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MODELS FOR AIDING HAZARDOUS WASTE FACILITY SITING DECISIONS

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ABSTRACT

Proposals for locating hazardous waste treatment and disposal facilities typically encounter strong opposition from the affected communities. Technical analysis can examine the risks from alternative siting strategies, thereby aiding the political process by which the decision is made. This article presents models for calculating the health effects from accidents in transporting hazardous waste to treatment facilities, and from accidents at an incinerator facility. Starting with an ideal-type model, we introduce simplifications that make the analytical task easier, while providing answers to questions about the comparative risks from locating facilities in urban versus rural locations. An illustrative calculation for siting incinerators in the Los Angeles area indicates that the expected number of people exposed to the Environmental Protection Agency's "short-term exposure limit" is larger for urban sites than rural sites, because the transportation risks are comparable and the facility risks are much larger for the urban site. The expected value numbers are quite small, because of the low probability of accidents, but if an accident occurs in the urban area, hundreds of people could be exposed to the short-term exposure limit.

Public decisions about siting commercial (offsite) hazardous waste (HW) treatment facilities, especially incinerators, must address questions about the risks to nearby populations, both from accidents in transporting hazardous wastes and from releases of hazardous chemicals at the treatment facility. People living near proposed sites typically perceive the risks to be high and oppose having an incinerator nearby [1, 2]. Locating incinerators further from urban areas will reduce the risk from facility operation and the political opposition from people living near the site. However, it will increase the risk from transporting

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hazardous wastes and the opposition from people living along major transportation routes. In short, there is a tradeoff of risks between siting HW facilities close to the source of hazardous waste in urban areas, and far from the sources. Lave refers to this as a "risk-risk" situation (as opposed to a "how safe" situation) [3].

We believe that decisions in such risk-risk situations should be made by an open political process rather than by using technical analysis to override the political process. Furthermore, the evidence from actual decisions shows that policy makers have often been unable to impose "solutions" involving the siting of hazardous facilities on local communities [4]. We believe, however, that an open decision process would be aided by technical analysis that seeks to clearly display the relative risks involved in each alternative. Presenting the framework and models for such a technical analysis and illustrating their use is our objective for this article.

In choosing a modeling strategy for assessing relative risks, we considered two approaches: *optimization methods*, which promise to identify an "optimal" configuration of incinerator sites and sizes, and simpler *partial models*, which cannot make such a promise but are able to address more specific questions of interest to policymakers. Complex models and optimization methods are not always better. In fact, the preponderance of advice in the field of policy analysis is to use the simplest models that will do the job, and not to optimize–just try to do better [5-7]. Simpler models are not only likely to be more understandable and useful to policymakers but, as Alonso shows [8], they can also be more accurate where the quality of data is poor. Lee, in sounding a "requiem for large-scale models," makes a convincing argument that partial models are preferable to large scale simulation models, at least in the urban planning field [9].

We agree with these criticisms of optimization methods[1] and feel that such methods would not be suitable for our task–they would be expensive and politically naive; policymakers are not about to take such results and try to implement them. Indeed, the existence of an allegedly optimal facility siting plan would be a rallying point for political opposition, which would make it difficult to locate any treatment facilities.

On the other hand, partial models, which do not try to include all aspects of reality or try to provide an optimal solution, can provide insight into the issues and tradeoffs, and answer specific questions of interest to policymakers. The principal questions we address are: How do the risks from different locations and sizes of hazardous waste incinerators compare? Are the total risks lower if facilities are located in urban or in remote areas?

[1] An example of the use of optimization methods for minimizing transportation risk to hazardous waste facilities is Jennings and Suresh [10].

I. BACKGROUND AND PROBLEM DEFINITION

To reduce the threat from improper or insecure disposal of hazardous waste, the Environmental Protection Agency (EPA), acting under the amended Resource Conservation and Recovery Act (RCRA) [11], adopted regulations to eliminate land disposal of specified hazardous wastes. The prohibitions on land disposal have led to a search for treatment, recycling, and waste reduction methods that can replace land disposal. Among these alternative means, hazardous waste incineration is attractive for several reasons: it is capable of destroying nearly all of the hazardous chemicals in the wastestream (99.99% destruction efficiency is the minimum requirement); it can destroy a wide variety of waste mixtures in a single unit; it can be used at the site where wastes are generated (if there are enough wastes to be economically feasible) or offsite; and, it can provide large amounts of usable energy in the form of heat, thus lowering its net operating cost.

Applicants for a permit to build an incinerator must currently assess the potential hazards to human health from the proposed facility but they are not required to consider how to minimize the overall risks (including transportation risks) due to the facility. For example, California's Toxic Air Contaminant regulations require that the health risk from normal operations at new sources of toxic air contaminants–e.g., HW incinerators–be reduced to near background levels [12]. These regulations do not, however, address the "failure sequences" that could produce large accidental releases of toxic chemicals. Yet, the credibility of the incinerator siting process and the ability to gain public acceptance for any facilities, will depend on the public's perception that the risks of proposed incinerators have been thoroughly examined and are reasonably distributed [4, 13].[2]

The Decision Problem, Alternatives, and Evaluation Criteria

Local planners and legislative bodies face the problem of identifying and considering for approval, potential sites for HW treatment facilities in their city or county.[3] We believe that the generic choice in locating treatment facilities, especially incinerators, will be between two principal strategies: 1) using small-to-medium-sized HW incinerators close to the sources of the wastes in urban areas, and 2) using a few large HW incinerators located in rural parts of the

[2] Rayner and Cantor criticize the standard technical approach to making risk decisions, which addresses the question: "How safe is safe enough?" [13]. Instead, they assert that the level of risk that is, in fact, accepted cannot be objectively determined in advance but depends on how individuals perceive the fairness of the process by which risk decisions are made. They believe that the proper question to address is: "How *fair* is safe enough?"

[3] California has a statutory requirement for such a planning process.

county, as far as possible from the waste sources and areas of high population density.[4]

We organize the analysis by defining two alternatives to be evaluated:

Alternative #1 consists of a small number of medium-sized incinerators close to the sources of waste in urban areas.

Alternative #2 consists of one large incinerator in a remote location, far from the sources of hazardous waste.

Alternative #1 has the advantage of lower transportation cost and lower probability of a transportation accident. Smaller incinerators also permit operation to be more specialized by adjusting operating conditions to a few waste streams; such operation is inherently safer because less toxic pollution is likely to be released in normal operation. Alternative #2 requires wastes to be transported for longer distances, thus costing more, but the larger transportation cost may be offset by lower per-unit operating costs at large incinerators. We do not consider here the tradeoff between the greater safety of specialized operation and the lower cost of a large HW incinerator.

Our principal evaluation criterion is health risk, measured as the number of people exposed to dangerous levels of a toxic chemical. Although the focus of this article is on calculating health risks, we note that a complete policy analysis should consider other factors (evaluation criteria) such as the cost of hazardous waste incineration, the distribution of risks (geographically and among socioeconomic groups), and the political feasibility of adoption and implementation of the alternatives.

II. DESCRIPTION OF THE COMPLETE MODEL FOR CALCULATING HEALTH RISK

In this section, we describe the tasks and analytical processes that constitute an ideal-type model for calculating the expected value of health effects due to transportation accidents and incinerator releases (see Figure 1 for a diagram of the process). Section III describes the assumptions and simplifications that we propose for making the modeling task easier, so that planners can carry out a practical comparison of the siting alternatives.

1. Classification of Wastes: Determining the Amount of Incinerable Waste

To determine the number and size of incinerators needed, first estimate the amount of incinerable waste based on the amount and characteristics of

[4] In some heavily urbanized counties, there might not be any rural location for HW facilities. A third possible alternative is one or a few large incinerators in the urban area.

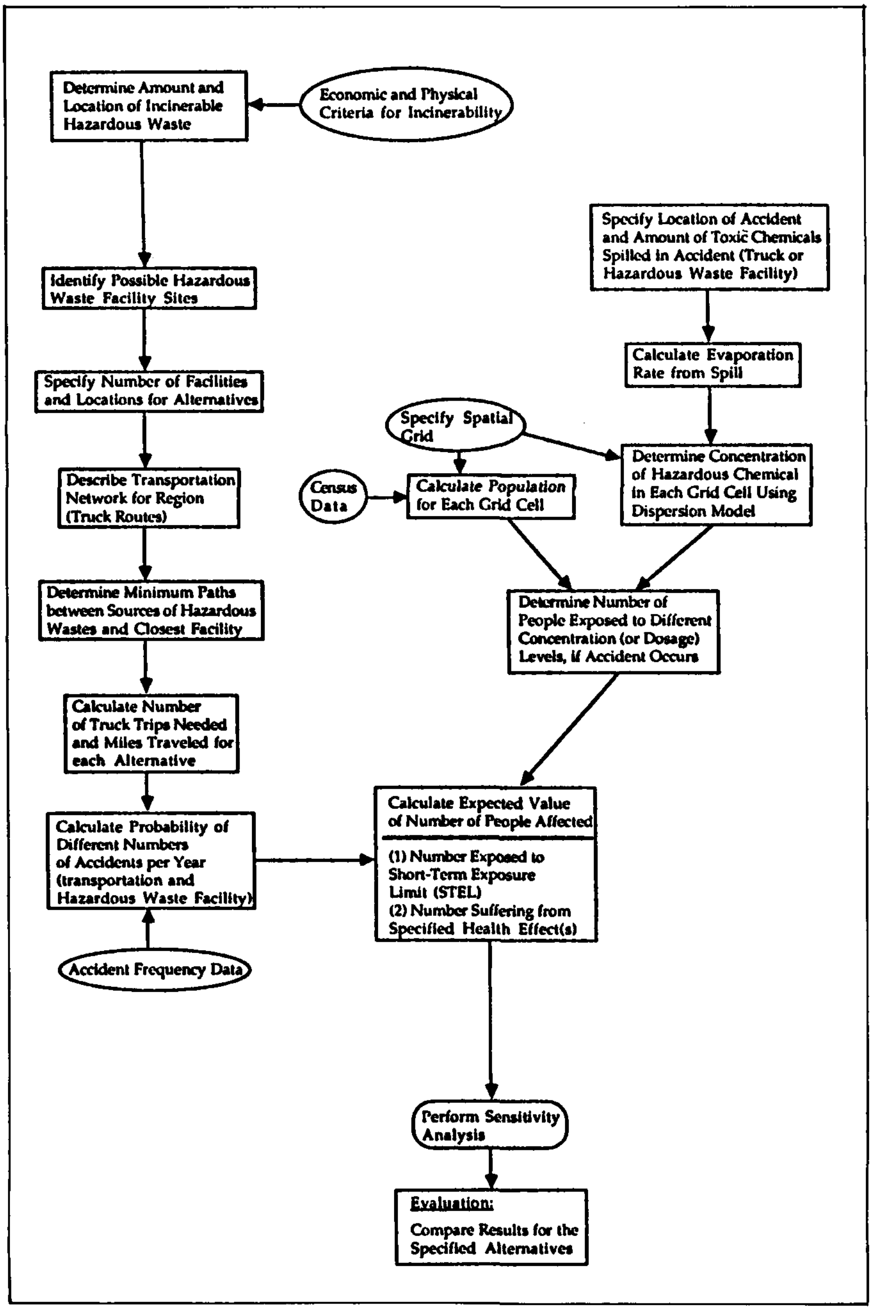

Figure 1. Flow diagram of calculations in the idea-type model.

hazardous waste produced in the region under consideration. Next, using both physical and economic criteria, determine which wastes are incinerable, and how much of those wastes exist.[5]

2. Specifying the Number of Incinerators

From estimates of the amount of incinerable waste in a region (step 1), projected rates of change in incinerable waste, and the capacity of incinerators, calculate the number of incinerators needed for Alternatives 1 and 2. Large rotary kiln incinerators are capable of thermal capacities of up to 150×10^6 BTU/hour and waste handling capacities in the range of as much as 50,000 tons per year. Smaller rotary kiln and liquid injection incinerators are available in sizes down to a small fraction (less than 1%) of the largest incinerators [15].

3. Identifying Potential Incinerator Sites

Identify potential incinerator sites based on criteria such as minimizing total trip distance (hence travel cost), or by examining land use maps for suitably zoned sites in industrial areas in communities that are likely to accept incinerators. We think the latter approach is likely to be more useful in aiding decisionmakers.

4. Modeling the Transportation Network to Determine Minimum Trip Length

After identifying potential incinerator sites for each alternative (step 3), calculate the number of hazardous waste-truck trips and the total travel distance to the designated incinerator sites. Calculating total travel distance requires a model of the road network representing the major truck routes in the urban area, and a minimum path algorithm which insures that the shortest trip paths are used.

5. Determining the Expected Number of Transportation Accidents and the Amount of Hazardous Chemicals Released during an Accident

Draw on existing data for truck accident rates and the volume of waste released in such accidents, for example that reported by Graf and Archulela [16] and Abkowitz et al. [17]. Graf and Archulela [16] estimate a mean accident rate of one accident in one million miles (1.0×10^{-6} per mile) for unarticulated trucks, whereas Abkowitz et al. [17] estimate a mean accident rate *for hazardous waste trucks releasing chemicals* at 0.13×10^{-6}. Abkowitz

[5] Bell, Jackman, and Powell [14] present methods for determining the amount of incinerable and recyclable hazardous wastes.

et al. [17] also developed an estimate of the fraction of waste released due to transportation accidents (per road mile traveled) and for spills in loading trucks and unloading at the facility. Accident probabilities can be made more precise by using separate accident rates according to type of road or traffic volume.

6. Determining the Amount of Hazardous Chemicals Released in an Accident or from Abnormal Plant Operation at the Facility

Accidents involving releases of toxic chemicals at incinerators are of three types: 1) spills involving unloading and handling of containers, 2) stack emissions due to improper operation, and 3) leaks from other equipment.[6]

Site spills – Abkowitz et al. estimate the amount spilled when loading trucks at the source and unloading them at the facility site, as a fraction of the total waste volume handled [17]. They label this number the "fraction-released." They give a combined number for loading and unloading, and do not give the probability of an accidental release or the distribution of amounts released if an accident occurs–more useful forms of data–for either transportation of facility accidents. From the Abkowitz "fraction-released" [17] it is possible to calculate the *probability of a spill per truck-unloading* at the facility (or truck loading at the source), but to do so it is necessary to assume a value for the expected amount released if an accident occurs and for the portion of the fraction released that is due to unloading (or loading). First we write the equation for the expected amount released per truck unloading, E(R):

$$E(R) = E(\text{amount released} \mid \text{accident}) \cdot Pr(\text{accident}) \qquad (1)$$

where Pr(X) = probability that event X occurs, and E(amount released | accident) = conditional expected value of the amount released given that an accident occurs.

We obtain E(R) from the "fraction-released" as follows: for a given truck unloading the expected amount released, E(R), is:

$$E(R) = (\text{fraction-released})(\text{truck volume}) \qquad (2)$$

Substituting Eq. 2 in Eq. 1 and solving for the probability of a spill per truck unloading:

$$Pr(\text{accident}) = \frac{(\text{fraction-released})(\text{truck volume})}{E(\text{amount released} \mid \text{accident})} \qquad (3)$$

The truck volume is known and the overall fraction-released (loading and unloading) is available from Abkowitz [17]. To calculate the probability of an

[6] We do not consider normal stack emissions in our model. These are emissions which meet prescribed destruction efficiency standards–99.99 percent for most toxic chemicals, and 99.9999 percent for dioxins and furans.

accident during unlaoding (loading), it is necessary to assume a value for the expected amount released if an accident (spill) occurs and the part of the fraction released that occurs during unloading. The probability of accident calculated here is used in Step 9 to calculate the expected number of people experiencing effects from facility spills.

Abnormal stack emissions – Improper stack emissions can occur at a properly designed and constructed incinerator for two main reasons: 1) misidentified or mislabeled waste, or 2) improper operation, which can be either intentional or accidental. It is intentional when operators reduce combustion temperature to save on auxiliary fuel costs. Oppelt concludes that there are insufficient data available for predicting the impact of abnormal operating conditions on incinerator emissions [18].

Leaks and tank venting – Leaks from equipment other than the stack fall into two categories: leaks from incinerator equipment during operation and venting of fumes from storage tanks [19].

7. Dispersion (and Evaporation) of Hazardous Chemicals Released in an Accident

Although chemical spills can produce health hazards via several pathways, the model focuses on the airborne pathway–evaporation of spilled chemicals, dispersion in the atmosphere, and subsequent inhalation of the toxic vapors.

Evaporation – Kelty gives the rate of evaporation as [20]:

$$W = \frac{0.0012\, C\, \theta}{760 - (1 - C)\theta} \tag{4}$$

where,

W = evaporation rate (gm/s)

$C = \dfrac{\text{molecular weight of substance}}{28.9}$

θ = vapor pressure (mm of Hg at 20° C)

Equation 4 assumes that both the spilled toxic chemical and the air are both at standard temperature and pressure, and that the toxic chemical is not mixed with other compounds. A typical calculation for benzene, based on Equation 4 yields an evaporation rate of 3.8 g/sec from a spill of 11.2 m diameter; 15 g/sec from a 22.6 m diameter, and 34.2 g/sec from a 33.9 m diameter.[7] We do not consider the rate of evaporation from complex mixtures typical of liquid wastes.

[7] These diameters correspond to surface areas of 100, 400, and 900 m^2, respectively, assuming circular spills.

Dispersion – Estimate the atmospheric concentrations of the hazardous chemicals resulting from an accident using the standard Gaussian plume equations (based on Stern et al. [21]). The plume equation estimates the concentration at a specified receptor point resulting from a continuously emitting source; the calculated concentration represents a time-averaging for about one hour [21; p. 277], and depends on wind speed and atmospheric turbulence. The standard deviation parameters, σ_y and σ_z, which specify how the plume disperses in the crosswind and vertical directions, are functions of the downwind distance from the source and the level of atmospheric turbulence.[8] Because an evaporating spill of substantial size is a continuously emitting source, we believe it is appropriate to apply the Gaussian plume model to determine concentration.[9] We define terms as follows (units in parentheses):

- C, pollution concentration, (g m^{-3})
- Q, emission rate, (g s^{-1})
- u, wind speed, (m s^{-1})
- σ_y, standard deviation of horizontal distribution of plume concentration (evaluated at the downwind distance *x* and for the appropriate stability), (m)
- σ_z, standard deviation of vertical distribution of plume concentration (evaluated at the downwind distance *x* and for the appropriate stability), (m)
- h, physical stack height, (m)
- H, effective height of emission, (m)
- x, downwind distance, (m)
- y, crosswind distance, (m)
- z, receptor height above ground, (m)

Concentrations at ground level *x* meters downwind and *y* meters laterally, given neutral stability and unlimiting mixing height, are given by Equations 5-7 [21, p. 277]:

$$C = Q \cdot \frac{1}{u} \cdot \frac{g_1}{(2\pi)^{1/2}\sigma_y} \cdot \frac{g_2}{(2\pi)^{1/2}\sigma_z} \quad (5)$$

[8] Turbulence is described empirically, for purposes of the model, by defining six stability (i.e., turbulence) categories; we use the classification developed by Pasquall and Griffin as described by Stern et al. [21]. The coefficients used to calculate the standard deviation parameters, σ_y and σ_z, are a function of the stability class. Data for stability class, wind speed, and wind direction, is reported for all major civilian and military airports by the National Oceanic and Atmospheric Administration (NOAA).

[9] If the accident results in a gaseous release, a puff model, which gives the time-dependent (instantaneous) values of concentration in a puff of chemical vapor moving through space, would be more appropriate. See Hopper and Chambers for a derivation of the puff model [22]. We also note that Hopper and Chambers support using simplified models for the task of dispersion modeling; they believe that given the quality of the data and the practical objectives of such modeling, simplified models are appropriate.

where:

$$g_1 = \exp(-0.5\, y^2/\sigma_y{}^2) \tag{6}$$

and:

$$g_2 = \exp[-0.5(z-H)^2/\sigma_z{}^2] + \exp[-0.5(z+H)^2/\sigma_z{}^2] \tag{7}$$

If the receptor population is located at ground level, a reasonable assumption, and the source is at ground level, both z and H are zero, and $g_2 = 2$.

8. Estimating the Number of People Exposed to Different Levels of Hazardous Chemicals Released in an Accident

This step combines the results of the dispersion calculation (step 7) with the population in each grid cell of the urban area to calculate the expected number of people exposed to each concentration or dosage level resulting from a single accident. This is a conditional expected value, given that an accident occurs; the expected value of the concentration for each grid cell is obtained by running the dispersion model for different values of the probabilistic variables—location of accident and atmospheric conditions (wind speed, direction, stability)—and calculating an average. Knowing the expected concentration at each grid cell (for a potential accident at a specified location), and the population of each grid cell,[10] an empirically derived function, N(C), which specifies the number of people exposed to concentration level C, is calculated.[11]

9. Calculating the Expected Value of Health Effects from Toxic Chemical Releases in Accidents

Using the results of step 8, this step calculates the *expected value of number of people affected* by chemicals released in accidents in transportation or at the incinerator site. This expected value calculation takes into account the probability of one *or more* accidents occurring during a specified time period. We treat acute (immediate, short-term) effects and chronic (long-term) effects separately.

Acute effects – Make the simplifying assumption that the effects of more than one accident are independent; this enables us to add the number of people affected in separate accidents. For example, if two accidents releasing the same amount and type of chemicals occur (in a year), the number of people suffering

[10] Because the number of people in any area varies with time of day, using census data, which gives residential population, will result in some error. Glickman [23] proposes estimating the number of people at work or otherwise away from home by examining models of traffic movement. This time-consuming procedure is probably unnecessary for our purposes.

[11] If dosage is used in calculating health effects, use N(D) instead of N(C).

ill effects is twice the number affected by one accident. This assumption is reasonable if the same people are not exposed to the different accidents, or, if they are, the effects from a second accident are not more serious because of a prior exposure.

Health effects may be due either to a short-term peak concentration or to a dosage—the integral of concentration over time. We develop the health effects calculation in terms of dosage, assuming the availability of a dose-response function, F(D). The health effects calculation takes the same form if it is in response to concentration rather than dosage; in that case we replace D by C in the functional notation.

- Let F(D) = fraction of the population experiencing the effect of interest at dosage D (use F(C) if the effect is in response to concentration).

From the dose-response curve, F(D), and the expected number of people exposed to dosage level D, given that an accident occurs (available from step 8), calculate the conditional expected value of the *number of people experiencing the negative effect, given that one accident occurs*, which we denote by E(N | 1 accident), or the shorthand, EN_1, as:

$$EN_1 = E(N \mid 1 \text{ accident}) = \sum_D N(D) \cdot F(D) \tag{8}$$

where N(D) = number of people experiencing dosage level D, and the summation is over the range of values of D.

If our objective is simply to calculate the number of people exposed to a critical dosage (or concentration) level, D_{crit}, we sum over N(D) for $D \geqslant D_{crit}$ using the function, N(D), available from step 8. The calculation of the short-term exposure limit (STEL) recommended by the EPA is of this form; however, we present it below (see Sec. IV) in terms of the more general calculation of health effects and a specially defined dose-response function (see Equations 14 and 15). Using the general form in this way exhibits the implicit assumption underlying the response function used in the STEL calculation.

- Calculate E(N), the *expected value of the number of people affected for however many accidents are likely to occur in a given year.*

This is the expected value calculation over the probability distribution of the number of accidents per year.[12]

$$E(N) = \sum_{n=0}^{\infty} n \cdot EN_1 \cdot Pr(n) \tag{9}$$

[12] The probability distribution of the number of accidents per year is calculated in Equation 11, below.

where

$Pr(n)$ = probability of n accidents in a year
EN_1 = conditional expected value of the number of people affected in one accident, calculated from Eq. 8.

As long as EN_1 is independent of the number of accidents, as we assume, EN_1 can be taken outside the summation, and E(N) is then the product of EN_1 and the expected number of accidents per year.

- Equation 9 requires calculating the *probability distribution for the number of accidents in a given time period*, Pr(n).

Transportation accidents – The probability of a transportation accident on a single trip for a given road segment is the product of the length of the segment and the accident rate per mile. Now, consider each trip (or trip segment) as a random (probabilistic) event. There are two outcomes for each event–an *accident occurs* or *it does not occur*. If the events are independent (i.e., the probability that an accident occurs on a given trip does not depend on any other trip), we calculate the probability of *n* accidents in *m* trips by applying the binomial probability distribution.[13] First, define p_i and q_i:

p_i = probability of an accident in one trip over road segment *i*
$q_i = 1 - p_i$ = probability of no accident on the given trip on segment *i*

The probability of an accident for a single trip (or trip segment), p_i, is calculated from the length of the trip and the accident rate:

$$p_i = d_i r_i \tag{10}$$

where

d_i = length of segment *i*
r_i = accident rate for segment *i* (number of accidents per mile; the accident rate, in general, is a function of road type).

And, applying the binomial distribution, the probability of *n* accidents in *m* trips is:

$$\Pr\begin{pmatrix} n \text{ accidents} \\ \text{in } m \text{ trips} \end{pmatrix} = \frac{m!}{(m-n)!n!} p^n q^{m-n} \tag{11}$$

There is a simple recursive form for carrying out this computation. For n = 0, we get $Pr(0) = q^m$. The recursive relationship for calculating the next term $Pr(n + 1)$ when the value for Pr(n) is known is:

[13] See Lindgren [24] for a derivation of the binomial probability distribution, and its application to determine the number of times each of the two outcome states occur in a sequence of *m* trials.

$$\Pr(n+1) = \Pr(n) \cdot \frac{(m-n)}{(n+1)} \cdot \frac{p}{q} \tag{12}$$

Since we know Pr(0), substituting n = 0 in Equation 12 gives Pr(1), and so forth.

Loading and unloading (facility) accidents – Equation 3 is used to calculate the probability of a single accident at the incinerator facility from unloading a HW truck, or from an accident in loading a truck at the source. The probability of *n* accidents per year at the facility (or source) is obtained from Eq. 11 (or Eq. 12), using for the value of *p* the probability of a single truck unloading (or loading) accident from Eq. 3. The calculation of the expected number of people affected by spills in loading or unloading hazardous wastes follows the same procedures as for transportation accidents.

Chronic effects – If the chronic effect (e.g., cancer), depends on dosage over a long period, it will be difficult to calculate the effects of the accidents of concern to us, because other sources can contribute. If, however, the additional statistical cancer risk from a short-term exposure to chemicals released in an accident can be estimated, we can calculate the expected value of the number of people affected by a single accident or a small number of accidents in much the same way as for acute effects. The validity of this calculation depends, of course, on the soundness of the models used to estimate cancer risk.[14]

To calculate the expected increase in the number of people affected (cancer deaths) requires the information available from step 8—the number of people exposed to dosage level D—and a functional relationship for cancer risk showing the average increase in lifetime cancer risk for each value of D. Assume this function is available and label it $F_2(D)$.[15] The statistically expected increase in the number of cancer deaths is:

$$E(\text{number of people affected}) = \sum_D N(D)\ F_2(D) \tag{13}$$

where N(D) is the number of people exposed to each dosage level resulting from an accident (available from step 8).

III. SIMPLIFICATIONS TO THE IDEAL-TYPE MODEL

We describe and illustrate how simplified (partial) models can provide useful information to decisionmakers about accident risks, toxic pollution concentrations resulting from accidents, and the relative advantage of remote

[14] We do not assess the quality of the models for risk assessment here. For discussions of risk assessment models see [25].

[15] This function shows the number of excess deaths (over a lifetime) resulting from a dosage D, for a population of a specified size; dividing the number of deaths by the population size gives a risk number, such as one in one hundred thousand (1×10^{-5}).

and urban incinerator sites. In doing so, we use the "ideal-type" model presented in Section II as a guide, but make simplifying assumptions to reduce the burden (on information and resources) of carrying out an analysis based on the complete model. First we present the generic types of simplifications that we think will make the modeling and analytical task easier yet will produce useful insights and results; then (in Section IV), we state the specific assumptions and simplifications we use in an illustrative calculation.

ASSUMPTIONS AND SIMPLIFICATIONS FOR CALCULATING ACCIDENT PROBABILITIES AND HEALTH EFFECTS

1. Number and Location of Incinerators

We compare one large incinerator located at a remote site outside the urban region (Alternative #2), with two medium-sized incinerators located in the urban region close to existing industrial sources of incinerable hazardous waste (Alternative #1).

Instead of locating sites by an optimization program which gives minimum travel distance, we propose a less formal map analysis: 1) identify several possible sites by locating on a map the major sources of hazardous wastes; 2) choose centrally located sites that would keep travel distances between sources and sites close to a minimum; 3) apply the transportation network program to calculate total miles traveled by HW trucks (step #4, section II); and, 4) adjust the combination of sites selected based on travel distance and other constraints.

2. Transportation Accidents and Chemicals Released

Assume that the same type and amount of hazardous chemical is released when a transportation accident occurs, and that no fire or explosion occurs–only an airborne plume is formed.

3. Site Accidents– Sources and Incinerator

Consider spills in loading trucks at the sources of the hazardous wastes. At the facility site consider only spills during unloading and handling of wastes at the facility. Do not include stack releases, storage tank venting, or normal operational leaks from incinerator equipment.

4. Meteorological Conditions and Spatial Pattern of Pollution Concentration

Use only a few values of atmospheric stability, wind speed, and wind direction, starting with the most frequently observed values. Also consider less frequent wind directions which could affect areas of high population density. Run the dispersion model for each specified set of atmospheric conditions and apply probabilities of those conditions to calculate an approximate average value of concentration.

5. Population Distribution

Account for spatial variation of the population by using small grid cells, much smaller than census tracts, as the unit of analysis; assume all people in a grid cell are exposed to the concentration or dosage at the center point of the cell. Calculate the population of each grid cell by first estimating the population density of each cell; this can be done by locating the census tract(s) in which the grid cell resides and dividing the population of the census tract(s) by its area. A simpler approach is to use a single population density for the entire area exposed to the plume, calculated as the average for those census tracts receiving the plume. Preparing the spatial data for identifying the boundaries of the census tracts and writing a computer program that identifies the census tract(s) for each grid cell could take considerable time and effort.

6. Expected Value of Number of People Affected

Calculating a true *expected value of effects* (section II, step 9) over all possible accident locations and wind conditions would require running the dispersion model for thousands of combinations of these variables. We propose two simplified methods.

Method 1 – Consider only a few accident locations, chosen to represent areas of different population density and wind conditions (perhaps 6 locations and 6 values of wind direction and speed). Calculate hazardous chemical concentrations if an accident occurs at any of these potential accident locations and wind conditions; average the results over the wind conditions for a given site. Calculate an approximate expected value of the number of people affected in the entire region by weighing the results (effects) for each accident location according to the probability of an accident occurring in each area defined by population density.

Method 2 – Accuracy can be increased by calculating concentrations for several potential accident locations *on each road segment or trip path*. Then, using the probability of an accident on each road segment or trip path, an expected value of effects is calculated using the spatially detailed information for health effects that would result if accidents occur on each road segment (i.e., the conditional expected value of effects given an accident on each road segment). The strategy here is simply to increase accuracy by obtaining finer-grained estimates of effects for many potential accident locations, and averaging over these potential locations, using probabilities of an accident occurring along a particular trip path.

It is not necessary to consider all locations to answer the questions of interest to policymakers. What is important are the comparative numbers between the two alternatives, particularly for worst case conditions.

IV. APPLICATION OF SIMPLIFIED MODELS

Assumptions for Our Illustrative Calculation

To illustrate the application of simplified models, we choose the Los Angeles region as our site. Our specific assumptions and details of our calculations are described below.

1. Number and location of incinerators – For alternative #1 we considered several possible sites in the urban area close to sources of hazardous waste, including a proposed incinerator site at Vernon, Los Angeles County. On a map, we entered the location of each major industrial source and the amount of waste it generates. We identified possible sites for alternative #1 in industrial areas (Vernon, Torrance, and Pasadena), and chose three pairs of these sites for detailed analysis. Alternative #2 is a single incinerator located in San Bernardino county, about 60 miles east of downtown Los Angeles, in a sparsely populated area.

2. Truck trips – Using the waste classification program described by Bell, Jackman and Powell, and their data [14], we estimate that 121,000 tons per year of incinerable waste is generated in the Los Angeles basin. We do not know, however, exactly how much of that amount is likely to be recycled. As a baseline value we assume that 50 percent is recycled (the preferred economic alternative), so that the amount of waste to be incinerated in the region is 60,500 tons per year; for sensitivity analysis, we vary the percentage recycled. At the baseline value, 2,272 truck trips from sources to the incinerator(s) are required, assuming fully loaded tanker trucks of 5,000 gallon capacity.

3. Accident location and size of spill – We assume that: transportation accidents can occur on each road segment of the highway network; spills in loading HW trucks can occur at twenty source locations; and, spills in unloading can occur at four incinerator locations. We calculate effects for an assumed accident at each of these locations. For a given set of runs we assume that the same amount of hazardous chemicals are released in each accident. We report results for releases of 1,250 gallons (one-quarter of a tanker truck).

4. Loading and unloading accidents – Using the total "fraction-released" of 7.6×10^{-6} [17] for spills in loading and unloading HW trucks, we assume that one-half the spills occur during loading and one-half during unloading. Thus, the "fraction-released" is 3.8×10^{-6} for loading and the same for unloading. Applying Equations 1, 2, and 3, and assuming an average spill size of 1,250 gallons, we calculate the probability of an accident as 1.52×10^{-5} per truck unloading (or loading). We assume that this probability applies to different spill sizes.

5. *Meteorological conditions for dispersion calculations* – We use six frequently occurring combinations of wind speed, wind direction, and atmospheric stability observed at Los Angeles International Airport. Among the six is a "nearly-worst case" combination.

6. *Spatial distribution of population and plume concentration* – We found that census tracts are too large a spatial unit for our analysis–our results were inconsistent for small spill sizes (below 800 gallons). Using smaller, uniformly-sized grid cells (starting at 100 m on a side), produced consistent results.[16] Using small grid cells enables us to identify quite precisely which parts of the geographical area experience concentrations above a critical level (or any level). Although we use average population density for the affected area (sector) to calculate the number of people in each grid cell, the function N(C) is more accurate because of the smaller grid cell.

In calculating the population affected for any potential accident location, we examine a sector of specified radius (typically 10 kilometers), and an angle of ±40 degrees from the wind vector. The radius and angle are chosen, based on preliminary calculations with the plume model, so that concentrations are negligible outside this sector. For each road segment, we apply the plume equations (Equations 5-7) to calculate the concentration at the center of each grid cell, for five assumed accident locations along the segment and for six sets of atmospheric conditions. From the calculated populations of the grid cells, we tabulate the number of people receiving each concentration level and calculate the average for the thirty runs for each road segment.

7. *Exposure to hazardous concentrations* – We consider only acute effects as measured by two criteria: 1) the number of people exposed to the short-term exposure limit (STEL),[17] *given that an accident occurs*, and 2) the *expected value* of the number of people exposed to the STEL, which accounts for the probability of an accident as well as the magnitude of its effects.

An important issue for analysts and decisionmakers is what criterion (or criteria) of risk to use. Although the expected value criterion is the normative criterion preferred by most risk analysts and decision theorists, increasing

[16] Instead of using uniform size grid cells, we used very small cells (100 m on a side) near the accident site, and successively larger cells as distance from the accident site increased. We believe that this strategy is computationally more efficient and nearly as accurate as using small uniformly sized cells.

[17] The EPA defines and uses the STEL as an indicator of risk [26]. The STEL calculation is not a true health effects calculation because it assumes that below the critical concentration nobody suffers ill effects and above the critical level everybody is affected. Such a response function is unrealistic, but the calculation is useful nevertheless.

evidence indicates that many people do not behave as the rational (expected utility) model predicts [27]. Behavior in risk situations is much more complex. People may focus on the magnitude of low probability-high consequence events and disregard the probabilities [13]–i.e., they do not think about the likelihood of occurrence but only worry about how bad the outcome might be if an accident occurs. Some people assume that a low-probability event will happen to them [27]. An individual's response to a risk situation might also depend on feelings of entitlement to certain levels of safety, so he or she may value an increase in risk much differently than an equivalent decrease [28]. For our purposes, we believe that our first criterion–the number of people exposed to the short-term exposure limit (STEL) *given that an accident occurs*–may be more appropriate for the political process than the expected value criterion. We consider both.

To calculate the number of people exposed to the short-term exposure limit (STEL) *given that an accident occurs*, we follow step 7 (method 2) described in Section III, and rewrite Equation 8, replacing dosage by concentration, as shown in Eq. 14:

$$EN_1 = \sum_{C} N(C) \cdot F(C) \tag{14}$$

where

C = concentration in the plume resulting from a spill
N(C) = number of people in the urban area experiencing concentration level, C.
F(C) = response function–the fraction of the population suffering the effect of interest at concentration, C.

For calculating the number of people exposed to a critical concentration, C_{crit}, where C_{crit} is the short-term exposure limit (STEL), we define F(C) as a step-function (Eq. 15):

$$\begin{aligned} F(C) &= 0 \quad \text{for } C < C_{crit} \\ &= 1.0 \text{ for } C \geqslant C_{crit} \end{aligned} \tag{15}$$

To calculate the *expected value* of the number of people exposed to the STEL, we use Equation 9, with the value of EN_1 calculated from Equations 14 and 15, and the probabilities of accidents calculated from Equation 11.

Comment on our programming effort – Our programming effort involved considerable experimentation and some false starts. Because we reran some parts of the model many times under different assumptions, we used a different sequence than we present in Section II, in order to achieve greater computational efficiency. We wrote the program in TurboBasic so that it can be examined (and revised) by analysts who are not expert programmers. Running on an 80286-AT (at 8 mHz), a full set of calculations with a specified spill size takes less than one minute.

Results

Vehicle miles traveled by HW trucks and average trip distance – The total number of vehicle miles traveled per year by trucks carrying hazardous waste is 33,208 miles for alternative #1 (facilities at Vernon and Torrance), and about 12 percent more for the other two pairs of urban sites; average trip distance is 14.6 miles to the Vernon-Torrance pair. Based on our preliminary analysis of other possible sites, we are confident that the type of map analysis we performed is likely to identify feasible sites for which travel distance is within approximately 10 percent of that for the pair of facility sites with the lowest travel distance. For alternative #2 the total travel distance is 114,812 miles and the average trip distance is 50.5 miles.

Table 1. Probability of *n* Transportation Accidents Per Year, and Expected Number of Accidents Per Year, for Each Alternative[a]

Number Accidents (n)		*Alternative #1* *Probability of n Accidents [Pr(n)]*	*Alternative #2* *Probability of n Accidents [Pr(n)]*
Accident rate: 0.13×10^{-6} per mile			
0		0.9958	0.9823
1		0.0042	0.0175
2		0.0000	0.0002
3 or more		0.0000	0.0000
E (number of accidents per year)[b]	=	0.0043	0.0150
Accident rate: 0.13×10^{-5} per mile			
0		0.9584	0.8368
1		0.0407	0.1491
2		0.0009	0.0133
3		0.0000	0.0008
4 or more		0.0000	0.0000
E (number of accidents per year)	=	0.0431	0.149

[a] Number of trips = 2272 per year
Average trip distance:
Alternative #1 = 14.6 miles
Alternative #2 = 50.5 miles

[b] The expected value of the number of accidents is calculated as:

$$E\text{ (number of accidents per year)} = \sum_n n \cdot Pr(n)$$

Table 2. Truck Miles Traveled and Expected Number of People Exposed to the Short-Term Exposure Limit (STEL) for Alternative Incinerator Locations

		Expected Number of People Exposed to the Short-Term Exposure Limit (Benzene)[a]			
Incinerator Location(s)	*Truck Miles Traveled*	*Transport Accidents*[b]	*Loading Accidents*	*Unloading Accidents*	*Total*
Alternative #1					
Ver-Tor[c]	33,208	1.95	17.9	18.6	38.5
Ver-Pas	37,421	2.10	17.9	19.4	39.4
Tor-Pas	37,093	2.20	17.9	19.3	39.3
Alternative #2					
Elsinore	114,812	3.17	17.9	0	21.1

[a] Annual number.
[b] Accident rate = 0.13×10^{-6} accident/mile.
[c] The abbreviations are: Ver = Vernon; Tor = Torrance; Pas = Pasadena

Number of transportation accidents per year and probabilities of more than one accident – The expected number of accidents per year is in direct proportion to the total distance traveled. Hence, alternative #1 will have only 24 percent of the number of accidents as alternative #2. For an accident rate of 0.13×10^{-6} per mile, the *expected value of the number of accidents per year* is 0.0043 for alternative #1 and 0.0150 for alternative #2. The probabilities of more than one accident per year (calculated from Equation 11) are negligible at this accident rate (see Table 1).

Since we do not know how reliable the accident rate involving hazardous waste trucks is, we do a sensitivity calculation, using an accident rate ten times as large (1.3×10^{-6}). The result for the *expected number of accidents per year* is simply ten times as large: 0.043 for alternative #1 and 0.150 for alternative #2. These are still quite small values. The *probabilities of more than one accident per year* are 0.0009 for alternative #1 and 0.010 for alternative #2. (Table 1).

Number of loading and unloading accidents per year and probability of more than one accident – For the calculated probability of an accident (spill) while unloading or loading a hazardous waste truck of 1.52×10^{-5}, the expected number of accidents per year is 0.0345 while loading and 0.0345 while unloading. The probability of one accident per year is 0.0334 at each end, and the probability of more than one accident is 0.0006. Thus, the expected number of loading and unloading accidents per year is about 16 times the number of transportation accidents for alternative #1 (at an accident rate of 0.13×10^{-6} per mile) and about seven times the number for alternative #2.

Number of people exposed to the short-term exposure limit given that an accident occurs – We examined the high, low, and mean values for the thirty calculations of concentration resulting from accidents on each of the eighty-five road segments in our road network, at twenty sites where hazardous waste is generated, and at four potential facility sites. For *transportation accidents* with a spill size of 1,250 gallons, the peak value of number of people exposed to the STEL given that an accident occurs is typically between 300 and 600 in the urban area (see Figure 2 for the distribution of peak values); the average of the peak values is 393.1. The low values are typically between 6 and 20 (average low = 11.5). The mean values are typically between 150 and 300 (average mean = 203.6; see Figure 3 for the distribution of mean values). The highest value calculated is 1,187 and the highest mean is 578.

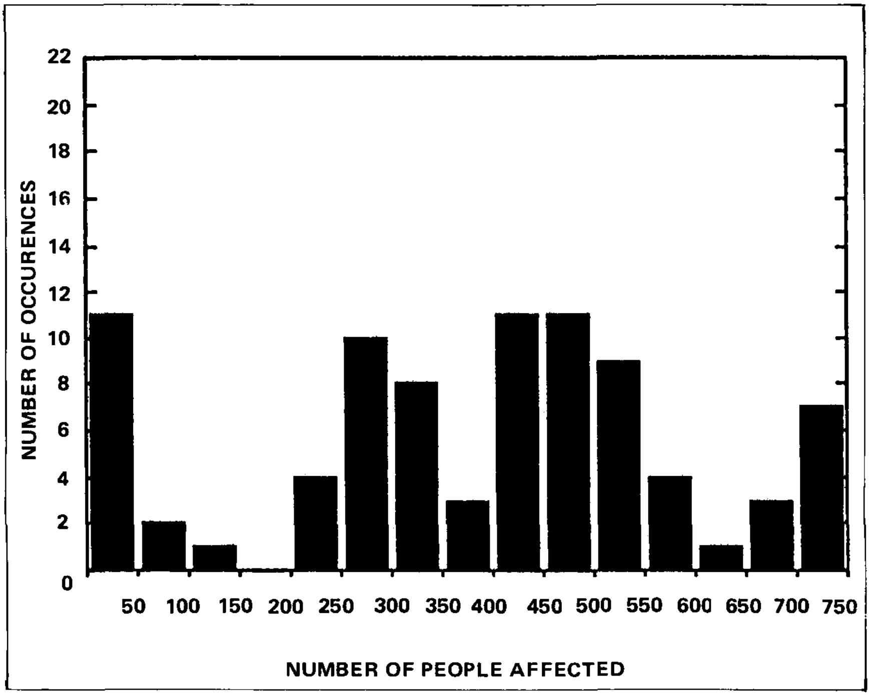

Figure 2. Distribution of high values of number of people affected, given an accident on each road segment. The abscissa refers to a range of numbers between the values shown.

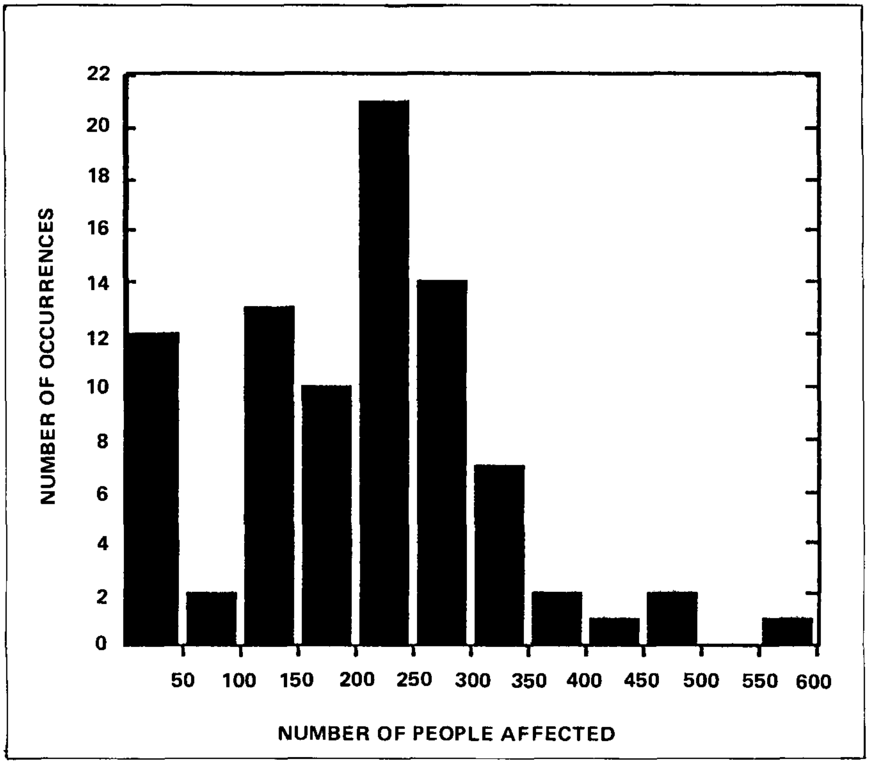

Figure 3. Distribution of mean values of number of people affected, given an accident on each road segment. The abscissa refers to a range of numbers between the values shown.

For *spills during unloading* (1250 gallons) at the three urban facility sites, the peak number exposed to the STEL concentration is between 509 and 572, the low is between 77 and 117, and the mean is between 296 and 324. At the rural site, no member of the public is exposed to the STEL.

For *spills during loading* at the twenty sites where waste is generated, the peak number exposed to the STEL concentration is typically between 650 and 1300, with a high value of 1731 (average of peak values = 884); most of the low values are less than 60 (13 are zero); and, most mean values are between 300 and 600 (average of mean values = 423).

Expected number of people exposed to the short-term exposure limit – For transportation accidents enroute to the urban facilities (alternative #1), at an accident rate of 0.13×10^{-6} the expected value of the number of people exposed to the short-term exposure limit (STEL) is between 1.95 and 2.10 per year; for alternative #2 it is 3.17 per year (for spill size of 1,250 gallons). For spills at the facility site, the expected value of number affected is between 18.6 and 19.4 persons per year for alternative #1, and zero for alternative #2. For spills in loading, the expected value of number affected is 17.9 persons per year for both alternatives. This number is the same for all facility locations since it is determined by the location of the hazardous waste sources. We consider these numbers for completeness even though they do not affect the ranking of alternatives.

Employing the expected value criterion, the risk from accidents during loading and unloading (combined) is larger than the risk from transportation accidents by a factor of about 17 at the urban sites; at the rural site there is no public risk from unloading, but the risk from loading is about six times the risk from transportation. The combined risk–expected number of people affected by both transportation and facility accidents–varies between 38.5 and 39.4 persons per year for the urban alternatives, and is 21.1 for the rural alternative. The large difference between the rural and urban alternatives is due almost entirely to the higher risk from spills during unloading at the urban facilities.

V. SUMMARY AND CONCLUDING COMMENTS

We have presented an ideal-type model for calculating the health effects from accidents in transporting hazardous wastes and unloading them at a treatment facility. We propose several simplifications to the ideal-type model to reduce the task of carrying out these calculations so that it is within the capability of most local planning agencies faced with the task of evaluating a siting decision. Our strategy is to perform calculations that can usefully answer questions of interest to policymakers rather than try to make precise predictions of future outcomes. In presenting these models, we emphasize that we believe they should be used as an aid to decisionmakers and interest groups involved in a politically delicate, and very likely contentious, decision process. We do not advocate using these models to provide a technical fix that overwhelms political participation. Our models focus on health risks and not on costs or sociopolitical issues, such as equity, which are extremely important factors in most decisions [4, 13]. Because our calculations are illustrative and do not treat all situations and all factors important to the decision, we urge caution in applying our results.

Our illustrative calculations, for a realistic setting in Los Angeles county, do, however, indicate to us that partial models are capable of providing useful insights and answers. The conclusions that can be drawn depend in part on the criterion that is used. If we consider the number of people affected if an accident occurs, without considering probabilities of an accident, both alternatives are capable of affecting substantial numbers of people if the accident occurs in the urban area. The rural alternative is more likely to produce a transportation accident in the urban area because of the larger number of miles driven by HW trucks to the rural facility; however, the rural alternative is clearly preferable for minimizing the effects from facility accidents.

Applying the expected value criterion indicates that the rural alternative is preferable. Transportation risks do not differ by much between the urban and rural alternatives, and risks due to spills in loading trucks do not differ at all. However, facility accident risks differ greatly—they are much larger at the urban facility sites. When facility accidents other than from unloading trucks are considered, which we do not do, the rural site is even more desirable. Note that there is very little difference in risk among the three urban facility combinations we examined. It is possible that if we were to use dose-response functions for specific health effects rather than the STEL, and examine the effect of different chemicals than benzene, the results could be different. Thus, we are cautious not to generalize these results.

Our results, if followed, raise equity problems between urban and rural areas. People living in rural areas will not welcome facilities to treat hazardous wastes generated mainly in urban areas, and will resist pressure to accept such facilities, however beneficial they might be to the entire society. Getting local governments to act in a manner that is perceived as desirable from the point of view of the entire society, but creates costs to the residents of a few jurisdictions, has proven to be a difficult challenge. State governments will need to consider various mechanisms for resolving conflict, including compensatory payments to jurisdictions that accept facilities. The task will not be easy.

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