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Modeling Toxic Corridors: A Metropolitan Phoenix Case Study Using TRI Data

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Abstract

This research assesses the geographic distribution of risk associated with the transfer of hazardous materials (hazmat) throughout metropolitan Phoenix. The Environmental Protection Agency's (EPA) Toxics Release Inventory (TRI) is used to identify the origins and destinations of hazardous materials for study years 1990 and 2000. Routes between these sites are traced via shortest path algorithms that are minimized with respect to: (1) travel time; (2) incident probability; (3) total population exposure; and (4) minority population exposure. Levels of risk are then allocated to areas adjacent to hazmat routes based on the specific volume and toxicity of the materials being transported. Negative binomial specifications are used to regress the number of hazmat shipments over community-level socioeconomic indicators in order to identify the various economic, environmental and social tradeoffs associated with the four routing scenarios. This research extends environmental equity research by using spatially explicit TRI data to model discrete pathways of hazardous materials and by offering a descriptive assessment of spatiotemporal variations in environmental risk in Phoenix along highway transportation corridors.

Keywords: Environmental justice; transportation networks; hazardous materials; economic efficiency; Toxics Release Inventory (TRI)

Introduction

Anthropogenic pollution has increased dramatically over the last several decades due, in part, to an upsurge in the production, storage, disposal and transport of toxic substances. In 2001, for example, over six billion pounds of toxic chemicals were released by large industrial producers in the United States (USEPA, 2003).¹ This number is likely to rise over time as the production of hazardous materials continues to grow in numerous sectors of national and global economies. Since the shipment of hazardous materials (hazmats) is an unavoidable part of the economic functioning of industrialized economies, it is expected that the population exposed to risks associated with hazmat transport will likewise increase (FMCSA, 2001).²

Despite the regulation, monitoring, and evaluation of toxic substances by federal agencies (e.g. the Environmental Protection Agency, Federal Drug Administration and Occupational Safety and Health Administration), only a fraction of these chemicals have been extensively studied with respect to their short- and long-term human and environmental health effects (Scorecard, 2004). Further complicating matters, both the human exposure pathways and the diverse media through which toxic hazards are released into the environment, are rarely straightforward. Many noxious materials arise from diffuse sources and are transported through the environment via complicated trajectories that make exposure scenarios difficult to predict.

Moreover, toxic hazards are unevenly distributed across space due to the geographically explicit patterning of physical infrastructure (e.g. roads and housing) which often juxtaposes residential areas and industrial sites. It has been well established in environmental equity research that exposure to technological pollution is frequently greatest in lower income and minority communities proximate to industrial facilities and waste disposal sites (Bolin et al., 2002; Bullard & Johnson, 1997; Buzzelli, Jerrett, Burnett, & Finklestein, 2003; Martinez-Alier, 2002). Given that the real and perceived risks of toxic exposure are individual-specific, locally contingent, and socially constructed (Ahearne, 1993), communities may respond differently to otherwise similar hazmat events. In short, documented uncertainties and social inequities prevail with respect to the management of environmental hazards and toxic emissions, in general, and of the risks of hazmat transfers, in particular.

¹ This is a conservative figure limited to firms that report to the Environmental Protection Agency's Toxics Release Inventory. The average annual sum of toxic releases into the environment is considerably greater.

² For example, the annual amount of hazmat shipments in 1997 exceeded 1.5 million tons. This number is forecasted to exceed 5 million tons over the next twenty-five years due predominantly to population growth and industrial advancements.

In what follows, we draw off both risk analysis and environmental justice studies to develop a theoretical and methodological framework for evaluating the functioning and performance of regional hazmat transfer systems. Section two applies this framework via a case study that examines the human risks associated with the transfer of toxic substances throughout metropolitan Phoenix over a ten year period. The article concludes with policy considerations for urban planners and other stakeholders concerned about the risks associated with hazmat transport.

Hazmat Risk Analysis

The modeling or optimizing of hazardous transport routes differs greatly from the cost-minimizing objectives of non-hazardous shipment routing. This is because hazmat incidents impose intensified risks—both real and perceived—on communities, in contrast to incidents involving non-hazardous materials. Hazmats, unlike other commodities, are potentially extremely harmful to ecosystems and human health when they are spilled or otherwise released into the atmosphere in an unregulated fashion. For this reason, it is important for planners to consider the underlying uncertainties and potential exposure inequities associated with the transfer of hazardous substances in populated areas.

A study by the Federal Motor Carrier Safety Association (FMCSA), for instance, assessed and compared risks associated with the transportation of hazardous and non-hazardous material shipments. Injuries and deaths, hazard mitigation, and environmental damage were among the costs considered in the study. The results show that hazmat transfers accounted for four to eight percent of all transported shipments in 2000. Costs incurred as a result of vehicular accidents involving hazmats have been estimated at \$1.2 billion.³ This is considerably less than the estimated \$43 billion incurred due to non-hazardous shipments accidents the same year. Nonetheless, the average cost of hazmat incidents on US highways was, on average, 58 percent greater than non-hazmat events (FMCSA, 2001).

Furthermore, media coverage of hazmat incidents sensitizes both the general public and regulators, to the dangers of transporting toxic materials (Erkut & Verter, 1998). Thus, in spite of the relatively low number of fatalities attributed to hazmat transport accidents—7 versus 42,815 highway fatalities in 2002 (US DOT, 2004)—modeling risk and developing hazmat transportation strategies is an important and difficult planning task. In particular, special attention must be paid to the potential risks that arise from transporting hazardous materials in heavily populated and

³ In this study, researchers analyzed two types of hazmat events—accidents and incidents. An accident occurs when a vehicle transporting hazardous goods is involved in a collision, regardless of whether any material is spilled or released in the atmosphere. An incident occurs when a vehicle transporting hazardous goods spills some of the cargo, but is not involved in a collision.

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environmentally sensitive areas. Urban areas present specific difficulties to emergency managers in cases where population evacuations are necessitated by acute hazmat incidents proximate to residential areas.

While researchers agree that there is a difference between the modeling of non-hazmat and hazmat routes, there is scant consensus with regard to what hazmat risk model is best. The most commonly used model is specified in the U.S. Department of Transportation's (US DOT) *Highway Routing of Hazardous Materials* report (USDOT, 1996). The model utilizes a path evaluation function where risk is the probability of a truck incident multiplied by a measure of the population exposed to the accidental release of a hazardous material. Or more generally:

$$\text{Risk} = \text{Probability} \times \text{Consequences} \quad (1)$$

The values yielded by Equation 1 reflect relative differences in the risk among routes. It does not attempt to exhaustively define a hypothetical accident nor calculate specific consequences (e.g. number of fatalities and injuries) associated with a release of specific hazardous substances. Rather, risk is generalized from incident probabilities associated with various road categories and population densities along the chosen route. The policymaker then selects among routes based on the estimated risk values of alternate paths for hazmat transport.

Erkut and Verter note that the relative risk values yielded by the above model are not intuitive because the product of probabilities and consequences is not easily interpreted by the public at large (Erkut & Verter, 1998). Furthermore, the risk values derived from the model do not account for the inherent social, political and economic differences among communities along hazmat routes which—according to most risk arbitragers, and, indeed, numerous state and federal directives—should be considered.

In response to the DOT model limitations, Erkut and Verter explore alternate methods to model risks involved in the transport of hazardous materials (Erkut & Verter, 1998). To do this, they apply five prevalent transport risk models—traditional risk, population exposure, incident probability, perceived risk, and conditional risk—in order to compare the selected optimal routes that each model generates between specific origin and destination pairs. The authors find that the assumptions and objectives underlying the alternative models differ greatly. For example, the population exposure model assumes that public opposition to hazmat shipments will be proportional to the size of the population exposed. Thus, the objective is to minimize population exposure in order to simultaneously curtail public opposition. In contrast, the incident probability risk model assumes equal population densities along routes and seeks only to minimize the probability of hazmat incidents irrespective of other considerations. An alternate perceived risk or risk aversion model uses both population densities and incident probabilities but flags specific route segments based on the perceived risks of potentially

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endangered communities. This is based on the assumption that policymakers prefer routes with high probability-low consequence incidents to routes with low probabilities and high consequences.

Most researchers suggest that no one model can or should be used for every hazmat routing decision. However there is general agreement that all risk models satisfy the following three axioms: (1) as one segment is linked to an existing route, the total impact of the route does not decrease; (2) all segments of an optimal path should themselves be optimal; and (3) increased probability or consequence on an edge cannot result in reduced path risk (Erkut, 2003; McMaster, Sheppard, & Leinter, 1997; Sheppard, Leinter, McMaster, & Tian, 1999). Most hazmat models, including the US DOT's traditional risk model, the incident probability model, the population exposure model, and the models implemented in this report, satisfy all three axioms.

Environmental Justice and Transportation

Transportation infrastructure is geographically explicit and the locations of major highway and railroad corridors can reflect urban planning decisions made over an extended historic period in a city's development. An inevitable result is that the benefits and costs of transportation investments are unequally distributed across communities. Accessibility to opportunities (e.g. jobs and shopping) and services (e.g. health care and education) is, in part, contingent on residential location and the functioning and performance of transportation systems. While proximity to major transportation routes is perceived as desirable for improving access to opportunities and services (Smith, 2003), it can also be a liability with respect to the associated exposure to air and noise pollution as well as potential transportation-related hazmat releases (Schwietzer, 2004).

US DOT's guidelines mention the need to consider "special" land uses and populations along hazmat shipping routes. These guidelines state that careful forethought should be used when optimizing hazmat routes in order to minimize potential risks to "schools, sports stadia, hospitals, prisons, and senior citizens homes" (USDOT, 1996). This suggests that routing decisions should recognize both vulnerable populations (e.g. elders and children) and populations that cannot be easily evacuated in the case of a hazmat release. These criteria, however, do not identify other populations of concern when environmental justice criteria are considered. In response to a growing grass-roots environmental justice movement in the US, a number of different federal policy changes were instituted in the 1990s. Of particular importance was Executive Order 12898 signed into law by former President Clinton in 1994. The order mandated that:

"[t]o the greatest extent practicable and permitted by law, and consistent with the principles set forth in the report on the National Performance Review, each Federal agency shall make achieving environmental justice part of its mission by identifying and addressing,

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as appropriate, disproportionately high and adverse human health or environmental effects of its programs, policies, and activities on minority populations and low-income populations in the United States.”

All major federal agencies were directed to establish guidelines that would follow the spirit of the order in their activities and the Environmental Protection Agency (EPA) established a special office of Environmental Justice to oversee compliance with the executive order. The US DOT issued their final environmental justice directive in 1997, requiring four actions to take place as part of all federally funded transportation-related programs: (1) identify and evaluate environmental, public health, and interrelated social and economic effects; (2) propose measures to avoid, minimize, and/or mitigate disproportionately high and adverse environmental and public health effects and interrelated social and economic effects; (3) consider alternatives when they would enable disproportionately high and adverse effects to be avoided and/or minimized; and (4) elicit public involvement including soliciting input from affected minority and low-income populations, to consider alternatives.

Not surprisingly, application of the US DOT initiatives in the routing of toxic transfers is rare given the present uncertainties and controversy concerning, among other issues, levels of exposure and their associated health effects and what is meant by disproportionate environmental burden across demographic groups. Given that physical transportation infrastructure cannot be easily relocated, hazmat routing will likely continue through existing paths. As a result, the total avoidance of impacts on special land uses, minorities and low-income communities cannot be easily accomplished using existing highway infrastructure.

Nonetheless, recent studies have made attempts to construct quantitative methods for evaluating environmental justice impacts of transportation corridors and the movement of hazardous materials. Mills and Neuhauser, for example, used demographic data to compare two alternative hazmat routes in the San Francisco area (Mills & Neuhauser, 2000). For each route, the ratio of minority to total population was computed for all census blocks lying wholly or partially within a half-mile exposure or buffer zone of the route in order to estimate disproportionate impact. Forkenbrock and Schweitzer also attempted to operationalize the US DOT environmental justice guidelines via a Waterloo, Iowa case study. The authors used census block data and two EPA air dispersion models to measure pollution and estimate exposure to disadvantaged groups along transportation routes (Forkenbrock & Schweitzer, 1999).

However, transportation-related environmental justice studies are still relatively rare (Bullard & Johnson, 1997). In their comprehensive review of GIS-based environmental equity and risk assessment, McMaster et al (1997), pointed out that most environmental justice research focuses on the impacts of fixed hazardous facility sites (McMaster et al., 1997). Bolin et al, for

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example, studied the distribution of technological facilities and hazardous waste sites in the metropolitan Phoenix area in relation to the demographic composition of adjacent neighborhoods (Bolin et al., 2002). That study illustrated the disparate locations of Treatment Storage and Disposal Facilities (TSDF) in relation to TRI sites but did not track the movement of hazardous materials among sites. The lack of detailed data on the transportation of hazmats, according to McMaster, is one of the primary limitations of studies using point-source hazards in calculating environmental justice impacts.

Another limitation of environmental justice research is the lack of longitudinal data available to assess changes in risk distributions over time. Buzzelli et al, for example, contend that environmental inequities result from a “complex web of social relations, including planning practices, racialized job markets, and housing” that is in constant flux both spatially and temporally (Buzzelli, Jerrett, Burnett, & Finklestein, 2003: p.558). This suggests that, there is a need to develop methodological approaches for monitoring shifts in the geographic distribution of environmental hazards and measures of their environmental justice impacts over time. The case study developed here attempts to address these limitations by performing an analysis of intra-regional hazmat shipments in the metropolitan Phoenix area for the years 1990 and 2000, examining the environmental justice implications of hazardous materials moving across urban space.

Metropolitan Phoenix Case Study

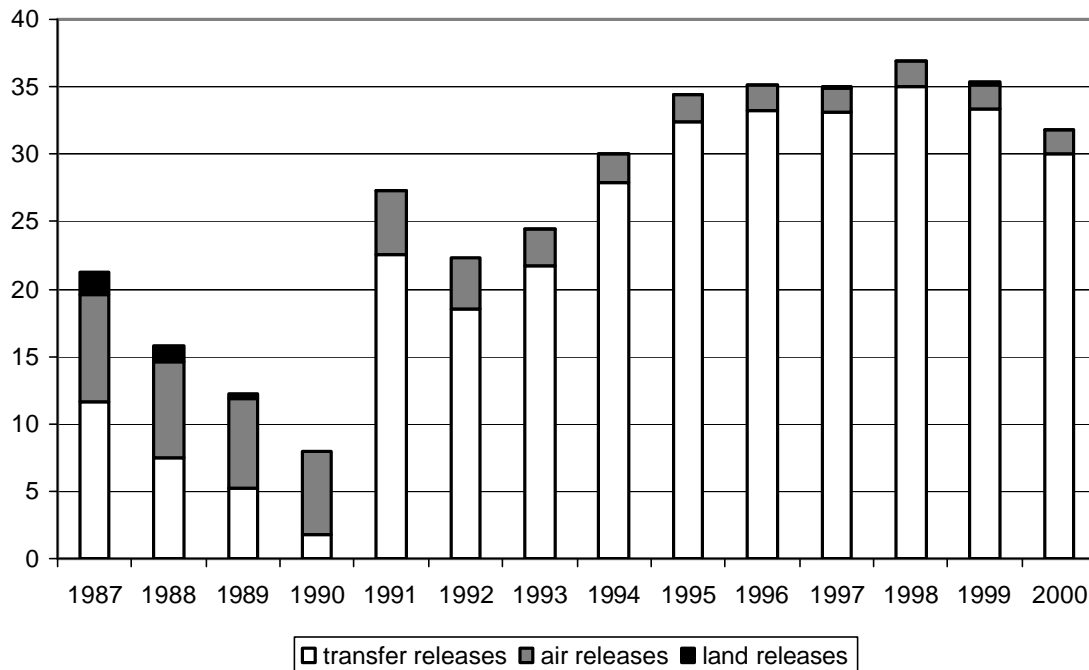
We begin by describing the data and methods used to construct an environmental risk model for hazmat transportation in the context of metropolitan Phoenix, Arizona. We also tabulate the results of nested negative binomial regression models that explain ecological variations between four alternative hazmat risk exposure scenarios. There are three major objectives in developing this case study. The first is to identify intra-regional flows of hazardous materials considering both the volume and the toxicity of shipments. The second is to assess hazmat transport exposure among different socioeconomic groups in order to identify environmental justice concerns. The third is to examine how the environmental equity patterns change over time.

Metropolitan Phoenix, with a current population in excess of 3.2 million and an urbanized area of more than 2000 sq. km. is an appropriate setting for examining intra-regional hazmat transport risk. First, it is a large urban center and among the nation’s leaders in population and economic growth. Second, its limited rail network relegates most hazmat shipments to be conveyed via its rapidly expanding intraurban highway system, thus easing the network modeling assumption that hazmats are transferred over street segments. Furthermore, historical TRI data show that a majority of monitored toxic substances by volume are transferred offsite for management and disposal rather than being directly released into the environment at the point of production (Figure 1). This suggests that for a

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given TRI reporting year millions of pounds of hazardous substances are being moved between sites in Phoenix.

**Figure 1. Volume of Toxic Chemicals by Release Type, 1987-2000
Maricopa County, Arizona (In 1,000,000 lbs increments)**



Data Source: Environmental Protection Agency TRI, 1987-2000

Greater Phoenix also shares some common social and physical development patterns with its eastern and Midwestern metropolitan counterparts. For example, the area has a long history of institutional racism, including mandated race-based residential segregation that, in the post-Civil Rights Era has transitioned into *de facto* residential racial and ethnic segregation which is still conspicuously present in the metropolitan area today (Luckingham, 1994). As with other urban areas in the US, federal dollars have been instrumental in shaping the spatial configuration of transportation and housing land uses in Phoenix through federal highway administration grants, public housing programs, and other federal grant and loan programs (Norquist, 1998).

However, unlike industrial cities of the US 'rustbelt', Phoenix lacks a concentrated zone of 'Fordist' heavy industry or their adjacent working class neighborhoods (Bolin et al., 2002). Phoenix does have a zone of mixed industrial uses adjacent to its historic rail corridor south of the Central Business District. This zone is adjacent to South Phoenix, the city's long-standing area of Black and Latino neighborhoods, a district now bisected by major freeway corridors. While there is industrial concentration near the CBD, more recent industrial development, particularly in electronics and semiconductor manufacturing have been in suburban locations. The bulk of Phoenix's hazardous waste handling facilities (Treatment, Storage, and Disposal Facilities or TSDFs) are located in the older industrial corridor near the central city, requiring movement of hazardous wastes toward the urban

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core for facilities seeking to use the TSDFs (Bolin et al., 2002). These factors make Phoenix an ideal case study to examine the environmental justice implications of hazmat transportation.

Data

EPA's Toxics Release Inventory

The EPA's Toxics Release Inventory (TRI)—established in 1986 by the Emergency Planning and Community Right-to-Know Act (EPCRA)—provides the most comprehensive, spatially explicit and systematic information for modeling regional hazmat shipments. High-level summaries of these data provide the volumes (in pounds) of toxic releases by facility, chemical and release type (i.e. land, air, water). TRI data also include street addresses of the origins and destinations of off-site hazmat transfers which can be used to model discrete transportation network paths. Lastly, TRI data are available for every year since 1987, thus making it easier to perform longitudinal analyses.

However, the number of chemicals that facilities were required to report to the EPA's TRI increased considerably between 1990 and 1993. The original 1990 TRI chemical list comprises nearly 250 chemicals but additional chemicals were added in each of the years 1991, 1992 and 1993. Presently, facilities are required to report on approximately 650 chemicals referenced in what is commonly called the third CERCLA (Comprehensive Environmental Response, Compensation, and Liability Act) list. For this study the 1990 and 2000 datasets were standardized to the 1990 TRI chemical list in order to facilitate meaningful comparisons over time. As such, our approach is conservative as we do not include new chemicals from the 2000 data set which are now part of hazmat flows.

Scorecards Toxic Equivalency Potentials

As stated above, the 1990 TRI chemical list reports releases of approximately 250 different substances. Since it is not feasible to run a separate transport risk model for each chemical, the toxicity of each substance was standardized according to its toxic equivalency potential (TEP). Scorecard's TEP rating is defined as the ratio of the risk posed by the release of one pound of chemical *x* to the risk posed by the release of one pound of a reference chemical, in this case, toluene (Scorecard, 2004). The TEP considers mode of release (air or water), the concentration or dispersion tendencies of each chemical, its cumulative effects on populations exposed. It is based on CalTOX, a scientifically established and highly regarded fate and exposure model for toxic chemicals (Scorecard, 2004) For example, the noncancer risk posed by 414 pounds of mercury (the total volume of mercury released by metropolitan Phoenix facilities in 2000) is equivalent to 2.3×10^8 pounds of toluene. These standardized measures of toxicity are used to estimate the degree of risk TRI chemicals pose on human populations when released into the environment.

Census and Incident Probability Data

Standard TIGER/Line files for the years 1990 and 2000—made available by the US Census Bureau—were used to model the metropolitan Phoenix transportation network. The road quality attributes and spatial data provided in this dataset were input into a geographic information system (GIS) and used to estimate travel costs by road segment. Speed limits and incident probabilities—derived from the national Hazardous Materials Information System or HMIS—were assigned to network segments based on road categories identified by Census Feature Classification Codes (CFCCs). Travel times in minutes were then calculated based on the length of each segment. Table 1 presents the average speeds and accident, incident and release probabilities for each major road category in the TIGER dataset.

Table 1. Speed Limits and Risk Probabilities by Road Category (per million miles traveled)

Road Category (CFCC)	Description	Average Speed	Accident Probability	Incident Probability	Release Probability ¹
A1	Primary highway with limited access	65	2.8	0.062	0.14
A2	Primary highway without limited access	50	13.02	0.055	0.77
A3	Secondary and connecting road	35	8.66	0.069	0.60
A4	Local, neighborhood, rural road	25	8.66	0.069	0.60

Data Source: HMIS, 2000

Note: ¹ Release probability is the product of the two mutually exclusive events: namely accident probability (the probability that a vehicle transporting hazardous goods is involved in a collision) x incident probability (conditional probability that a vehicle transporting hazardous goods spills cargo due to a collision).

TIGER/Line census geographies were also input into a GIS in order to examine 1990 and 2000 demographic compositions by census tract. The 1990 census tract geography for Maricopa County comprises 466 tracts while in 2000 the number of tracts totaled 663. For this analysis, the 2000 census data were aggregated to 1990 tracts using an areal weighting procedure (Simpson, 2003) to ensure geographic consistency over time. Demographic data for 1990 and 2000 were acquired from the decennial census Summary Tape Files 3A. Census 2000 block group-level geographies and demographic data were used to construct variables for the negative binomial regressions because of their fine-scale spatial resolution.

Methods

The initial step was to estimate four sets of network paths or routes based on the TRI offsite transfer data for the years 1990 and 2000. These data include 480 geocoded origin-destination pairs that represent unique chemical transfers between facilities by year.⁴ These paths were minimized with respect to: (1) travel time; (2) release probability; (3) total population exposure; and (4) minority population exposure. Under each criterion, the routing problem for the origin-destination pairs was estimated using a shortest-path algorithm or, more formally, the Dijkstra shortest-path implementation provided in the Network Analyst extension of ArcGIS 9.0 (ESRI, 2004).

While the estimation of network paths based on travel time is widespread and relatively straightforward, clarifications concerning the release probability, total population exposure and minority population exposure models are in order. The release probability network model assumes that the likelihood of a hazmat release is constant along each link segment s (Note, however, that risk probabilities do vary by quality of link segment as shown in Table 1). For each route r , risk probability was calculated with respect to Equation 1 below:

$$\sum_{s=1}^r l_s P_s \quad (1)$$

where l is the segment length, and P is the probability of having a hazmat release.

In contrast, the total population and minority population exposure shortest-path algorithms establish routes based on the characteristics of residential communities adjacent to road segments. Each offsite-transfer path developed under these scenarios minimize either total or minority population exposure without any consideration for travel time or release probability. Another notable assumption for all models is that offsite transfers were transported by vehicle over the regional road system.⁵ This is a valid assumption given Phoenix's limited rail network and also that 98.6 percent of

⁴ While the TRI datasets do provide origin and destination addresses for hazmat transfers by chemical and year, they do not provide information concerning the number of shipments between these facilities. Therefore, each unique transfer-chemical-year combination was assumed to be transferred in a single shipment regardless of the volume of release. While this does not change the estimated volume and toxicity allocations in the exposure models, it likely underestimates the number of shipments.

⁵ Phoenix's Deck Park Tunnel is the only Maricopa County roadway where hazmat shipments are restricted (West, 2004). The two-mile road segment was removed from the network model.

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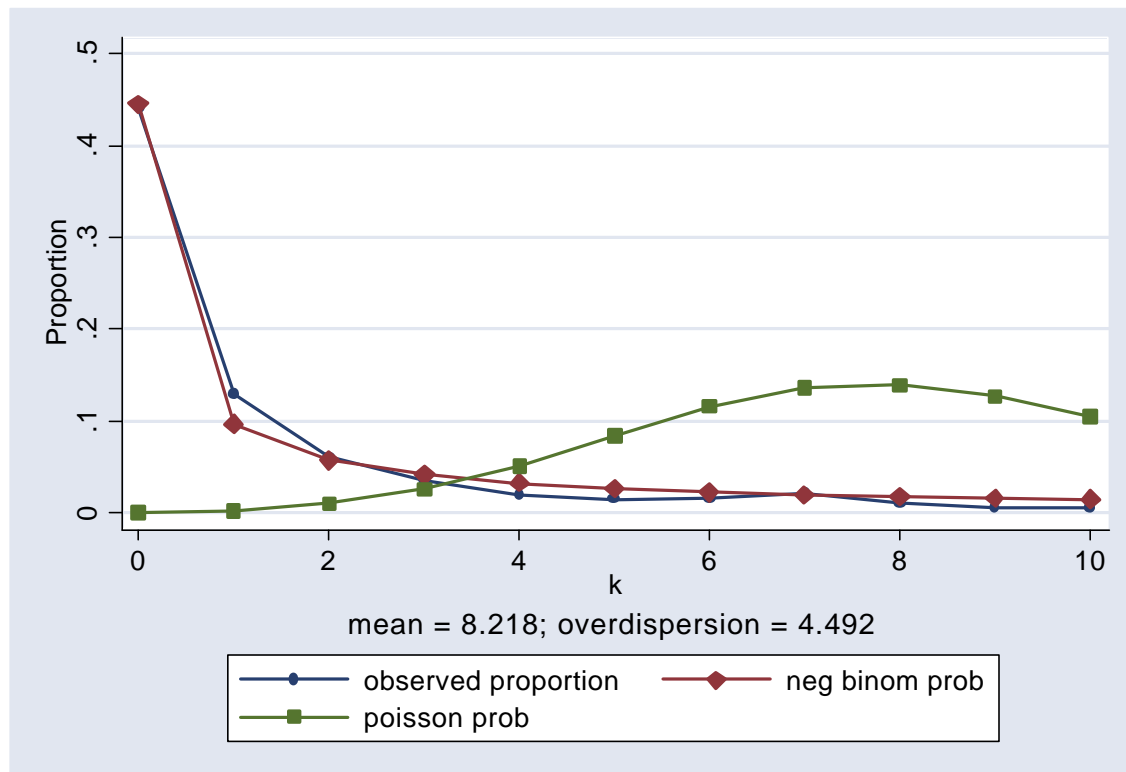
national hazmats do not change transportation modes during shipment (US DOT, 2002).

Once the optimized paths were established, a buffer or exposure zone was calculated for each route. A standard half-mile buffer distance was used based on Transport Canada's evacuation requirement which has been implemented in similar studies (Mills & Neuhauser, 2000). Each GIS route and buffer zone theme was attributed with an associated hazmat volume and noncancer toxicity value. Lastly, census geographies were programmatically attributed with the volume and toxicity information associated with the routes and exposure zones and standardized by area of overlap. These operations yielded neighborhood-specific datasets comprised of demographic, toxicity and volume information for each study year and minimum path type.

Negative Binomial Regressions

Four negative binomial regression (NBR) models were specified in order to better assess characteristics of the exposure scenarios across different socio-economic groups in 2000. NBR is a more appropriate modeling approach than, say, ordinary least squares regression given that the hazmat trip data are non-negative frequencies rather than continuous data. The use of ordinary least squares regression for count outcomes can result in inefficient, inconsistent and biased estimates (Long, 2003). NBR is also preferred over a Poisson model since, in all four specifications, the variance of the dependent variable displays signs of overdispersion such that the value of the variance is over twice the value of the mean. Figure 1 plots observed proportions for the Model A dependent variable with the Poisson and negative binomial probabilities; the negative binomial yields a much better fit to the data.

Figure 2. Observed, Negative Binomial and Poisson Proportions for Model A Dependent Variable



A variety of measures were used to evaluate the statistical performance of the NBR models. Unlike the true R^2 in ordinary least squares regression, NBR models do not have a single, straightforward goodness of fit measure that reflects the proportion of variance explained by the predictor variables. The Stata statistical package, for example, provides over ten “pseudo- R^2 ” measures for categorical and limited dependent regression models, each having their own interpretation (Stata, 2004; Long, 1997; Long, 2003). The usefulness of such statistics, however, has been challenged by some authors who favor information criterion measures such as the Akaike's Information Criterion (AIC) over pseudo- R^2 statistics (Hosmer and Lemeshow 2000). Others argue that particular pseudo- R^2 statistics offer meaningful interpretations (Shtatland, Kleinman, and Cain 2002). We allay this conflict by way of redundancy and offer two popular estimates of model fit—the AIC and McFadden's adjusted R^2 or R_{MF}^2 . The AIC is an estimate of the log-likelihood function and includes a measure of model error that penalizes for additional variables. In general, better models yield lower AIC scores. Lastly, R_{MF}^2 uses the same model correction as AIC but takes on values between 0 and 1, which are easier to interpret. Better fitted models yield higher R_{MF}^2 values.

Table 2. Negative Binomial Regression Variable Names and Definitions

Dependent Variables ¹	
SHIPMENTS_A	Number of hazmat shipments: Model A, minimum trip travel time
SHIPMENTS_B	Number of hazmat shipments: Model B, minimum probability of release
SHIPMENTS_C	Number of hazmat shipments: Model C, minimum total population exposure
SHIPMENTS_D	Number of hazmat shipments: Model D, minimum minority population exposure
Explanatory Variables ²	
PCTAFAM	Percentage African American, Non-Latino
PCTLATINO	Percentage Latino
PCTASIAN	Percentage Asian, Non-Latino
PCTNATIVE	Percentage Native American, Non-Latino
MDHHINC	Median household income (US dollars)
PCTPOVERTY	Percentage of population earning below poverty level
PCTUNEMP	Percentage 16 and older, unemployed
MDVALUE	Median value of owner-occupied housing units (US dollars)
PCTOWNOCC	Percentage of housing units, owner-occupied

Notes: ¹ Variables adapted from the EPA's TRI, 2000; ² U.S. Census Bureau STF3A, 2000

Table 3. Descriptive Statistics of Explanatory Variables by Census Block Group, 2000

Variable	Mean	Median	Standard Deviation
PCTAFAM	3.5%	2.3%	4.8%
PCTLATINO	25.2%	15.1%	23.9%
PCTASIAN	2.1%	1.4%	3.5%
PCTNATIVE	1.6%	0.8%	4.8%
MDHHINC	\$48,395	\$43,429	\$23,589
PCTPOVERTY	12.1%	7.2%	13.2%
PCTUNEMP	5.3%	3.9%	5.6%
MDVALUE	\$124,180	\$104,941	\$88,069
PCTOWNOCC	62.5%	71.5%	28.1%

Notes: U.S. Census Bureau STF3A, 2000

Results

Given the Phoenix metro area's rapid population and economic expansion during the 1990s, it is not surprising that the number, volume and toxicity of offsite hazmat transfers increased between 1990 and 2000 (Table 4). The number of offsite transfers rose from 115 to 198 (72.2 percent) over the ten-year period while the reported volume of offsite transfers experienced a net gain of over 271 million pounds. Most dramatic, however, was the increase in toxicity of the transferred chemicals. In 1990 the hazards posed by the 17.4 million pounds of substances were equivalent to the health risks presented by approximately 54.9 billion pounds of toluene. Whereas in 2000 the toxic equivalency potential of hazmat transfers escalated to over 21,690 trillion pounds. These simple descriptive statistics suggest that increases in hazmat shipments, while relatively modest, have rapidly intensified with respect to toxicity over time thereby substantially exacerbating the potential health risks associated with offsite transfers.

Table 4. Characteristics of TRI Offsite Transfers in Maricopa County Arizona, 1990 and 2000

Year	Total O-D Pairs/ Offsite Transfers¹	Chemical Volume of Offsite Transfers (100,000 lbs)	Standardized Toxicity of Offsite Transfers² (100,000 lbs)
<i>1990</i>	115	17.4	54,946.7
<i>2000</i>	198	289.1	21,690,476.5

Data Source: U.S. Environmental Protection Agency TRI, 1990 and 2000

Notes: ¹ Includes only transfers between geocoded facilities that transferred chemicals represented in EPA's 1990 TRI chemical list; ² Values reflect the standardized toluene equivalency potentials or the noncancer human health risk posed by one pound of toluene.

The distribution of risks associated with hazmat transfers, however, vary with respect to their routing along the regional road network. Figures 2a and 2b map the estimated annual toxicity-weighted chemical volumes by network segment for the years 1990 and 2000 based on the Model A, travel time optimization. Table 5 presents bivariate correlation coefficients between shares of racial and ethnic groups, frequency of hazmat shipments and levels of volume and toxicity by census tract. Shipments, volume and toxicity values are estimated based on the Model A travel time network which—because of its theoretical link to the predominant classical economic approach to routing—most likely reflects the actual offsite transfer paths. These relationships indicate that hazmat shipments and volume are significantly positively correlated with Latino/Hispanic, African-American and Native population percentages. In contrast, hazmat shipments, both volume and toxicity are significantly negatively correlated with Non-Hispanic, White neighborhood percentages. These patterns are consistent across the two study years.

Table 5. Bivariate Correlations Between the Racial and Ethnic Compositions and Offsite Transfer Characteristics of Neighborhoods, 1990 and 2000

	Total Shipments	Total Volume	Total Toxicity	% Latino	% White, NH ¹	% AfAm, NH ²	% Asian, NH	% Native, NH
1990								
Total Shipments	1							
Total Volume	0.9219	1						
Total Toxicity	0.8145	0.8051	1					
% Latino	0.3773	0.3409	0.3508	1				
% White, NH ¹	-0.3953	-0.3660	-0.3272	-0.9463	1			
% AfAm, NH ²	0.1819	0.2017	0.0737	-0.6120	0.3757	1		
% Asian, NH	-0.0001	-0.0467	-0.0358	0.1578	-0.2250	-0.1045	1	
% Native, NH	0.1794	0.1642	0.1111	-0.2836	0.1474	0.0284	-0.0403	1
2000								
Total Shipments	1							
Total Volume	0.9177	1						
Total Toxicity	0.5595	0.7214	1					
% Latino	0.4136	0.3761	0.3193	1				
% White, NH ¹	-0.4256	-0.3819	-0.3468	-0.9698	1			
% AfAm, NH	0.1605	0.1161	0.1953	-0.5262	0.3663	1		
% Asian, NH	-0.0133	-0.0183	0.0270	0.1971	-0.2790	-0.1037	1	
% Native, NH	0.1579	0.1549	0.1269	-0.2563	0.1227	0.0677	-0.0382	1

t-values in bold are significant at the $p < 0.05$ level; $N = 466$, 1990 census tracts.

Note: ¹ NH=Non-Hispanic/Latino; ² African-American, Non-Hispanic

Table 6 lists coefficients and goodness of fit measures for the four negative binomial models. The likelihood ratio (LR) chi-squared statistics indicate that each model exhibits a statistically significant fit. Model C yields the most favorable AIC score with Models D, B and A following closely behind. Perhaps the most telling goodness of fit statistic is the R_{MF}^2 which shows that the explanatory variables improve Model A's likelihood function by 2.6 percent and Model D's by less than 0.4 percent. This suggests that knowledge of a neighborhood's race and income characteristics is more helpful for predicting the frequency of hazmat shipments routed through that community with respect to the travel time Model A compared to the minority population exposure Model D. Model D, we reason, offers a more egalitarian routing system since risks are distributed evenly across different socioeconomic groups.

The degree to which specific socioeconomic characteristics are related to potential hazmat exposure can be evaluated via the individual beta (b) coefficients. For example, in Model A, the unstandardized beta coefficient for the variable PCTAFAM can be interpreted as: For every additional percentage increase of a community's total population that is African American, the number of expected hazmat shipments routed through the community increases by a factor of 1.026 (i.e. $\exp[0.026]$), holding all other variables constant. Or equivalently, for each additional percentage increase of a community's total population that is African American, the number of

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expected hazmat shipments increases by 2.6 percent (i.e. $100[\exp(0.026) - 1]$), holding all other variables constant. Increases in shares of Latino and Asian populations are also significantly and positively correlated with the number of hazmat shipments estimated by Model A. Conversely, the variables, median housing value and percentage owner-occupied housing, are significantly negatively associated with potential hazmat accident exposure.

Model D exhibits notably different socioeconomic status and hazmat shipment interactions. For instance, percentages of African-American, Latino and Asian are no longer statistically significant but the share of the community's population that is Native becomes so. This reversal is due to the location of Indian reservations bordering the metropolitan area.. Thus, although Model D successfully reduces risks for most minority groups, it effectively increases the estimated number of hazmat routes through Native American communities, an unintentional consequence.

Standardized beta coefficients (b^{s_x}) for model variables are also listed in Table 6. The x-standardized coefficients are useful to compare the relative effect of statistically significant explanatory variables in increasing or decreasing the dependent variable, number of hazmat shipments. Percentage Latino, for example, was the most powerful predictor in Model A (0.461) and Model B (0.561) followed by median value of housing and percentage Asian. Lastly, the predictive power of the variable, percentage owner-occupied housing, is strongest in Model B (-0.271) and relatively weak, although significant, in Model D (-0.177).

Table 6. Unstandardized and Standardized Coefficients and Model Fit Statistics for Negative Binomial Regression Models

VARIABLE	Model A		Model B		Model C MINIMUM TOTAL POPULATION EXPOSURE		Model D MINIMUM MINORITY POPULATION EXPOSURE	
	<i>b</i>	<i>b</i> ^{s_x}	<i>b</i>	<i>b</i> ^{s_x}	<i>b</i>	<i>b</i> ^{s_x}	<i>b</i>	<i>b</i> ^{s_x}
PCTAFAM	0.026	0.124	0.016	0.076	0.000	0.002	-0.009	-0.043
PCTLATINO	0.019	0.461	0.023	0.561	0.012	0.295	0.002	0.056
PCTASIAN	0.068	0.240	0.067	0.238	0.021	0.073	0.001	0.003
PCTNATIVE	0.022	0.104	0.034	0.161	0.038	0.179	0.032	0.154
MDHHINC	2E-06	-0.071	6E-06	0.030	9E-06	0.173	9E-06	0.025
PCTPOVERTY	-0.004	-0.051	-0.006	-0.083	0.006	0.084	0.007	0.091
PCTUNEMP	-0.004	-0.023	-0.011	-0.062	0.018	0.100	0.017	0.094
MDVALUE	-3E-06	-0.363	-3E-06	-0.420	-9E-07	-0.021	-3E-06	-0.018
PCTOWNOCC	-0.007	-0.207	-0.010	-0.271	-0.009	-0.253	-0.006	-0.177
a								
N		2,113		2,113		2,113		2,113
LR χ^2 (df), p-value		306.3 (9), p<0.01		243.4 (9), p<0.01		95.7 (9), p<0.01		53.8 (9), p<0.01
AIC		5.138		4.880		3.306		3.392
McFadden's adj-R ²		0.026		0.021		0.010		0.004

Notes: *b* is an unstandardized coefficient; *b*^{s_x} is an x-standardized coefficient; coefficients in bold have z-test statistics significant at the ten percent level or greater; LR χ^2 is the log-likelihood ratio chi-square; and AIC is the Akaike's Information Criterion.

The bivariate correlations and negative binomial models described above, like many other environmental justice studies, explore relationships between socioeconomic status and potential exposure but largely ignore the economic and environmental consequences of the modeled routing systems.

Therefore, Table 7 compares the ecological implications of the four network exposure scenarios for the years 1990 and 2000.

As stated earlier, Model A optimizes offsite transfer routes with respect to travel time and, as a result, most closely represents the classical economist's cost-minimizing objective of reducing the amount of fuel and/or time expended. This cost-minimization approach yields environmental benefits that are reflected in the relatively low total number of miles traveled for all shipments and reduced average trip lengths between origin and destination facilities. The total areal footprint and mean areal statistics suggest that the buffered travel-time street network—or area at risk of acute releases—is minimal in comparison to the other models which suggests a more ecologically efficient routing system.

While Model A performs well in terms of economic and environmental efficiency, it founders with respect to population exposure. The most expedient freeway routes run through the most densely populated areas in the region. As a result, both the total population exposed within the network footprint and the average per trip population exposure values are higher than all other models.

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Model B seeks to minimize the likelihood of releases thus resembling a risk-minimization approach to routing hazards. Since limited access thoroughfares have the lowest incident probabilities due, in part, to the unimpeded and unidirectional flow of traffic, total environmental exposure to hazmat risk is spatially concentrated along regional highways. For this reason, Model B yields relatively low environmental and population footprints. Yet, similar to Model A, highway-intensive routes are directed through densely populated areas and, as a result, the average populations exposed to hazmat risk are greater relative to all other exposure scenarios.

Model C assigns hazmat routes by minimizing exposure to the total population, irrespective of race or ethnicity. The resulting network deviates considerably from the previous two scenarios in that it utilizes peripheral roadways through sparsely populated areas. As a result, hazmats are transported greater distances which are reflected in the higher average and total miles traveled. The area exposed to hazmat risk exposure is also higher relative to the previous models, however Model C imparts considerably lower risks to populations adjacent to hazmat routes.

The economically and environmentally inefficient outcomes of Model C also hold true for Model D, which minimizes network routes with respect to minority population exposure exclusively. Routes are relegated outside the area's central city thereby reducing exposure to minority groups as directed by the US DOT Environmental Justice guidelines (see Figure 3). While the total miles traveled and average trip lengths are radically higher than Models A and B, exposure to minority populations is reduced by as much as a factor of six.

All of the above patterns are consistent across the two study years although the total miles traveled and footprint values are greater in 2000 due to 83 additional shipments. Models A and B also reported greater average trip lengths and per shipment area and population exposures in 2000 compared to a decade earlier. These increases are likely due to regional population growth and industrial decentralization.

Table 5. Network Optimization and Risk Exposure Model Results, 1990 and 2000

	Model A	Model B	Model C	Model D
	MINIMUM TRIP TRAVEL TIME	MINIMUM PROBABILITY OF RELEASE	MINIMUM TOTAL POPULATION EXPOSURE	MINIMUM MINORITY POPULATION EXPOSURE
1990 (N=115)				
Miles traveled, total	2,699.5	2,850.7	10,543.7	13,780.4
Miles traveled, trip mean	23.5	24.8	91.7	119.8
Area exposed, footprint (mi ²)	351.5	304.1	718.9	866.5
Area exposed, trip mean (mi ²)	23.8	25.0	85.5	100.8
Population exposed, footprint	690,618	595,026	350,491	420,024
Population exposed, trip mean	46,578	58,451	10,939	12,683
Minority pop. exposed, footprint	216,852	178,928	112,734	116,949
Minority pop. exposed, trip mean	18,991	24,084	4,543	4,078
2000 (N=198)				
Miles traveled, total	5,241.6	5,608.9	17,269.2	22,764.8
Miles traveled, trip mean	26.5	28.3	87.22	115.0
Area exposed, footprint (mi ²)	443.5	443.7	782.4	906.6
Area exposed, trip mean (mi ²)	26.8	28.5	80.37	100.00
Population exposed, footprint	1,157,362	1,015,486	681,416	663,923
Population exposed, trip mean	66,543	76,466	18,093	18,717
Minority pop. exposed, footprint	522,870	440,571	276,537	245,281
Minority pop. exposed, trip mean	36,936	43,543	8,576	8,010

Policy Considerations for Planners

Hazardous materials are increasingly viewed as commodities in or byproducts of viable markets. As a result, planners and other stakeholders will likely need to develop strategies that mitigate externalities associated with hazmat transport risk for years to come. Until recently, demographic data near potential transportation routes were not available with adequate spatial resolution. Now, given the availability of spatially explicit hazmat facilities and geographic information systems to estimate shortest paths, planners are in a better position to consider optimum routing for shipping hazardous materials based on economic, environmental and social criteria. However, as this analysis has shown, reducing risks to vulnerable populations may be at odds with cost minimizing strategies, the prevailing model pursued by commercial interests.

It should be noted, however, that high levels of uncertainty are inherent in hazmat risk data and the complex and dynamic patterning of hazmat flows over time and space. And given that hazmat shipments account for only a marginal amount of the risks present in urban communities, there is a need to consider cumulative hazards from multiple sources (fixed and mobile) when performing risk assessments. This also necessitates the consideration of questions related to chronic exposure to ambient and point-source air pollution as well as acute releases as a result of industrial and highway accidents in assessing overall risk exposures. The goal of risk arbitrage is to deal with uncertainty and reduce it through probabilities of future events that

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provide a foundation for action. Therefore, the more planners and community stakeholders understand the nature and meaning of risks in their environment, the more they are able to develop strategies for improving environmental protection (Rubin, 2002).

Moving forward in an environment of increasing uncertainty requires broader public participation and debate concerning environmental issues and an increased recognition of the challenges we face with regard to developing policy responses. The participation of disempowered and marginalized communities in these discussions is a critical step in addressing environmental justice concerns on an inclusive basis (e.g. Bullard and Johnson, 1997). In addition, more effective means of risk communication and the broad availability of community right to know information will enhance informed public participation in hazard mitigation and risk reduction strategies, particularly as they affect populations designated by the DOT's environmental justice directives.

This paper has discussed various ways to frame hazmat transport risk and their associated exposure patterns. The difficulties primarily arise out of the need to model numerous chemicals simultaneously over time and space and the ethical and legal responsibility to ensure equitable outcomes. Planners and stakeholders should work toward integrating similar risk analyses with other policy frameworks that can better metabolize qualitative assessments of risk and social equity in the decision making process.

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Figure 2a. TEP Volumes by Road Segment: Model A (Minimum Travel Time) Optimization, 1990

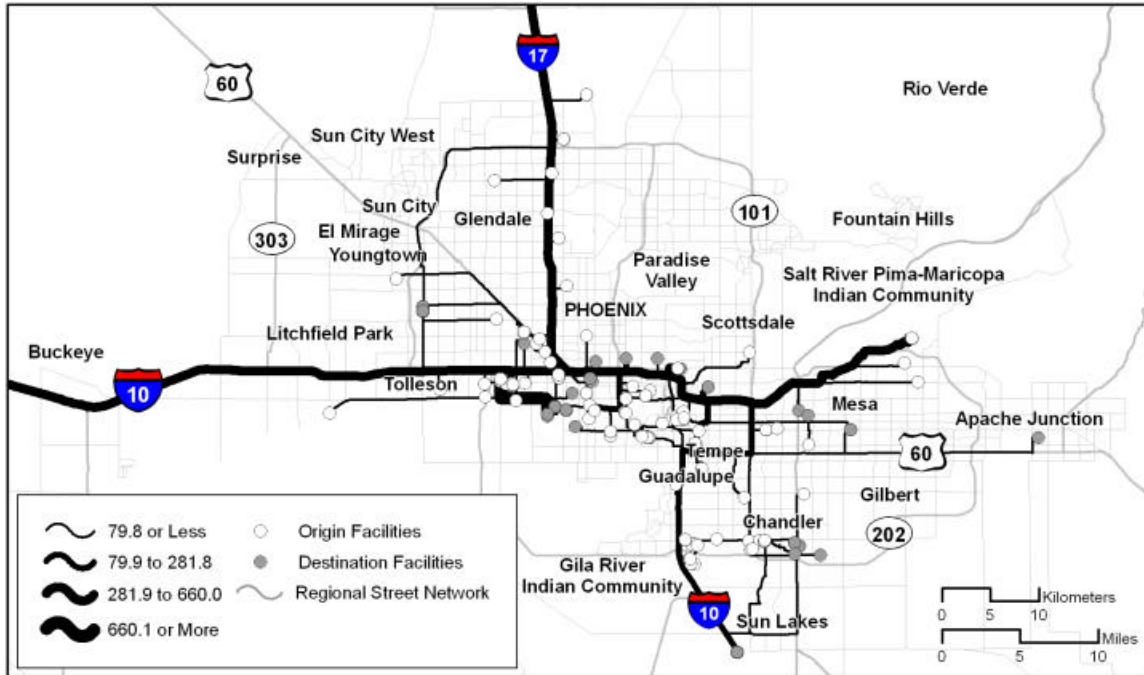
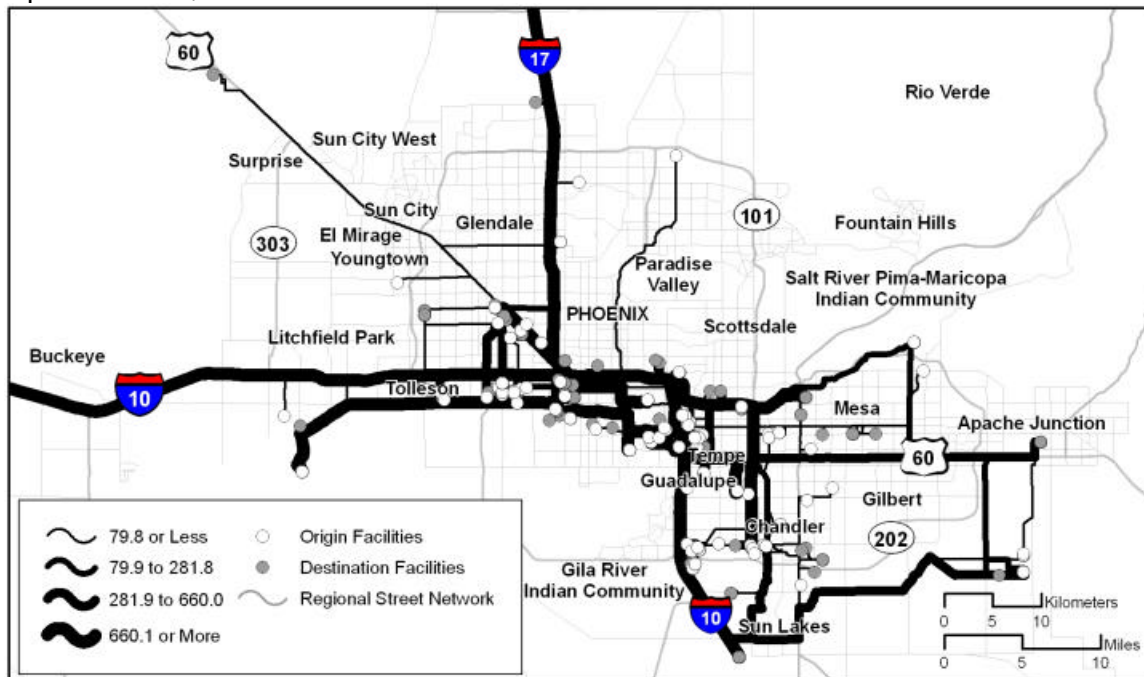


Figure 2b. TEP Volumes by Road Segment: Model A (Minimum Travel Time) Optimization, 2000



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Figure 3. TEP Volumes by Road Segment: Model D (Minimum Minority Population Exposure) Optimization, 2000

