applied.

Estimated Annual Pedestrian Volumes

The two-hour manual count at each of the 50 intersections was multiplied by the appropriate adjustment factors to estimate a weekly intersection pedestrian volume. This weekly volume estimate was then multiplied by 52.18 (365.25 days in a year/7 days in a week) to estimate the annual intersection volume. Since the July, August, and September count periods may have had different pedestrian volumes than other times of the year (e.g., many schools were out and the weather tended to be slightly warmer), seasonal adjustments could be identified in the future to refine the annual volume estimates. Finally, the annual volume was multiplied by five to produce a five-year pedestrian intersection volume estimate since five years of pedestrian collision data were available for comparison. This five-year volume estimate was used control for exposure and estimate pedestrian crossing risk (e.g., reported crashes per 10 million pedestrian crossings) at several of the study intersections (TABLE 2).

TABLE 2 Estimated Pedestrian Volumes and Crossing Risk at Study Intersections

Location Information		Manual Count Information					Intersection Volume Estimates		Intersection Crossing Risk	
Intersection	General Land Use Category	Date	Day of Week	Weather (°F, conditions)	Time	2-Hour Volume	Estimated Weekly Volume	Estimated Five-Year Volume	Reported Ped Crashes (11/04-10/09)	Ped Crashes per 10M Crossings[5]
4th St. & Market	Central Business District	9/17/09	Thu	75, sunny	4-6PM	20,084	746,121	194,657,535	11	0.57
6th St. & Market	High-Density, Mixed-Use	9/16/09	Wed	71, sunny	4-6PM	6,024	352,524	91,971,119	18	1.96
California & Montgomery[1]	Central Business District	8/11/10	Wed	61, overcast with some sun	4-6PM	5,514	291,746	76,114,380	1	0.13
8th St. & Market	Central Business District	9/17/09	Thu	75, sunny	4-6PM	6,570	268,450	70,036,740	5	0.71
16th St. & Mission	Mid-Density, Mixed-Use	9/15/09	Tue	60, sunny	7-9AM	3,391	229,266	59,813,734	8	1.34
Beach & Hyde	Tourist Area	9/16/09	Wed	71, sunny, then foggy	4-6PM	4,062	188,761	49,246,433	4	0.81
3rd St. & Howard	Central Business District	9/8/09	Tue	66, sunny, windy	4-6PM	2,365	176,736	46,109,277	5	1.08
Columbus & Union[1]	Mid-Density, Mixed-Use	8/18/10	Wed	68, sunny, nice	4-6PM	3,462	168,496	43,959,283	5	1.14
Jackson & Powell[1,2]	High-Density, Mixed-Use	8/10/10	Tue	70, cloudy, cold	4-6PM	2,279	162,052	42,278,194	0	0.00
9th Ave. & Irving	Low-Density, Mixed-Use	9/15/09	Tue	60, sunny	7-9AM	1,192	159,490	41,609,697	2	0.48
Chestnut & Steiner[3]	Mid-Density, Mixed-Use	9/15/09	Tue	67, sunny	4-6PM	2,548	150,714	39,320,258	2	0.51
6th St. & Mission	High-Density, Mixed-Use	9/16/09	Wed	71, clear	4-6PM	2,198	123,154	32,129,983	11	3.42
Pine & Polk[1]	High-Density, Mixed-Use	8/24/10	Tue	90, hot, windy at times	4-6PM	1,551	99,357	25,921,547	4	1.54
7th St. & Folsom	High-Density, Mixed-Use	9/17/09	Thu	62, overcast	7-9AM	1,195	85,145	22,213,677	1	0.45
24th St. & Castro	Low-Density, Mixed-Use	9/15/09	Tue	67, sunny, then foggy	4-6PM	1,341	85,140	22,212,441	1	0.45
18th St. & Castro	Low-Density, Mixed-Use	9/10/09	Thu	80, clear	4-6PM	1,375	77,399	20,192,781	8	3.96
4th St. & Berry[1]	High-Density, Mixed-Use	8/19/10	Thu	69, clear, windy	4-6PM	1,155	73,989	19,303,280	0	0.00
Golden Gate & Jones	High-Density, Mixed-Use	9/17/09	Thu	62, sunny	7-9AM	1,071	73,910	19,282,515	12	6.22
25th Ave. & Geary	Low-Density, Mixed-Use	9/9/09	Wed	57, gloomy overcast	7-9AM	765	69,316	18,084,079	1	0.55
Mission & Silver[1]	Low-Density, Mixed-Use	9/17/09	Thu	68, clear, dry	4-6PM	1,374	64,331	16,783,415	9	5.36
Divisadero & Geary	Mid-Density, Mixed-Use	9/10/09	Thu	70, clear	4-6PM	1,808	61,906	16,150,812	4	2.48
Geneva & Ocean	Residential	9/10/09	Thu	80, sunny, warm	4-6PM	808	50,888	13,276,274	3	2.26
Embarcadero & Washington	Tourist Area	9/10/09	Thu	80, sunny, warm	4-6PM	1,008	47,739	12,454,733	2	1.61
Geary & Laguna	Mid-Density, Mixed-Use	9/16/09	Wed	60, overcast	7-9AM	487	38,467	10,035,755	3	2.99
JFK & Stanyan	Mid-Density, Mixed-Use	9/17/09	Thu	75, sunny, clear	4-6PM	831	34,661	9,042,810	0	0.00
19th Ave. & Taraval	Low-Density, Mixed-Use	9/9/09	Wed	64, foggy , cool	4-6PM	693	28,054	7,319,041	5	6.83
20th St. & South Van Ness	Mid-Density, Mixed-Use	7/20/10	Tue	65, partly cloudy[4]	4-6PM	565	25,724	6,711,325	0	0.00
25th St. & Harrison[1]	Low-Density, Mixed-Use	7/22/10	Thu	66, partly cloudy[4]	4-6PM	473	22,146	5,777,697	0	0.00
Randall & San Jose	Low-Density, Mixed-Use	9/16/09	Wed	60, foggy, chilly	7-9AM	533	18,275	4,767,935	2	4.19
Baker & Page[1]	Low-Density, Mixed-Use	8/11/10	Wed	61, foggy, not too cold	4-6PM	206	10,706	2,793,083	0	0.00
18th St. & Texas[1]	Low-Density, Mixed-Use	8/3/10	Tue	64, sunny, slight breeze, cool, pleasant	4-6PM	226	10,581	2,760,591	0	0.00
Buchanan & Page	Low-Density, Mixed-Use	7/28/10	Wed	65, sunny	4-6PM	214	10,133	2,643,601	1	3.78
Leland & Rutland[1]	Residential	8/3/10	Tue	64, overcast	4-6PM	191	9,252	2,413,811	0	0.00
6th Ave. & Lake[1]	Low-Density, Mixed-Use	8/5/10	Thu	65, foggy, cold	4-6PM	140	7,276	1,898,212	2	10.54
Bayshore & Oakdale[1]	Mid-Density, Mixed-Use	7/22/10	Thu	66, partly cloudy[4]	4-6PM	142	6,911	1,803,067	1	5.55
3rd St. & Jerrold	Low-Density, Mixed-Use	8/26/10	Thu	65, clouds, wind	4-6PM	121	5,844	1,524,613	1	6.56
Alemany & Mount Vernon[1]	Residential	8/10/10	Tue	70, cold, foggy	4-6PM	92	4,457	1,162,673	1	8.60
Beverly & Garfield[1]	Residential	8/10/10	Tue	70, cloudy, cold	4-6PM	91	4,408	1,150,036	1	8.70
34th Ave. & Ulloa	Residential	9/9/09	Wed	57, overcast	7-9AM	44	4,172	1,088,422	0	0.00
Walnut & Washington[1]	Low-Density, Mixed-Use	8/3/10	Tue	64, foggy, cold	4-6PM	69	3,586	935,547	0	N/A[5]
Athens & Cordova	Residential	8/11/10	Wed	61, fog, almost drizzle, windy, cold	4-6PM	51	3,381	882,161	0	N/A[5]
30th Ave. & Cabrillo	Residential	8/11/10	Wed	61, cloudy	4-6PM	49	2,771	722,837	0	N/A[5]
Sargent & Victoria	Residential	8/25/10	Wed	78, fair	4:30-6:30PM	36	2,704	705,538	1	N/A[5]
34th Ave. & Kirkham	Residential	8/17/10	Tue	68, sunny, breezy	4-6PM	60	2,612	681,557	1	N/A[5]
Evelyn & Juanita	Residential	8/25/10	Wed	78, semi overcast	4-6PM	88	2,511	655,008	0	N/A[5]
Kansas & Mariposa[1]	Mid-Density, Mixed-Use	8/26/10	Thu	65, sunny	4-6PM	50	2,434	634,883	0	N/A[5]
43rd Ave. & Anza	Residential	8/17/10	Tue	68, sunny	4-6PM	62	2,088	544,624	1	N/A[5]
Castenada & Pacheco	Residential	8/24/10	Tue	90, clear, hot	4-6PM	38	1,609	419,657	1	N/A[5]
Ingalls & Palou	Residential	9/17/09	Thu	75, sunny, clear	4-6PM	60	1,465	382,104	0	N/A[5]
Burrows & Hamilton[1]	Residential	8/10/10	Tue	70, sunny, windy, freezing	4-6PM	10	436	113,854	1	N/A[5]

1) No continuous data were available to estimate week adjustment factor at location. Week adjustment factor was generated from average values of other locations in same land use category with automated counts.
2) Location was counted for 1.75 hours (4:15 p.m. to 6:00 p.m.), so the 2-hour count has been extrapolated by multiplying the original count by (2/1.75).
3) Location is a 3-leg intersection, but the fourth leg (sidewalk side) is counted for comparison with other 4-leg intersections.
4) Weather observations for several sites were estimated from National Weather Service daily high temperature and general daily cloud cover information (http://www.nws.noaa.gov/climate/index.php?wfo=mtr).
5) Due to the infrequent nature of pedestrian crashes, a single crash can make a large difference in the crash rate, especially at intersections with low pedestrian volumes. Therefore, crash rates were not calculated for intersections with fewer than 200,000 estimated pedestrian crossings per year.

REGRESSION MODELING

Regression modeling was used to identify surrounding land use, transportation, infrastructure, neighborhood socioeconomic, and other physical environment characteristics having a statistically-significant association with pedestrian volume at the 50 study intersections.

Model Structure

A log-linear model form was chosen to represent the relationship between total annual pedestrian crossings and explanatory variables. This model was expressed as:

$$\ln Y_i = \beta_0 + \beta_1 X_{1i} + \beta_2 X_{2i} + \ldots + \beta_j X_{ji} \qquad (1)$$

where:
Y_i = annual pedestrian crossing volume at intersection i
X_{ji} = value of explanatory variable j at intersection i
β_j = model coefficient for variable j

The explanatory variable coefficients were estimated using ordinary least squares regression. The logarithm of the annual pedestrian crossing volume was used as the dependent variable in the model rather than the actual number of annual pedestrian crossings in order to avoid predicting negative values for low-volume intersections. Based on this model structure, the following equation was used to predict the total annual pedestrian crossings at any intersection in San Francisco:

$$Y_i = exp(\beta_0 + \beta_1 X_{1i} + \beta_2 X_{2i} + \ldots + \beta_j X_{ji}) \qquad (2)$$

where:
Y_i = estimated annual pedestrian crossing volume at intersection i
X_{ji} = value of explanatory variable j at intersection i
β_j = model coefficient for variable j

Explanatory Variable Selection

Sixteen explanatory variables were considered during the modeling process. Descriptive statistics for these variables (and two versions of the dependent variable) are shown below (TABLE 3).

TABLE 3 Variable Descriptive Statistics for 50 Study Intersections

Variable Name	Description	Mean	Std. Dev.	Minimum	Maximum	Source
Pedestrian Volume	Estimated annual pedestrian intersection crossing volume[1]	4,250,000	6,700,000	22,800	38,900,000	SF Municipal Transportation Agency (2009, 2010)
Natural Log of Pedestrian Volume	Natural logarithm of estimated annual pedestrian intersection crossing volume[1]	14.0	1.81	10.0	17.5	SF Municipal Transportation Agency (2009, 2010)
Total Population	Total population within 0.25 mi. (402 m) of the intersection divided by 100,000	0.0526	0.0363	0.00137	0.166	US Census and SF Planning Department (2000)
Total Households	Total number of households within 0.25 mi. (402 m) of the intersection divided by 10,000	0.227	0.163	0.0571	0.718	US Census and SF Planning Department (2000)
Number Zero Auto Households	Total number of households within 0.25 mi. (402 m) of the intersection without a car	1000	1400	26	5380	US Census (2000)
Proportion Zero Auto Households	Proportion of households within 0.25 mi. (402 m) of the intersection without a car	0.324	0.244	0.0694	0.860	US Census (2000)
Total Employment	Total number of jobs within 0.25 mi. (402 m) of the intersection divided by 100,000	0.0565	0.117	0.00368	0.753	Assn. of Bay Area Govts. (ABAG) projections (2010)
Population/Employment	Ratio of population to jobs within 0.25 mi. (402 m) of the intersection	3.64	3.22	0.0245	12.2	US Census (2000); ABAG (2010)
Retail Employment Mix	Proportion of total jobs that are retail jobs within 0.25 mi. (402 m) of the intersection	0.235	0.116	0.0552	0.515	ABAG (2010)
Muni Combined PM Peak Frequency Index	Combined frequency of Muni bus and rail within 0.25 mi. (402 m) of the intersection[2]	83.5	72.0	6.00	328	SF Municipal Transportation Agency (2010)
Number of Muni Stops	Total number of Muni bus and rail stops (by line) within 0.25 mi. of an intersection	51.1	37.0	6.00	205	SF Municipal Transportation Agency (2010)
High-Activity Zone	Intersection is in a "high-activity" zone (had metered on-street parking) (1 = yes; 0 = no)[3]	0.460	0.503	0	1	SF Planning Department parking meter data (2010)
Maximum Slope	Maximum percent slope of any approach to the intersection divided by 100	0.0752	0.0449	0.0200	0.180	SF Municipal Transportation Agency (2010)
Near a University Campus SF Planning Department	Within 0.25 mi. (402 m) of one of the 5 major campuses in San Francisco (1 = yes; 0 = no)	0.0800	0.274	0	1	SF Planning Department (2010)
Intersection Density	Number of intersections within 0.25 mi. (402 m) of the intersection[4]	50.5	24.9	23.0	148	SF Municipal Transportation Agency (2010)
Signalized Intersection	Intersection is controlled by a traffic signal (1 = yes; 0 = no)	0.580	0.499	0	1	SF Municipal Transportation Agency (2010)
Arterial Intersection	At least one approach to the intersection is designated as an arterial road (1 = yes; 0 = no)	0.440	0.501	0	1	SF Municipal Transportation Agency (2010)
High-Crime	Intersection had a crime rate higher than the average intersection crime rate[5]	0.26	0.44	0	1	SF Police Department (2009)

1) The pedestrian volume represents the sum of all crossings on each approach leg within 50 feet of intersection. The annual volume estimate is extrapolated from a two-hour manual count taken in September 2009 or July-August 2010. The extrapolation method accounts for variations in pedestrian activity by time of day, day of week, weather, and land use.

2) The Muni combined frequency index variable measures PM peak period Muni service frequency per hour for all routes that stop within 0.25 mi. of the intersection.

3) Intersections were designated as being in a high-activity zone if parking meters were present on at least one approach to the intersection. Parking meters tend to be sited in high-activity areas such as local commercial corridors.

4) Major university campuses in San Francisco were considered to be: University of San Francisco Lone Mountain, University of California San Francisco Parnassus, University of California San Francisco Mission Bay, City College Ingleside, and San Francisco State University Park Merced.

5) Crime rate is calculated as number of police-reported crimes within 0.25 miles (402 m) of the intersection in 2009 divided by the sum of population and jobs within 0.25 miles (402 m) of the intersection. Intersections with a rate higher than the average of all intersections were classified as high-crime.

A series of model runs was conducted to identify variables having a statistically-significant association with annual pedestrian volume at the study intersections. Variables were not included in the recommended model for the following reasons:

- Variables were correlated (two variables were considered correlated if their correlation coefficient was $\rho < -0.5$ or $\rho > 0.5$). A high level of correlation existed between some of the land use variables.
- Variable coefficients did not have precise estimates ($p > 0.10$). The variable for intersections located near a university was not within the threshold of statistical significance in the final model ($p = 0.15$), but it was theoretically important and significant in many of the other model runs, so it was included.
- Variables showed counterintuitive relationships with pedestrian volume (e.g., intersections in high-crime areas were positively associated with pedestrian volumes). These variables may have had indirect associations with pedestrian volume through other unmeasured variables.
- Variables had enough correlation with other variables to decrease the accuracy of their parameter estimates (e.g., intersection density).

The first stage of modeling generated 12 potential models of annual pedestrian intersection crossing volumes. Each model had between six and eight statistically-significant independent variable coefficients plus a constant. Each model included a different set of predictor variables, but all models included variables representing land use (population and/or employment) within 0.25 miles of the intersection, intersection located in a high-activity zone with metered on-street parking, maximum slope on an approach leg, and intersection located within 0.25 miles of a university.

Preferred San Francisco Pedestrian Volume Model

The 12 potential models had generally good fit (adjusted-R^2 values between 0.78 and 0.83) and were all significantly better than a model based only on a constant (F-values between 28.4 and 34.4). The final recommended model was selected because it had a combination of good overall fit and intuitive explanatory variables that would be useful for both evaluating existing pedestrian crossing risk and informing pedestrian safety policy and investment decisions (TABLE 4).

TABLE 4 Preferred San Francisco Pedestrian Volume Model

Dependent Variable = Natural Logarithm of Total Annual Pedestrian Intersection Crossings[1]			
	Recommended Model		
Model Variables[2]	**Coefficient**	**t-value**	**p-value**
Total households within 1/4 mile (10,000s)	1.81	2.12	0.040
Total employment within 1/4 mile (100,000s)	2.43	2.22	0.032
Intersection is in a high-activity zone	1.27	3.79	0.000
Maximum slope on any intersection approach leg (100s)	-9.40	-3.07	0.004
Intersection is within 1/4 mile of a university campus	0.635	1.45	0.154
Intersection is controlled by a traffic signal	1.16	4.03	0.000
Constant	12.9	33.29	0.000
Overall Model			
Sample Size (N)	50		
Adjusted R^2-Value	0.804		
F-Value (Test value)	34.4 (p < 0.001)		

1) The dependent variable is the natural logarithm of the annual pedestrian intersection crossing volume at each of the 50 study intersections. This represents the sum of all crossings on each approach leg within 50 feet of intersection. The annual volume estimate is extrapolated from a two-hour manual count taken in September 2009 or July-August 2010. The extrapolation method accounts for variations in pedestrian activity by time of day, day of week, weather, and land use.
2) All distances used to calculate the model variables are straight-line distances rather than roadway network distances.

Model Evaluation

Several analyses evaluated the quality of the preferred San Francisco Pedestrian Volume Model. First, the geographic distribution of the difference between model-predicted values and manual count values were reviewed for the 50 study intersections. This review showed that the model did not consistently overestimate or underestimate volumes in specific areas of San Francisco. Second, a sensitivity test was conducted to ensure the pedestrian volumes predicted by the model would respond reasonably to changes in explanatory variable values (TABLE 5). The model sensitivity was determined to be acceptable. These evaluation steps were also conducted on five other candidate models, and the results confirmed the selection of the preferred model.

Finally, the preferred model estimates were validated against pedestrian volumes collected at 49 four-way intersections in 2002 (*13*). These intersections were different than the 50 intersections used to develop the model. This comparison showed that the model ranked intersections similarly to the previous counts in terms of overall volume. Seven of the 10 highest-volume intersections based on counts were among the 10 highest-volume intersections based on the model; eight of the 10 lowest-volume intersections based on counts were among the 10 lowest-volume intersections based on the model. Yet, when viewed individually, there were notable differences (more than 50%) between the model volumes and count volumes at a majority of intersections. Despite differences at specific intersections, the overall correlation between the count-estimated volumes and model-estimated volumes (0.387) was significant (p < 0.01).

TABLE 5 San Francisco Pedestrian Volume Model Variable Sensitivity

Model Estimate based on median values for all variables[1]	1,050,378
Model Variables[2]	**Change in Model Estimate[3]**
Total households within 0.25 miles (402 m)	
Median value +20%	+6.56%
Median value +10%	+3.23%
Median value (1,755)	0.00%
Median value -10%	-3.23%
Median value -20%	-6.56%
Total employment within 0.25 miles (402 m)	
Median value +20%	+1.03%
Median value +10%	+0.51%
Median value (2,099)	0.00%
Median value -10%	-0.51%
Median value -20%	-1.03%
Intersection is in high-activity zone with parking meters	
Other value (1=Yes)	+256.09%
Median value (0=No)	0.00%
Maximum percent slope on any intersection approach leg	
Median value +20%	-10.67%
Median value +10%	-5.48%
Median value (6)	0.00%
Median value -10%	+5.48%
Median value -20%	+10.67%
Intersection is within 1/4 mile of a university campus	
Other value (1=Yes)	+88.70%
Median value (0=No)	0.00%
Intersection is controlled by a traffic signal	
Median value (1=Yes)	0.00%
Other value (0=No)	-218.99%

1) The model estimate represents the number of pedestrian crossings at an intersection with the median values for each predictor variable. The median values for each variable are: Total population within 1/4 mile (4,578), Total households within 1/4 mile (1,755), Total employment within 1/4 mile (2,099), Population/employment within 1/4 mile (2.57), Proportion retail employment mix within 1/4 mile (0.22), Muni combined p.m. peak frequency index within 1/4 mile (62), Number of Muni stops within 1/4 mile (41), Inersection is in a zone with parking meters (0), Maximum slope on any intersection approach leg (0.06), Intersection is within 1/4 mile of a university campus (0), Intersection is controlled by a traffic signal (1).
2) All distances used to calculate the model variables are straight-line distances rather than roadway network distances.
3) Change in model estimate represents the percentage difference between the model estimate using the median values for all variables (median model) and the model estimate using the median values for all variables except the adjusted variable of interest (adjusted model). For comparisons where the adjusted model estimate is greater than the median model, the percentage difference is calculated as (adjusted - median)/median. For comparisons where the median model estimate is greater than the adjusted model, the percentage difference is calculated as (median - adjusted)/adjusted.

Factors Associated with Pedestrian Volumes in San Francisco

The variables in the preferred San Francisco Pedestrian Volume Model identified the following relationships with pedestrian intersection volumes:

- Population density, as measured by the number of households within 0.25 miles (402 m) of an intersection, was positively associated with pedestrian volume. When a greater number of people live close to an intersection, more people are likely to pass through it.
- Employment density was positively associated with pedestrian volume. This suggests that when more people are working close to an intersection, more people are likely to pass through it.
- Intersections in high activity zones (e.g., with metered on-street parking) were positively associated with pedestrian volume. Metered parking areas tend to be pedestrian-oriented commercial corridors with limited opportunities for automobile access (i.e., driving from one store to another is less convenient than walking), so intersections in these zones may have relatively more pedestrian crossings than other areas. In addition, people may be more likely to walk through intersections in these zones because driving and parking is a more expensive option to access activities in the area.
- Steeper slopes on approach legs were negatively associated with intersection pedestrian volume. Walking up steeper slopes requires more physical effort, and steep slopes can be difficult to navigate using wheelchairs and other assistive devices, so fewer pedestrians are likely to pass through intersections in hilly areas. Hilly areas of San Francisco also tend to have less frequent transit service, so fewer people may be walking to access transit stops.
- Intersections that were within 0.25 miles (402 m) of a university campus had a positive (though not statistically-significant) association with pedestrian volume. University areas are typically major activity centers with limited automobile parking that serve students who may not own cars. Therefore, intersections near campuses may be likely to have more pedestrians passing through them.
- Intersections controlled by a traffic signal were positively associated with pedestrian volume. After controlling for other land use and intersection characteristics, pedestrians are more likely to cross at intersections that have signals than those that do not. Like the other significant associations identified in the model, this result may not indicate causation. For example, pedestrians may choose to cross at signalized intersections rather than other locations because signals provide regular breaks in automobile traffic. Alternatively, traffic signals may have been significant in the model because they may have been installed at locations where high pedestrian volumes already existed (i.e., signals are sometimes installed because they meet specific pedestrian volume warrants).

MODEL APPLICATIONS

The San Francisco Pedestrian Volume Model is being used by public agencies in San Francisco to understand pedestrian crossing risk and to inform citywide pedestrian safety policy and investment priorities.

Pedestrian Crossing Risk Assessment

A total of 2,533 pedestrian-related intersection collisions were reported throughout San Francisco between November 2004 and October 2009. These collisions occurred at 1,329 different intersections (FIGURE 3). Although the total number of reported collisions at an intersection provides useful information for identifying collision patterns, this absolute figure does not explain the probability of an individual pedestrian being involved in a collision at a given location. Locations with high quantities of pedestrians, such as dense, mixed-use urban areas, will typically have a higher total number of pedestrian-involved collisions than areas with fewer pedestrians because there is much greater pedestrian-vehicle interaction.

To estimate pedestrian crossing risk (i.e., number of pedestrian crashes per 10 million crossings) at each intersection, the annual pedestrian crossing volumes from the model were compared to the reported five-year crash data. None of San Francisco's top 20 intersections by absolute number of crashes was in the top 20 intersections by crossing risk (FIGURE 3). In general, intersections with high absolute numbers of pedestrian crashes were concentrated in the greater downtown area, but intersections with the highest crossing risk were distributed across San Francisco's outlying districts. On average, San Francisco intersections experienced 0.73 pedestrian crashes per 10 million crossings. The 20 intersections with the highest pedestrian crossing risk ranged from 50.6 to 22.6 crashes per 10 million crossings.

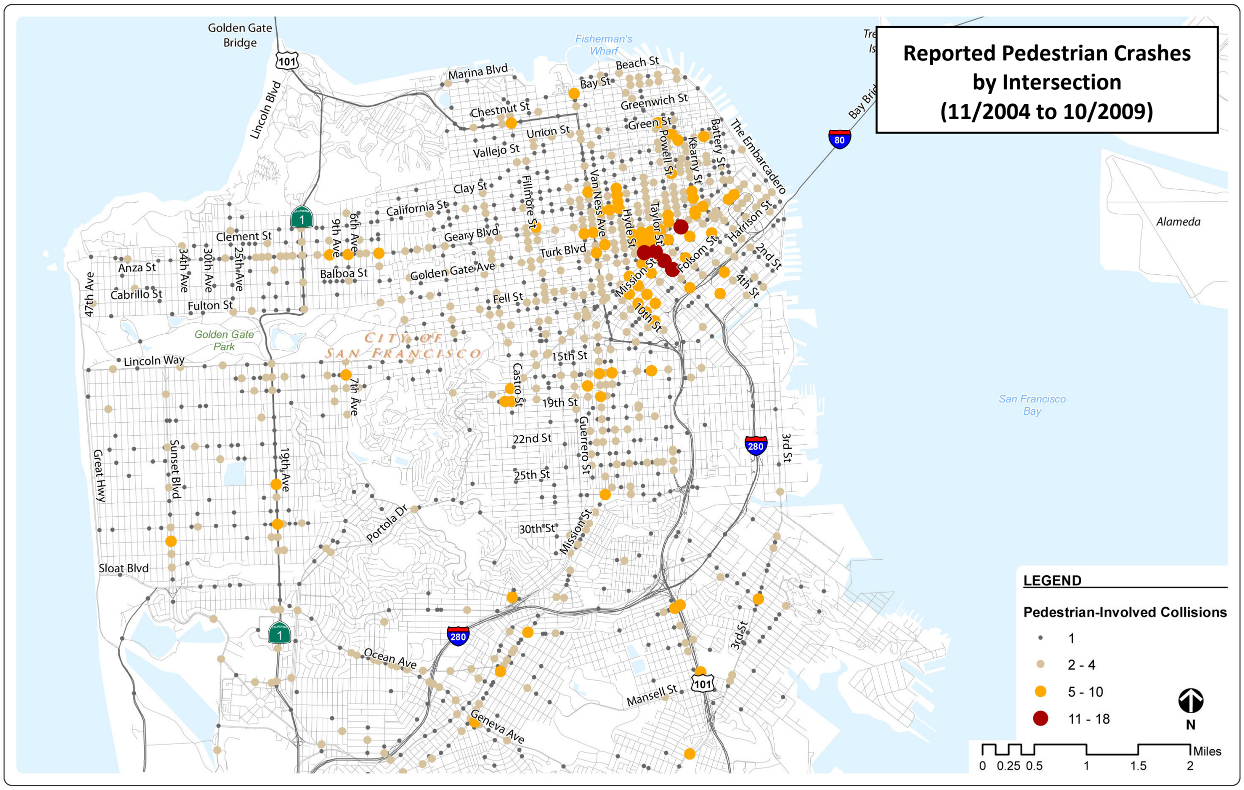
The SFMTA used the results to examine specific intersection locations with elevated risk. The 20 intersections with the highest crossing risk had the following characteristics:

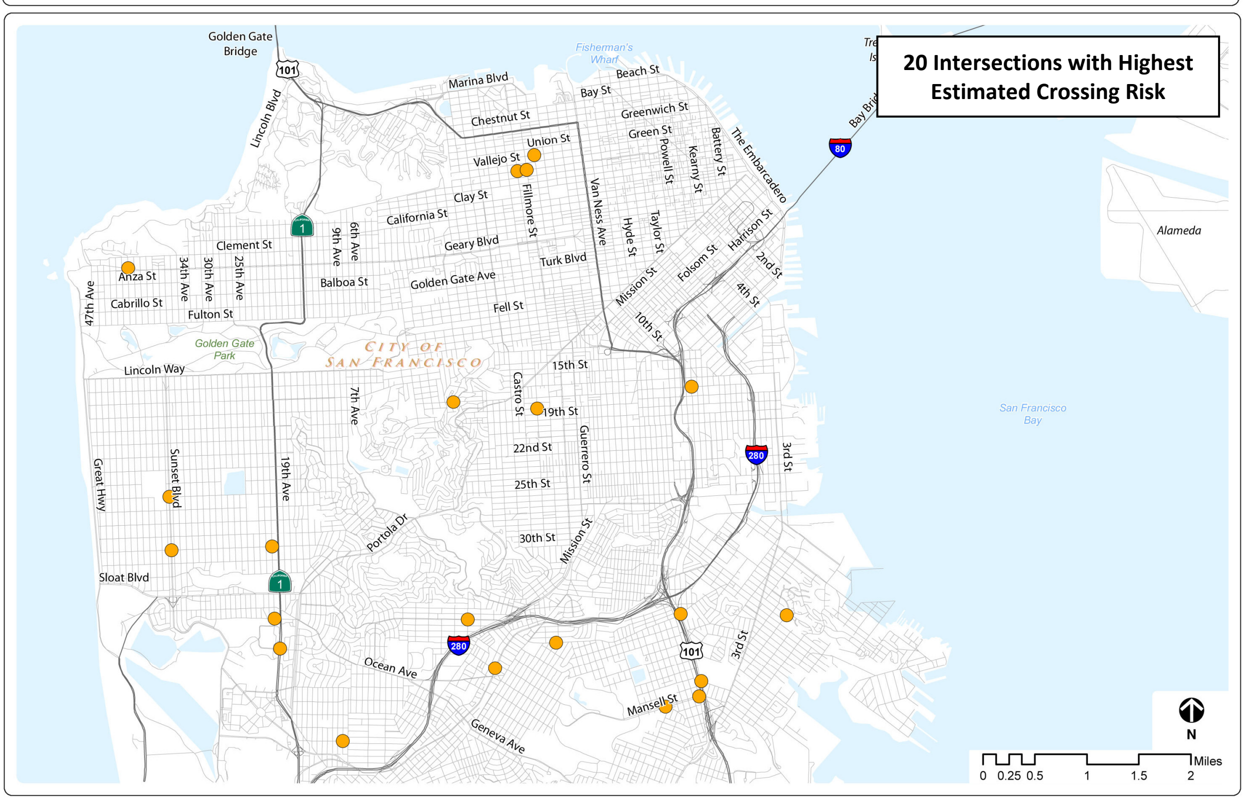
- Most were either unsignalized intersections with either all-way stop control or two-way stop control (e.g., had two uncontrolled crossings).
- Many were along multi-lane arterial roadways.
- Several were located near schools. This may suggest that the model underestimated pedestrian crossing volumes because it did not include a variable for proximity to schools. It may also suggest the need for pedestrian safety improvements near schools.
- Several were in areas with steep slopes.

The model results were also used to examine pedestrian crossing risk in specific types of locations, including signalized intersections. This separate list showed that many of the signalized intersections with elevated pedestrian crossing risk were on major arterial roadways and near on-ramps and off-ramps to freeways. Walking audits and detailed reviews of police crash reports at these and other high priority intersections could identify additional safety issues as well as opportunities for interventions and improvements.

The model is being used to identify and prioritize neighborhoods and corridors that might be under-represented in previous prioritization methods based only on reported pedestrian collision data. However, crossing risk calculated from the model is not the sole factor used to determine pedestrian safety improvement measures. Additional field analysis, public input, and engineering review are essential.

FIGURE 3 Reported Intersection Pedestrian Crashes and Estimated Crossing Risk





Citywide Pedestrian Policy Context and Implications

The SFMTA and the San Francisco County Transportation Authority (SFCTA) are currently working with other City agencies to develop a unified pedestrian policy and investment framework. This framework addresses diverse goal areas: safety (reduce pedestrian injuries and fatalities); functional pedestrian needs (provide basic accommodations for pedestrians of all abilities); the pedestrian realm (develop comfortable and inviting environments for walking); and sustainable growth (develop walkable, transit-oriented neighborhoods).

The pedestrian volume model helps planners and policy-makers take a balanced approach in advancing this multidimensional citywide strategy. Recent policy directives set targets for reducing severe and fatal pedestrian collisions by 25% within five years and by 50% within 10 years. Absolute levels of collisions are concentrated along arterials in the greater downtown. The geographic pattern of crash risk revealed by the model indicates the need to also address pedestrian safety in outlying districts, especially along a diverse set of arterial corridors in these areas.

Within the safety category, the framework must respond to three subcategories of need: 1) the need to reduce the absolute incidence of severe injuries and fatalities; 2) the need to improve walking conditions in areas with elevated crash risk and lower levels of pedestrian activity; and 3) the need to implement basic, effective safety measures (countdown signals, etc.) citywide. Prioritized interventions differ among these areas, with investments in the first subcategory focused on lower-cost, high-impact, innovative capital and operational strategies (paired with education and enforcement), while the second subcategory reflects a more traditional engineering design approach. The model informs geographic prioritization in each subcategory.

CONSIDERATIONS AND NEXT STEPS

The San Francisco Pedestrian Volume Model estimates are intended for planning, prioritization, and safety analysis at the community, neighborhood, and corridor levels. Since the model provides rough estimates of pedestrian activity, actual pedestrian counts should be used for site-level safety, design, and engineering analyses. In addition, the model may not perform well in locations close to special attractors, such as major parks, waterfronts, and sports arenas. Pedestrian volumes in these areas tend to be highly variable. Bridges and underpasses may also channel pedestrian activity, so more research may be necessary to adjust volume estimates near these features.

The model identified many statistically-significant relationships between the local environment and pedestrian volumes; however, the sample size (50 study intersections) was a relatively small number for regression modeling. Future efforts could increase the sample size and use a deliberate, stratified process to select study intersections representing particular combinations of land use, transportation system, and socioeconomic variables. Also, with additional time and resources, annual pedestrian volume estimates could be adjusted to account for seasonal differences in weather and school-related activity. This could refine the model equation and pedestrian exposure outputs.

The limited sample size and practical measurement constraints prevented including more explanatory variables in the preferred model. Relationships identified during the data analysis process but not incorporated in the model included:

- A more even balance between housing and jobs (represented by the ratio of population to employment near the intersection) was positively associated with pedestrian volume.
- Predominantly single-use residential areas may have lower pedestrian volumes because fewer activities are within walking distance of homes.
- Areas with more retail-related jobs were associated with higher pedestrian volumes. A high proportion of retail employment within 0.25 mile (402 m) of an intersection may be associated with more walking because these areas in San Francisco are often pedestrian-oriented areas with many storefronts adjacent to the sidewalk. These areas also tend to have on-street metered parking, which was a variable in the preferred model.
- Frequency of Muni transit service near an intersection during the peak hour was positively associated with pedestrian volume. Transit stops and stations attract a significant amount of pedestrian activity, so intersections near these locations are more likely to have a higher number of pedestrians than similar locations with poor transit access.

Other variables may also be related to pedestrian volumes. The following variables could be tested in future pedestrian model research:

- Overall land use mix.
- Special pedestrian generators, such as schools.
- Sidewalk width and buffer between roadway and sidewalk.
- Roadway width and number of motor vehicle lanes.
- Percentage of households with no vehicles available.
- Types of transit facilities (e.g., light rail stop versus bus stop).
- Presence of bicycle parking.
- Components of the San Francisco Pedestrian Environmental Quality Index (*21*) (e.g., traffic calming facilities, street trees, litter).

Unexplained variations in pedestrian counts are important to consider. A review of automated count data from the same hour of the week at 13 Alameda County sensors found that 95 percent of mid-day counts tended to be between 20 percent above and 20 percent below the mean value of that hour for the year-long study period. Less variation occurred between counts at times with higher pedestrian volumes and more occurred between counts at times with lower pedestrian volumes. Potential sources of variation from week to week include:

- *Weather conditions*. Weather adjustment factors were applied in both Alameda County and San Francisco to capture these components of pedestrian volume variation.
- *Measurement error*. Different people conducting pedestrian counts at different times may result in count variation.
- *"Unexplainable" variation*. This may include changes in neighborhood socioeconomic conditions and activity patterns, people choosing to walk along a different street on some days to experience different scenery, a store sale attracting more pedestrian customers for

a month, or other reasons. These variations are either too difficult or too expensive to quantify in a planning-level model.

The number of people walking in a particular community may also vary due to the overall condition of pedestrian facilities and attitudes towards walking in the community. These broader characteristics may change over time. Additional analysis in multiple communities could identify these broader geographic and social influences on pedestrian volumes.

Before developing the San Francisco Pedestrian Volume Model, the 2009 model from Alameda County (*12*) was tested. While the Alameda County model ranked the 50 San Francisco sample intersections similarly to actual counts from highest to lowest volume, its predictions were consistently lower than the actual counts. This suggested that it was important to develop a new pedestrian volume model based on San Francisco data. Future research could compare many of the intersection-based pedestrian volume models that have been developed in the last five years. Results could identify which models may be most applicable in communities that do not have resources to develop their own models.

CONCLUSION

The San Francisco Pedestrian Volume Model has a good overall fit, and it incorporates several variables that have not been included in previous intersection-based pedestrian volume models. Specifically, significantly higher pedestrian volumes are associated with intersections in high-activity zones with metered on-street parking, in areas with fewer hills, near university campuses, and controlled by traffic signals. Results will be used by public agencies in San Francisco to understand pedestrian crossing risk and to inform the development of citywide pedestrian safety policy and investment priorities.

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