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Space Syntax: An Innovative Pedestrian Volume Modeling Tool for Pedestrian Safety

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INTRODUCTION

There has been a significant increase in pedestrian research in the United States during recent years. This interest is the result of a growing awareness among urban planners and public officials that walking is vital to the health of cities and their residents, and that in general, Americans walk far too little. According to the US Department of Health and Human Services, at least 60% of American adults do not meet Surgeon General recommendations for 30 minutes of moderate-to-vigorous activity most days of the week. In addition, over 25% of American children are clinically obese (1). Physical inactivity is estimated to be responsible for more than 200,000 deaths annually and over \$77 billion dollars in direct health care costs each year (2).

While it is known that the majority of Americans are insufficiently active, the reasons are not fully understood. Much of the literature has focused on pedestrian safety as a major barrier to walking in American cities. In 2002, about 4,808 pedestrians were reported to have been killed in motor vehicle crashes in the US. An additional 80,000 pedestrians were reported injured in motor vehicle collisions, and such injuries are likely underreported (3). A significant amount of attention has therefore focused on pedestrian safety (4, 5, 6, 7). Several US cities have drafted their first pedestrian master plans in efforts to improve walk-ability and pedestrian safety, including Portland, Oregon, Cambridge, Massachusetts, and Oakland, California.

Some literature has explored the aspects of the physical and social environment that encourage or stimulate walking (8, 9). Physical factors such as residential population density, mixed land use, street connectivity, and adequate pedestrian facilities have been identified as key physical variables that influence the number and types of walking trips. Frank and Pivo found that increased vehicle transportation is associated with decreased levels of walking and biking, and that walking is positively associated with land use measures such as residential density, proximity of services, and high street connectivity (10). Moudon and colleagues found that neighborhoods with higher street connectivity, continuous sidewalk conditions, and small block size experienced an average of three times higher pedestrian travel than other neighborhood with similar population density, land use mix, and income, but which lacking these facilities (11). Physical design also affects the type and kind of walking trip in addition to the overall amount. Shriver found that three times more respondents walked to work in higher density mixed-use “traditional neighborhoods” and walked to do errands with 65% greater frequency than those in lower density neighborhoods with poor pedestrian facilities (12). Many other researchers have found similar connections between the built environment and pedestrian activity.

Despite increased understanding and interest, most urban planners and policymakers charged with making US cities safer and more walkable are forced to do so with limited tools and resources. Many US cities have access to pedestrian crash data through police reports, which give planners a detailed picture of the amount and location of pedestrian-vehicle collisions occurring each year. But without pedestrian volume counts to determine walking rates, this information paints an incomplete picture of actual pedestrian risk.

EXPOSURE AND RISK ANALYSIS FOR PEDESTRIAN SAFETY PLANNING

The Federal Highway Administration (FHWA) and the National Highway Traffic Safety Administration (NHTSA) recently identified four major areas of need in pedestrian planning (13). Among these, accurate pedestrian exposure data was identified as the least understood and most important area of research for pedestrian planners and decision-makers.

The term “exposure” originates from the field of epidemiology and is defined as the rate of contact with a potentially harmful agent or event (14). Applied to the world of transportation planning, pedestrian exposure is defined as a pedestrian’s rate of contact with potentially harmful vehicular traffic. Pedestrian exposure is therefore measured by pedestrian volume, as expressed in units of pedestrians per hour.

Many US cities have access to pedestrian crash data through police reports, which give planners a detailed picture of the amount and location of pedestrian – vehicle collisions occurring each year. But without pedestrian volume counts to determine walking rates, this information paints an incomplete picture of actual pedestrian risk. High volume intersections may experience a large number of collisions per year, but they may be relatively safer than intersections that experience less annual collisions but also less usage. This mismatch often results in funding

pedestrian planning projects based on the “squeaky wheel” principle instead of on objective data analysis (i.e., intersections with the highest rates of collision are given attention instead of those that experience the greatest risk).

Figure 1 demonstrates the concept of exposure as it relates to pedestrian risk. Intersection A experiences 10 collisions per year, with an average annual pedestrian volume of 10,000 pedestrians per year. Intersection B experiences 20 collisions per year, but has an average annual pedestrian volume of 100,000 pedestrians per year. Which intersection is the most dangerous? At first glance, it would appear that Intersection B is the most dangerous, with 20 collisions per year. This would be accurate, based on the absolute number of collisions alone. But dividing the annual number of collisions by the pedestrian volume rate (exposure) gives a measurement of relative risk and reveals that Intersection A experiences 0.001 annual collisions per pedestrian, while Intersection B experiences 0.0002 annual collisions per pedestrian. This approach reveals that Intersection A is actually the more dangerous intersection by volume, experiencing five times the likelihood of collision than Intersection B.

It can be seen that absolute collision data alone can provide an inaccurate or misleading picture of pedestrian risk when considered in isolation. It should be noted that utilizing collision rates a measure of risk provides an additional layer of interpretive data, but also has its own analytical limitations. Because pedestrian volume is often distributed non-linearly (with a few intersections experiencing a large percentage of total volume), the prevalence of low volume, low collision intersections can bias risk assessment towards these areas. Exposure is also technically distinct from risk, although these concepts are clearly related. For example, high exposure to low risk situations may not result in a harmful situation occurring. But low exposure to high-risk situations may result in greater likelihood of a harmful event occurring. It is therefore important to consider both factors when analyzing and interpreting pedestrian risk data and constructing pedestrian risk models.

USING SPACE SYNTAX TO PREDICT PEDESTRIAN VOLUME

Space Syntax is a suite of modeling tools and simulation techniques used to analyze pedestrian movement and to predict pedestrian volume. The model analyzes layout and connectivity of urban street grids to generate “movement potentials”, which it compares to sampled pedestrian counts at key locations and land-use indicators such as population and employment density. The resulting correlations can be extrapolated to predict pedestrian volumes on a street-by-street level for an entire city.

Space Syntax was created at the University College of London in the mid-1980s, and it has seen widespread use in planning projects throughout Europe and Asia. Over 300 articles and four books have been published using Space Syntax, and it has been used in a variety of high profile planning and transportation studies (15, 16, 17, 18). The method is currently employed by major development and planning firms such as Sir Norman Foster and Associates, SOM, Richard Rogers and Partners, and others. Despite its success, Space Syntax remains largely unknown in the US, although it offers many potential benefits to domestic planners.

Space Syntax was used in the city of Oakland, California, as part of their first pedestrian master plan. As part of this effort, the City sought to identify areas of high pedestrian risk to prioritize spending on streetscape improvement projects. Like many other US cities, Oakland had statistics derived from police reports. In California, the computerized system for storing and retrieving these data is known as the Statewide Integrated Traffic Reporting System (SWITRS). When geocoded in a GIS, the SWITRS database indicates the absolute number of pedestrian-vehicle collisions per year, on an intersection-by-intersection basis. In Oakland, it was found that the majority of collisions occurred within the downtown area.

Although analysis of SWITRS data identified where the greatest number of pedestrians had been hit, there was little information available on pedestrian volumes, creating an incomplete picture of pedestrian risk. To solve this problem, the Space Syntax pedestrian volume modeling approach was used to generate pedestrian volume estimates on a citywide level. These volumes were then compared to the existing crash data to create a more accurate measure of pedestrian risk.

METHODOLOGY

The city of Oakland is located directly across the bay from San Francisco. Oakland has a population of about 400,000 people. From a land use perspective, Oakland is part of a larger urban fabric that stretches uninterrupted to Berkeley in the north and to San Leandro to the south. Oakland's population is primarily middle and lower income and is extremely racially diverse.

Seven steps were taken to model pedestrian volume and exposure using Space Syntax. These were:

- Creation of a pedestrian route network base map
- Input base map for processing in Space Syntax software
- Addition of Census 2000 population density data
- Calibration of output using existing pedestrian counts
- Addition of 1997 Economic Census employment density data
- Creation of volume co-efficient and estimation of pedestrian volumes
- Comparison to SWITRS crash data to estimate pedestrian exposure and risk

The first step in modeling pedestrian volumes for Oakland was the construction of a pedestrian-network base map. To accomplish this, publicly available TIGER/line GIS centerline files were used to construct a detailed pedestrian route network of the entire 7,000 street, 56 square mile (145 square kilometer) area of the city. Interstates and similar pedestrian barriers were not included in the base map, although cut-throughs and pedestrian malls were added, based on field observation and inspection of publicly available digital orthophotography. No data were available on sidewalk presence or condition (factors which have been found to relate to pedestrian Level of Service demand). These variables were not included in the model. Figure 2 displays the street network used for Oakland's base map.

The completed pedestrian network was then converted to a readable format and input into the Space Syntax software for processing. The Space Syntax model treats pedestrian networks as a graph and utilizes topological analysis to analyze the mathematical properties of the network. Several variables are measured, but the most important of these are connectivity, mean depth, and relative asymmetry (also known as integration). Connectivity is defined as the number of nodes that connect directly to a given node. Mean depth defines the average number of steps from any node to any other node, and integration measures how easily accessible a node is from other nodes in the system. Relative asymmetry, henceforth referred to as "integration" as per Space Syntax convention, is the most important variable for pedestrian-volume modeling. The formula for calculating the integration of a network node is found in Equation 1,

$$I = \frac{2(MD - 1)}{k - 2}$$

where MD equals the mean depth of the entire system, and k equals the number of nodes within the system. This formula compares an ideally connected graph (one where each point connected to every other point) with the properties of the graph in question to determine a measure of accessibility for each node or intersection. Integration is derived from this value for each node in the system.

From a practical standpoint, the integration of a node within a pedestrian network has been found to relate empirically to the amount of utilization it receives (17). Higher connectivity nodes offer greater accessibility to a larger number of other nodes, resulting in proportionally greater utilization. This holds true in the urban context as well. Streets that offer greater access to large number of other streets act as conduits for more origin/destination pairs than streets with less connectivity. These streets consequently experience more utilization than less connected and accessible street. Integration is a quantitative measurement of this conductivity to pedestrian movement, also known as "movement potential".

A key assumption of this approach is that it assumes even population distribution across a pedestrian network, and all-point-to-all-point travel throughout the pedestrian grid. Although this is not often the case in the real world, the Space Syntax model can be modified to account for distortions caused by local traffic generators or attractors. To account for this variation, population density was added to the model using Census 2000 data at the

block-group level. This allowed for basic measurement of the influence of land use on pedestrian levels, as well as a more realistic distribution of trip origins and destinations. These files included population density, median household income, age, race, and other standard demographic characteristics. Figure 3 displays the population density of the study area with predicted volume counts from the processed Space Syntax model.

To evaluate the preliminary accuracy of the model and to translate its findings into pedestrian volume, citywide pedestrian counts from previous planning studies were added to the GIS as point files. Pedestrian counts from past planning studies were collected for a total of 94 counts at 42 different intersections. Counts were conducted continuously in two-hour segments on weekdays and weekends, between the hours of 7 A.M. to 9 A.M. and 4 P.M. to 6 P.M. Both the number of pedestrians and the turning direction of each pedestrian were also recorded. Counts were then averaged to estimate the average annual pedestrian volume for each intersection. A total of 670 intersections were analyzed, of which 42 had pedestrian-volume counts.

Preliminary correlation between predicted volumes and observed pedestrian counts resulted in a relatively low correlation ($R^2 = 0.56$, $p < 0.001$). Analysis of outlying data points revealed that many of the points within the central business district (CBD) fell significantly outside of the predicted regression line. It was hypothesized that this was due to the fact that a large number of people work in the CBD during the time pedestrian counts were conducted, but few people actually live in the CBD and were therefore not included in the Census 2000 population counts.

To account for this variation, employment figures from the 1997 State of California Economic Census were added to the population density. These data were only available at the zip code level, so employment density per census block was determined by dividing the total number of employees found in that zip code by the total area of that zip code. This resulted in an employee-per-square-mile measure for the entire zip code. This figure was then multiplied by the area of each block group within that zip code to determine the average distribution of employees per block group. The resulting employment-population density was added to the population density from the 2000 Census, producing a more accurate picture of the number of people present during peak hours. The application of population-density modifiers to the CBD using this approach resulted in a more significant correlation between predicted and observed pedestrian volumes ($R^2 = 0.7717$, $p < 0.001$).

This correlation was used to estimate annual pedestrian volumes for streets throughout the rest of the city's 670 intersections where pedestrian counts were not available. This was accomplished through the use of a "volume-coefficient", which translated population/employment density and integration values into quantitative estimates of pedestrian volume. This was done by analyzing the relative contribution of integration and density to the multivariate correlation described above. It was found that integration was responsible for approximately 55% of the correlation and density was responsible for approximately 45% of the correlation. This was referred to as the relative weight of each variable. These relative weights were then multiplied by each observed pedestrian count to attain a proportional distribution of pedestrians for both integration and density. This was called "proportional integration" and "proportional density". Thus, if 100 pedestrians were counted at an intersection, the proportional quantity associated with integration would be 55 pedestrians, while the proportional quantity associated with density would be 45 pedestrians.

Once observed-pedestrian counts were proportionally segmented based on integration and density, these values were divided by the actual integration and density values to obtain a "pedestrians per proportional integration" value. The same was done for density. The resulting "volume co-efficient" empirically linked integration and density values to observed pedestrian counts, allowing empirical pedestrian counts to be predicted from integration and density alone. The resulting pedestrian volume map displays predicted annual pedestrian volumes for each street in the city.

The final step in the pedestrian-risk analysis was the comparison of pedestrian volumes to citywide pedestrian crash data provided by the California Highway Patrol. Three years of California Highway Patrol pedestrian/vehicle collision data were added to the GIS. A total of 1,067 incidents at 730 intersections were utilized over a three-year period between 1996 and 1999. The total number of collisions at each intersection was divided by three to determine the average annual collision rate. Figure 4 illustrates the distribution of collisions throughout Oakland.

The final Relative Pedestrian Risk Index was created using the simple equation included in the following equation:

$$\text{Relative Risk} = \frac{\text{Annual Pedestrian - Vehicle Collisions}}{\text{Average Annual Pedestrian Volume}}$$

For each intersection, annual pedestrian – vehicle collisions were divided by exposure (represented by average annual pedestrian volume) to determine relative pedestrian risk.

FINDINGS

The results of this analysis are mapped in Figure 5. This map displays predicted volumes by street segment, with darker shades of grey representing higher volume streets. The highest pedestrian volumes were found in the downtown area, where streets accounted for nearly 5% of total citywide pedestrian volume, but only 1% of total street area. The mean annual pedestrian flow for downtown was 536,550 pedestrians year, although several main arterials exhibited much higher volumes. Other clusters of high pedestrian volume were found to the north and east of the recreational lake found just east of downtown, Lake Merritt.

Figure 5 also displays pedestrian risk as a function of annual pedestrian accidents divided by predicted peak-hour pedestrian rates. A list of the city’s “Dirty Dozen”, or 12 most dangerous intersections, was derived using this Relative Pedestrian Risk Index. Surprisingly, 10 of the 12 most dangerous intersections were clustered in the eastern area of the city, an area with relatively low pedestrian volumes. Of these 12, only one was in the downtown area. This finding suggests that although the highest volume intersections may be within the downtown area, these intersections are much safer than those in East Oakland because they accommodate a greater number of pedestrians with fewer pedestrian accidents, even though they may have a higher number of absolute pedestrian crashes.

Figures 6 and 7 provide detailed examples using two intersections: one in downtown Oakland and one in East Oakland. The first intersection examined ranked as one of the most dangerous intersections in downtown Oakland. This intersection experienced an average of three (3) pedestrian - vehicle crashes per year and an estimated annual pedestrian volume of 998,000 people per year. Dividing the number of annual accidents by the annual pedestrian volume found that this intersection experienced an average of 0.000003 collisions per pedestrian. In contrast, one of the most dangerous intersections in East Oakland experienced an annual average of four (4) pedestrian-vehicle collisions, but it had an average pedestrian volume of only 343,000 pedestrians per year. Although this intersection experienced a similar number of collisions as the downtown example, it carried approximately three times less pedestrian volume, resulting in a Relative Risk Index score of 0.000017 collisions per pedestrian. Pedestrians crossing at this intersection were approximately 5.6 times more likely to be involved in a collision than they were at the intersection in downtown.

Similar rates were computed for every intersection in the city. The final Relative Pedestrian Risk Index ranked each intersection in the city for risk, defined by the number of annual collisions per pedestrian.

DISCUSSION

The creation of the Relative Pedestrian Risk Index for the City of Oakland yielded two important findings. First, the Index demonstrated the utility of the Space Syntax modeling approach in filling an important gap in city officials’ knowledge by providing reasonably accurate estimations of pedestrian volume that would have been too costly or time intensive to obtain. Second, this approach highlighted the importance of pedestrian volume, pedestrian exposure, and relative risk for transportation engineers and pedestrian planners.

The first major finding of interest to planners and engineers relates to the details of the Space Syntax volume-modeling process. As discussed earlier, accurate pedestrian volume data is essential for planners to implement successful pedestrian policies. The pedestrian-modeling process using Space Syntax was able to fill this need using existing data with a minimum of additional input. The key inputs to this model, Census 2000 and employment statistics, are freely available online for nearly every major metropolitan city in the United States. Furthermore, many states collect data on pedestrian/vehicle collisions through highway patrol and local police reports. While it was still necessary to possess a limited number of pedestrian counts to calibrate the model, this

project utilized existing pedestrian counts that were gathered as part of past planning studies. (For cities without such counts, the Space Syntax method enables cities to conduct a small number of sample counts and then extrapolate these counts to the entire city.) A further benefit of the Space Syntax approach was its high level of detail. Unlike traditional travel-demand models, which often analyze traffic at the Traffic Analysis Zone (TAZ) or census tract level, Space Syntax allowed for a much more detailed level of prediction on an intersection-by-intersection or street-by-street basis. The model was also significantly less complicated than other advanced pedestrian-modeling packages such as Paramics, which uses micro-simulation, cellular automata, and other “agent-based” approaches requiring extensive preliminary programming. The Space Syntax combination of readily available data, reduced data requirements, and high analytical detail makes the system an appealing option for cities requiring pedestrian-volume measurement.

Despite its success, there were also several limitations to this approach. Utilization of pedestrian counts over a three-year period from multiple planning studies reduced the effectiveness of the initial volume estimations. These were corrected using elementary land-use variables such as residential and employment density, which added additional explanatory power to the model. Despite this, the Space Syntax model underestimated the volume of several high volume streets in and around the downtown area. Observations made on streets surrounding a large recreational park just east of downtown found that the park experienced over four times the predicted pedestrian volume. Anecdotal evidence indicates that the lake is a popular place for joggers during peak hours of the day, implying that street connectivity and population density alone cannot account for this variation. A similar phenomenon was observed on several of the busiest streets within the CBD. There are three underground train stations within downtown Oakland that connect the city to the surrounding region by way of the Bay Area Regional Transit (BART) system. These downtown stations experience high rider ship from employees working in the CBD. It is therefore likely that the model’s under prediction of these streets was related to their connection to regional mass transit systems. These observations reflect the findings of other pedestrian trip-generation literature that supports the theory that street connectivity is but one part of an integrated complex of variables affecting levels of walking activity that includes not only population and employment density, but land use mixture, trip purpose, and transit connections as well (20, 21, 22). It is recommended that specific additional pedestrian counts be conducted at the twelve most dangerous intersections (“The Dirty Dozen”) to further validate or falsify the findings of the Space Syntax model. Furthermore, a detailed sensitivity test would estimate the degree of variance in the predicted pedestrian volumes and improve the overall reliability of the Space Syntax model (23).

The second finding relates to the general relevance of pedestrian exposure for pedestrian safety planning and policy. It was found that using absolute collision statistics from the SWITRS database provided an incomplete and partially accurate picture of real pedestrian risk for the City of Oakland. Contrary to expectations, the most dangerous intersections in the city were not necessarily those with the highest number of absolute annual collisions. Many of the most dangerous intersections actually experienced lower annual incidences of collisions, but they also experienced low pedestrian volumes. High collision intersections tended to have a lower relative risk per pedestrian due to their increased pedestrian volume, making them safer than low collision, low volume intersections. It is known that the utilization of pedestrian collision rate can bias risk assessments to low exposure intersections. To guard against such bias, additional data collection and verification may be required to further test this measurement approach.

It can be concluded that high pedestrian exposure does not necessarily correlate to increased collisions and vice versa. The specific causes of these differences were not analyzed in this study, but they were likely due to a variety of factors. These factors probably relate to the specific conditions at each intersection and likely included automobile traffic and speed, street width, poor visibility, crossing time, signalization, or other pedestrian facility or human factor related variables. Nonetheless, it was surprising that there was little correlation between attributable and relative risk.

These findings suggest that the absolute number of collisions alone may misrepresent true pedestrian risk. Statewide SWITRS data provide a detailed picture of where collisions and fatalities occur, but without pedestrian exposure data, it is impossible to determine if high-collision intersections are actually the most dangerous. In many cases, high collision intersections experienced very high volume as well, implying that the high number of collisions was a function of the utilization they received and not a measure of safety. This raises several important policy questions. Is it more important to focus pedestrian-safety resources on high-risk, low-collision areas or on lower-

risk, but high-collision areas? Should planners' priorities be to reduce risk or save lives? Could more lives be saved with less money by focusing on the most risky areas? Which is approach yields more useful policy guidelines?

The answer to these questions depends upon local policy goals and planning efforts. Relative risk appears to provide a more accurate picture of the risk to individual pedestrians, while absolute risk appears to provide a more accurate picture of the number of lives lost and injuries incurred, regardless of usage. If the goal is merely to reduce the number of lives lost, irrespective of utilization, then absolute risk is a more suitable measure. If the goal is to increase safety based upon risk to the individual pedestrian or upon utilization, then relative risk is more suitable. To build a truly accurate picture of risk, pedestrian safety planners must be aware of the benefits and biases of both approaches and be committed to considering the entire picture when crafting pedestrian-safety initiatives. The value and impact of different mitigation schemes must also be weighed against both types of risk when considering intervention.

CONCLUSION

Future research opportunities will focus on integrating automobile volumes and speeds into the risk-modeling approach. It is well known that as vehicle speed increases, so does the risk to pedestrians. Although engineering solutions often reduce this risk, it is likely that there is strong relationship between pedestrian exposure, traffic volume, and collision incidence. This approach would allow planners to take a more proactive role in risk assessment when existing pedestrian/auto collision data like SWITRS are not available.

Additional improvements will also be made to increase the accuracy of the Space Syntax pedestrian-volume model by integrating more specific land-use characteristics such as those explored recently by Stonor, Arruda-Campos, and Smith (15). Additional analysis using the volume predictions generated in this project could analyze the relationship between pedestrian volume and a variety of other factors including criminal activity, retail behavior, and rates of physical activity and obesity. Many of these issues have already been or are already being explored by researchers in Europe and elsewhere (17, 19, 24, 25). It is likely that as Space Syntax develops, it will become easier to use and more analytically robust, offering an improved capability to make valuable contributions to the urban planning process in the United States.

Local governments are dedicated to protecting the health and safety of the public at large. Because governments and public officials operate in resource-limited environments, it is important that resources be directed where they will do the most good. The relative risk assessment methodology outlined in this article offers an effective approach to focusing pedestrian safety resources most effectively. The 2000 FHWA report, which discussed pedestrian exposure, concluded that "decision-makers require data." Better pedestrian data will raise the priority of pedestrian issues in city and subdivision planning and will increase the likelihood of pedestrian design projects getting funded. Better data can also make communities more aware of pedestrian issues, leading to increased advocacy and support. Finally, better data for professionals will result in better planning and a safer, more enjoyable urban experience.

ACKNOWLEDGEMENTS

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REFERENCES

1. U.S. Department of Health and Human Services. An Update: Prevalence of Overweight Among Children, Adolescents, and Adults: United States 1988-94", *Morbidity and Mortality Weekly Report* 46, p.199-202.
2. Koop, C.E. Physical Activity and Health: A Report of the Surgeon General. Centers for Disease Control and Prevention, 1996.
3. National Highway Traffic Safety Administration. *Traffic Safety Facts*. National Highway Traffic Safety Administration, 2002.

4. Zweig, C., Seiderman, C., Lagerway, P., Cynecki, M., Ronkin, M., and Schneider, R. H. *Pedestrian Facilities Users Guide – Providing Safety and Mobility*. Publication No. FHWA-RD-01-102, Office of Safety and Traffic Operations Research and Development, Federal Highway Administration (FHWA), 2002.
5. Knoblauch, R., Nitzburg, M., Dewar, R., Templer, J., and Pietrucha, M. *Older Pedestrian Characteristics for Use in Highway Design*. Office of Safety and Traffic Operations Research and Development, FHWA, Washington, D.C., 1995.
6. Campbell, B., C. Zegeer, H. Huang, and M. Cynecki. *Pedestrian Safety Research in the U.S.*, Federal Highway Administration., 1999.
7. Institute of Transportation Engineers, *Design and Safety of Pedestrian Fatalities*, Washington, D.C. ,1998.
8. Frank, L. and Engele, P. The Built Environment and Human Activity Patterns: Exploring the Impacts of Urban Form on Public Health, *Journal of Planning Literature*, 16(2), 2001, pp. 204–216.
9. Saelens, B., Sallis, J., Frank, L. Environmental Correlates of Walking and Cycling: Findings from the Transportation, Urban Design, and Planning Literatures. *Annals of Behavioral Medicine*, Vol. 25, 2003, pp. 80-91.
10. Frank, L. and Pivo, G. Impacts of Mixed Use and Density on Utilization of Three Modes of Travel: Single-Occupant Vehicle, Transit, and Walking. *Transportation Research Record 1466*, TRB, National Research Council, Washington, D.C., 1994, pp. 44-52.
11. Moudon, A.V., Hess, P, Snyder, M.C., Stanilov, K. Effects of Site Design on Pedestrian Travel in Mixed-Use, Medium-Density Environments. *Transportation Research Record 1578*, TRB, National Research Council, Washington, D.C., 1997, pp. 48-55.
12. Shriver, K. Influence of Environmental Design on Pedestrian Travel Behavior in Four Austin Neighborhoods. *Transportation Research Record 1578*, TRB, National Research Council, Washington, D.C., 1997, pp. 64-75.
13. NHTSA/FHWA Pedestrian and Bicycle Strategic Planning Research Workshops, Final Report, April, 2000
14. Rothman K J. *Modern Epidemiology*. Little, Brown, Boston, 1986.
15. Stonor, T., Arruda-Campos, M.B., Smith, A. Towards A Walkability Index. Presented at Walk21 3rd Annual International Conference, Donostia – San Sebastian, Spain, 2002.
16. Penn, A., B. Hillier, D. Banister, and Xu, J. Configurational modeling of urban movement networks. *Environment and Planning B-Planning & Design*, Vol. 25, No. 1, 1998, pp. 59-84.
17. Hillier, B. *Space is the Machine*. Cambridge University Press, Cambridge, England, 1996.
18. Desyllas, J. and Duxbury, E. Axial Maps and Visibility Graph Analysis: A comparison of their methodology and use in models of urban pedestrian movement. Presented at the 3rd International Space Syntax Symposium, Atlanta, Georgia, 2001.
19. Hillier, B. The Common Language of Space: A Way of Looking at the Social, Economic and Environmental Functioning of Cities on a Common Basis. <http://www.spacesyntax.org/publications/commonlang.html> Accessed, July 21st, 2003.
20. Cervero, R. and Radisch, C. Travel Choices in Pedestrian versus Automobile Oriented Neighborhoods. *Working Paper 644*, University of California at Berkeley, Berkeley, CA, 1995.
21. Landis, B., Ottenberg, R., and Vattikuti, V. The Roadside Pedestrian Environment: Toward A Comprehensive Level of Service. Paper 990570, TRB, National Research Council, Washington, D.C., 1999.

22. Kitamura, R., Mokhtarian, P. A. and L. Laidet. A micro-analysis of land use and travel in five neighborhoods in the San Francisco Bay Area. *Transportation*, Vol. 24, 1997, pp. 125-158.
23. Saltelli A., K. Chan K., M. Scott, Eds. *Sensitivity Analysis*. John Wiley & Sons Publishers, 2000.
24. Major, M.D., Stonor, T., and Penn, A. Passengers, Pedestrians and Shoppers: Space Syntax in Design. *Passenger Terminal World*, July, 1998.
25. Croxford, B., Penn, A., Hillier, B. Spatial Distribution of Urban Pollution. From *Proceedings of the Fifth Symposium on Highway and Urban Pollution*, Copenhagen, Germany, 1995.

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Figure 1 – Pedestrian risk as a function of exposure

Figure 2 – Study area pedestrian network

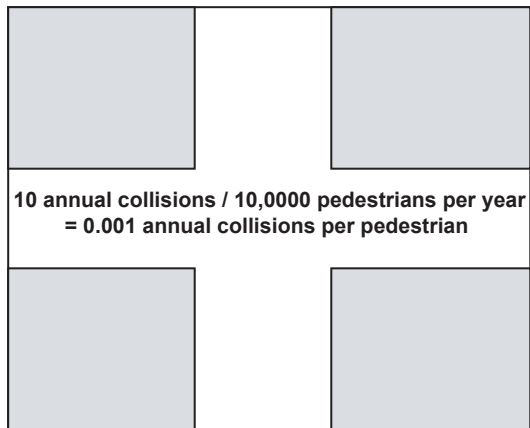
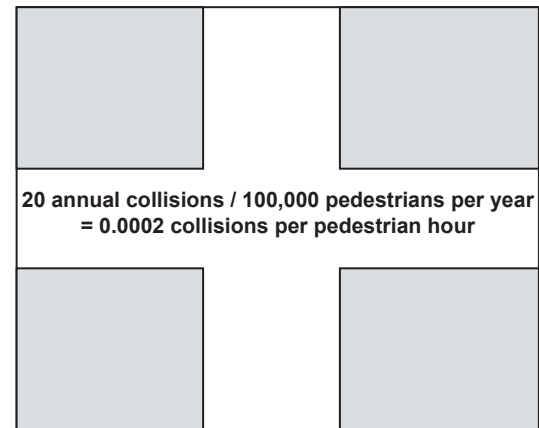
Figure 3 – Population density map

Figure 4 – Pedestrian – automobile collisions derived from the SWITRS database

Figure 5 – Final Relative Pedestrian Risk Index map

Figure 6 – Detail of pedestrian risk in downtown areas

Figure 7 – Detail of pedestrian risk in East Oakland area

FIGURE 1:**Intersection A****Intersection B**

Pedestrian risk as a function of the number of annual pedestrian – vehicle collisions divided by the amount of pedestrian exposure (pedestrians per hour).

FIGURE 2:

Pedestrian network for the city of Oakland, CA. Interstates and major pedestrian barriers were excluded from the model, and pedestrian malls, cut-throughs, and stairways were added.

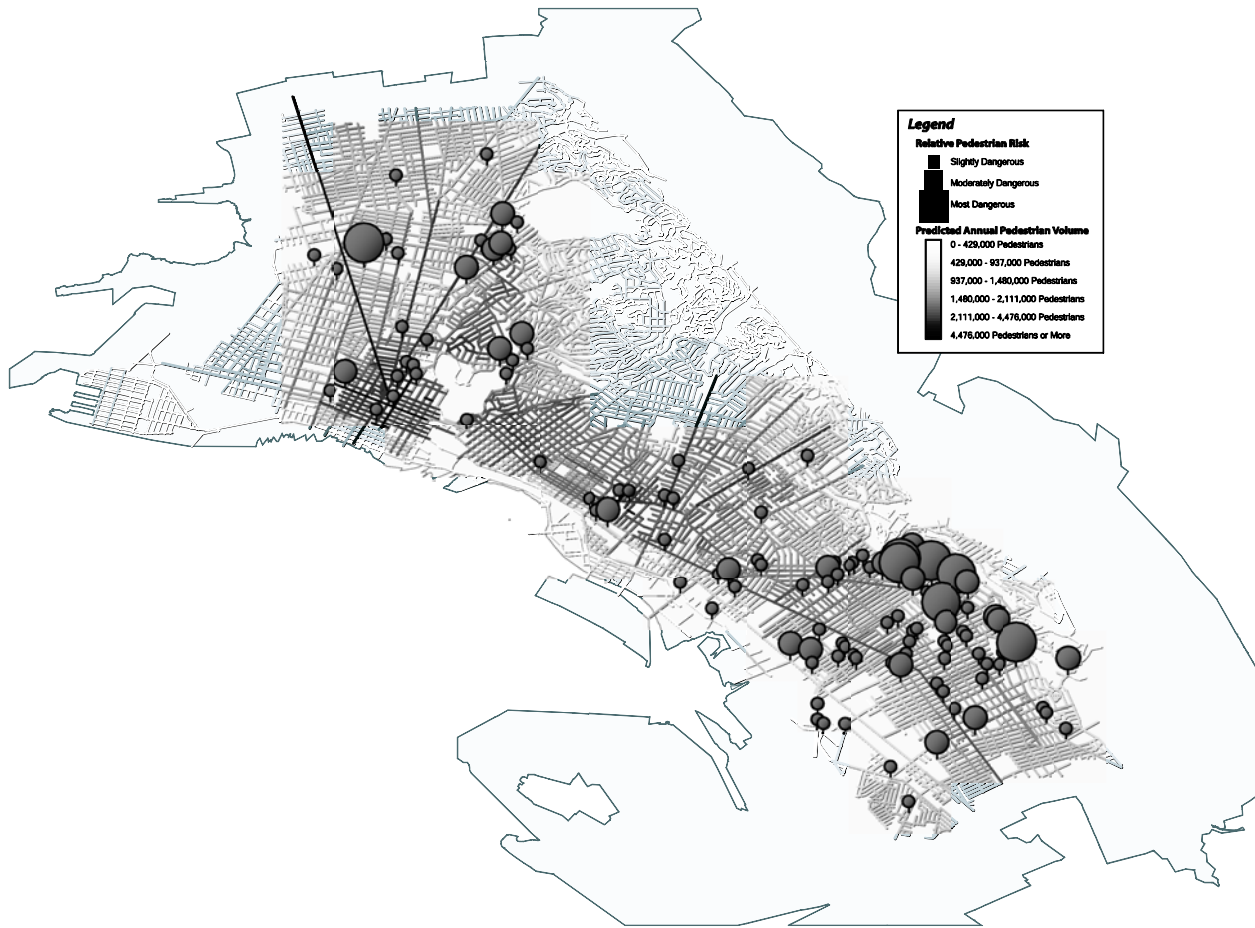
FIGURE 3:

Population density was added to the Space Syntax model using Census 2000 data to account for a more realistic distribution of trip origins and destinations.

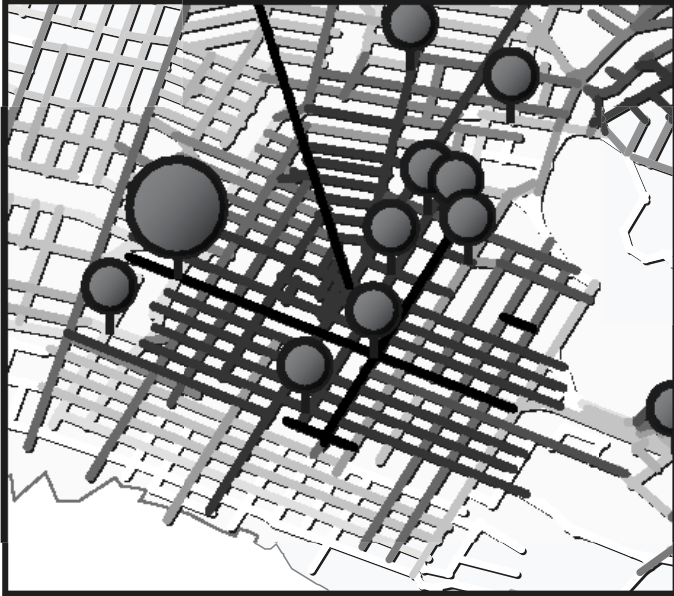
FIGURE 4:

Annual pedestrian – vehicle crashes as reported by the California Highway Patrol result in a detailed map of absolute pedestrian injuries. Note the concentration within the downtown area.

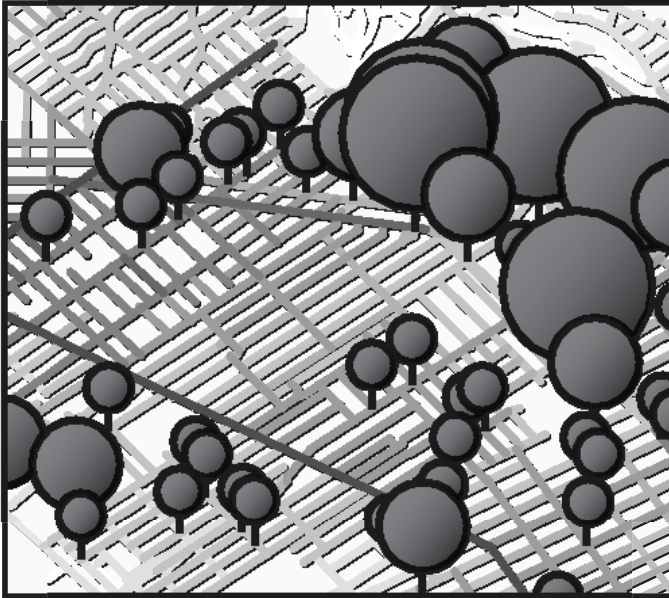
FIGURE 5:



Relative Pedestrian Risk Index. Predicted pedestrian volume is represented by shades of grey, with darker streets representing higher volumes. Balloons represent intersections with high relative pedestrian risk, expressed as a function of annual collisions per pedestrian.

FIGURE 6:

Intersections in downtown experience slightly more pedestrian – vehicle collisions per year than the intersection in East Oakland, but carry approximately three times more annual pedestrians, indicated a lower annual accident rate per pedestrian than that in East Oakland.

FIGURE 7:

Intersections in East Oakland experience both lower collisions, but also lower pedestrian volumes. In terms of relative risk, intersections in East Oakland are approximately 3.5 more dangerous than those in downtown.