Truck Transportation of Hazardous Chemicals

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Because data on truck movements of specific hazardous chemicals are not available, methods for estimating them are needed. One possible method of collecting data is through surveying or reporting movements by truckers or shippers. A less costly alternative is to use secondary data on production and consumption of chemicals to identify the chemicals that are moving, the probable origin-destination pairs of these movements, and the probable routes taken. An approach that relies chiefly on secondary data is developed. The basic data on production and consumption came from available data bases on chemicals and chemical producers in the United States. These data were used to determine the chemicals that account for at least 80 percent by volume of hazardous chemicals moving by truck in the United States and to identify major producers and consumers of each chemical. Through interviews with these producers and consumers, rules were developed for estimating the modal split among truck, rail, and water transport on a chemical-by-chemical basis. A gravity model was applied to estimate the origin-destination pairs and routes for truck shipments. A description of the approach and the results of its application to three large-volume hazardous chemicals are presented.

The transportation of hazardous materials is a matter of increasing concern to regulatory authorities. Actual data on the volume of hazardous materials transported throughout the United States are not available, but estimates place the total in excess of 1.5 billion tons per year (*1*). Truck, water, and rail account for nearly all hazardous materials shipments; air shipments are negligible in volume. Fuels such as gasoline and diesel account for about half of the hazardous materials transported; chemicals account for most of the remainder.

Data collected through the Interstate Commerce Commission's (ICC's) 1 percent Waybill sample have been analyzed to provide in-depth information on rail movements of hazardous chemicals. Some data on coastal and inland waterway movements are available through the Army Corps of Engineers. No data are available on truck transportation of chemicals.

Because of the increasing intermixing of freight and passenger vehicles on the nation's roads and highways, incidents involving truck movements of hazardous materials frequently involve exposure to the general population. The U.S. Department of Transportation (DOT) has extensive data on highway incidents involving hazardous materials and chemicals, but does not have comparable volume data with which to establish failure rates (i.e., the percentage of shipments involved in incidents). Consequently, regulatory authorities and planners lack the critical information they need to make decisions regarding training, regulatory policies and programs, and enforcement strategies. Inadequate or inappropriate emergency response training can delay cleanup and increase the hazards associated with spills and other incidents.

The importance of obtaining better information on truck transportation of hazardous materials is great. An approach that estimates the volume of specific chemicals moving by highway in the United States, the origins and destinations of these shipments, and the ton-miles moving through each state is described. The scope of the research includes

- Identification of the chemicals accounting for at least 80 percent of truck shipments of nonfuel hazardous chemicals in the United States (excluding those moving in international commerce);
- A methodology to estimate truck shipments of specific chemicals, including origins and destinations of major producers and consumers and ton-miles transported through each state by truck; and
- Application of the methodology to three chemicals to evaluate its ability to provide the information desired.

METHOD OF APPROACH AND PROJECT RESULTS

Identification of Hazardous Chemicals Accounting for at Least 80 percent of Truck Shipments

Review of Chemicals

To begin the process of identifying the chemicals that make up at least 80 percent of U.S. truck shipments of (nonfuel) hazardous chemicals in 1987, a list of chemicals meeting the following three criteria was prepared: (*a*) the level of 1987 U.S. production or consumption of the material was in excess of 25,000 short tons (or approximately 830 to 850 truckloads per year); (*b*) the chemicals were considered hazardous as defined by DOT's *Emergency Response Guidebook* (*2*); and (*c*) the chemicals were shipped by truck.

A total of 306 candidate chemicals or groups of chemicals with U.S. production or consumption of at least 25,000 short tons were identified. Of these chemicals, 108 large-volume chemicals were not included in the *Guidebook*; since they were not considered hazardous, they were dropped from study. In addition, 26 plastics and resin groups that are not listed

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separately in the *Guidebook* were excluded, as were two of the candidate groups that were gross mixtures, n-paraffins (C10-C16) and mixed linear alcohols (C6-C11), and 15 minerals and metals.

Each of the remaining 159 individual chemical candidates identified as large-volume and hazardous chemicals was studied to determine if it is shipped by truck. Five chemicals were excluded because they were not shipped by truck. Twenty chemicals were identified as "Note Presently Authorized" or "Forbidden" by the National Tank Truck Carriers, Inc., (NTTC) in the *Hazardous Commodity Handbook* (*3*). A representative of NTTC indicated that these chemicals cannot be shipped by tank truck, but they can be packaged in drums or similar containers and shipped by truck. Evidence was obtained indicating that only three (ethane, ethylene, and tetraethyl lead) of these "Not Presently Authorized" or "Forbidden" chemicals were not shipped in drums, bags, cylinders, cartons, and so forth. Therefore, it was concluded that the rest of these chemicals should be retained in the study. The 147 chemicals, given in Table 1, were identified as the large-volume hazardous chemicals that are moved by truck in the United States.

TABLE 1 LARGE-VOLUME, HAZARDOUS CHEMICALS SHIPPED BY TRUCK

Chemical	Production Volume, 1987 (Thousands of Short Tons)	Chemical	Production Volume, 1987 (Thousands of Short Tons)
Sulfuric Acid	39235	Chloroform	224
Propane	26896	Propylene Tetramer (Dodecene)	200
Nitrogen	24515	Maleic Anhydride	193
Oxygen	16669	Dichlorodifluoromethane (F12)	184
Ammonia	16100	Acetylene	182
Calcium Oxide	15733	Carbon Disulfide	180
Sodium Hydroxide	11486	Ethylene Glycol Monobutyl Ether	175
Chlorine Gas	11019	Bromine	168
Phosphoric Acid	10685	Ethyl Acrylate	162
Sulfur	10321	Hydrogen Peroxide	153
Carbon Dioxide	8307	Chlorodifluoromethane (F22)	142
Ethylene Dichloride	7878	N-pentane	142
Ammonium Nitrate	7612	Propionaldehyde	140
Nitric Acid (100% Hno3 Basis)	7225	Ferric Chloride	137
Benzene	5904	Nonylphenol	137
Ethylbenzene	4630	Sodium Chromate/dichromate	128
Vinyl Chloride	4201	Chlorobenzene	123
Styrene	4007	Naphthalene	121
Methanol	3769	Monoethanolamine	116
Toluene	3223	Activated Carbon	109
Ethylene Oxide	2921	Ethyl Acetate	107
Hydrochloric Acid (100%)	2869	Phosphorus Trichloride	102
P-xylene	2578	N-butyl Acetate	101
Methyl-t-butyl Ether	1757	Isobutyraldehyde	99
Phenol	1676	Trichloroethylene	98
Acetic Acid, Synthetic	1623	N-propanol	93
1,3-Butadiene	1465	Barium Sulfide	92
Ethanol (Synthetic)	1434	N-heptane	89
Aluminum Sulfate	1426	Calcium Hypochlorite	88
Carbon Black (Furnace Black)	1362	Sodium Cyanide	85
Vinyl Acetate	1253	Isobutanol	83
Acrylonitrile	1250	Pinene	78
Formaldehyde	1232	Sodium Hydrosulfite	78
Cyclohexane	1137	Ethyl Chloride	77
Propylene Oxide	1105	Tetrahydrofuran	77
Acetone	1048	Methyl Isobutyl Ketone	76
Butyraldehyde	879	Chloronitrobenzene	73
Acetic Anhydride	858	Sodium (Metal)	72
Adipic Acid	795	Phosphorus Pentasulfide	70
Isopropanol	685	Hexene-1	61
Nitrobenzene	625	Propionic Acid	59
1-Butanol	575	Acrylamide	56
Argon	560	Chlorinated Isocyanurates	55
Acrylic Acid	550	Isoprene	54
Hexamethylenediamine	543	Zinc Sulfate	54
Isobutylene	518	Ethylene Glycol Monoethyl Ether	53
Hydrogen Cyanide	516	P-dichlorobenzene	52
Methyl Methacrylate	514	Dicyclopentadiene	50
Phthalic Anhydride	508	Hydrofluosilicic Acid	50
O-xylene	470	Benzoic Acid	48
Methylene-diphenylene Diisocyanate	467	Isobutyl Acetate	44
Cyclohexanone	465	Atrazine	43
Barite	448	Ethylene Glycol Monoethyl Ether Acet	42
Aniline	430	Ethylenediamine Tetraacetic Acid	41
Hexane	426	Furfural	40
Phosgene	421	Sodium Hydrosulfide	40
Linear Alkylate Sulfonate	399	Ethylenediamine	39
Hydrogen	389	Dimethylamine	37
Carbon Tetrachloride	374	Cu Sulfate	36
Acetaldehyde	363	Ethylene Glycol Monomethyl Ether	36
Toluene Diisocyanate	357	N-propyl Acetate	35
Methylchloroform	347	Aluminum Chloride	33
Phosphorus	344	Benzyl Chloride	33
Methyl Ethyl Ketone	336	Phosphorus Oxychloride	31
Sodium Chlorate	289	Ethylene Dibromide	30
Tripropylene (Nonene)	275	Zinc Chloride	28
Hydrofluoric Acid	274	Isopropyl Acetate	27
Methyl Chloride	261	Isopropylamine, Mono	27
Methylene Dichloride	259	Methylamine	26
N-butyl Acrylate	258	Sodium Phosphate, Tribasic	26
Potassium Hydroxide	246	Amyl Alcohol	25
Perchloroethylene	237		
1-Butene	231	Total For 147 Chemicals	288792
Calcium Carbide	230		
Sulfur Dioxide	229		
Epichlorohydrin	225		

Source: SRI International

Verification That Chemicals Compose 80 percent of Truck Shipments

Alternative methods for determining whether the large-volume chemicals identified constitute at least 80 percent of the truck movements of hazardous chemicals were investigated.

In the absence of 1987 data on the quantity of the 147 chemicals and other hazardous chemicals shipped by truck in the *Guidebook*, available production data (or consumption data for the few cases where production data were unavailable) were used as a surrogate for shipment quantities to estimate the percentage of the total quantity of hazardous chemical truck shipments represented by the 147 chemicals. That is, it was assumed that the total quantities shipped by truck were proportional to the total quantities produced. Summation of the production data for the 147 chemicals gave a total production figure of approximately 289 million short tons. However, no production data were readily available for the other individual chemicals listed in the *Guidebook*, so a method to estimate these data was sought. Since known mixtures (e.g., mercaptan mixture, aliphatic) and unspecified compounds (e.g., organic compound of arsenic, liquid, not otherwise specified) listed in the *Guidebook* are specifically excluded from the study, these mixtures and compounds were deleted, and the remaining items in the *Guidebook* were then processed to eliminate duplicate names.

This produced a list of 1,338 individual hazardous chemicals (not including the 147 chemicals). Seven of these, with a total production of 69 million short tons, were previously identified as large-volume chemicals that are not shipped in significant quantities by truck. Of the remaining 1,331 smaller-volume chemicals, production figures were readily available for only 10. (These 10 chemicals had a total 1987 production of 0.1 million short tons, or an average production of about 10 thousand short tons.) An estimate was needed for the average production quantity of the remaining 1,321 individual hazardous chemicals in the *Guidebook*. Many of these chemicals were known to have very small production levels, although separate figures were not available. Nevertheless, an average production quantity for each of these chemicals of 12.5 thousand short tons (one half of the 25 thousand short tons used as the cutoff for identifying the 147 large-volume hazardous chemicals) was used to estimate their total production. The results of this analysis are summarized in Table 2.

As Table 2 indicates, the 147 chemicals represent at least 95 percent of the total production and, in spite of the uncertainties in the various assumptions, these 147 chemicals are believed to represent well over 80 percent of the individual hazardous chemicals shipped by truck. (Subsequent analysis indicated that it is likely that the larger the production volume, the lower the percentage of chemical transported by truck.)

TABLE 2 BREAKDOWN OF HAZARDOUS CHEMICALS

	Millions Tons Produced	Percent
147 large-volume chemicals	288.8	95
10 smaller-volume chemicals	0.1	nil
1321 other chemicals	16.5	5
Total	305.4	100

Source: SRI International

The preceding estimates are similar to ones developed by the Office of Technology Assessment, which estimated nearly 50 million tons of hazardous chemicals in the top five five-digit Standard Industrial Classification codes moved by truck in the United States in 1977 (*4*). We made the following calculation to demonstrate comparability: net product availability (i.e., production available for off-site deliveries) for the three chemicals analyzed account for 80 to 90 percent of total production. Approximately 20 to 25 percent of net production moves by truck. Multiplying 305 million tons by 80 to 90 percent and then by 25 percent gives 65 to 70 million tons shipped by truck in 1987, or a level consistent with 3 percent per year growth between 1977 and 1987.

Volume Transported by Truck

A methodology was developed for estimating the volume of a specific hazardous chemical transported by truck. Three chemicals were selected to test the methodology—1 butanol, dodecene-1, and phosphorus pentasulfide. For each chemical, the producers, plant locations, and capacities were identified from existing data bases. Since some chemicals are used in the manufacture of other chemicals at the same plant, the quantities used in this so-called captive production are not available for shipments elsewhere. To calculate captive production, other chemicals produced in the same plant as the chemical under investigation were identified and the amount of the chemical under investigation that is needed in the production of these other chemicals was determined. When this quantity was subtracted from the estimated production capacity, the net product availability for shipment off-site was determined.

The plants consuming the chemicals were next identified as well as their locations and the total quantity of the chemical needed to meet each plant's requirements. By subtracting the quantity of the chemical produced at the plant from the total plan requirement, the so-called net product requirement was calculated. For example, if Plant A produces 100 short tons of Chemical X and requires 50 tons of Chemical Y in the manufacture of Chemical X, then Plant A must either produce 50 tons (or more) of Chemical Y or obtain it from another plant or company. If a fraction of the 50 tons (e.g., 25 tons) is produced at Plant A, the net product requirement for Chemical Y is 25 tons.

Once these data were assembled, specific information from secondary sources and discussions with industry representatives was obtained on a chemical-by-chemical basis to estimate modal splits. The steps used to calculate modal share were as follows:

- The modes used to ship each chemical were determined through data from the ICC 1 percent Waybill sample, review of waterborne commerce and other data, and interviews with producers and consumers of the chemical.
- Using the information gained from the preceding sources, the modes that generally would be used for shipment sizes and location of shipping and receiving plants for each chemical were determined. For example, large consumers (e.g., those

requiring over 2,000 short tons per year) generally are served by rail or barge rather than truck; origin-destination pairs along inland or coastal waterways tend to use barge or ocean vessels for large shipments.

- Locations of terminals for each chemical, if any, were identified.
- Chemicals with multimodal shipments were identified; for example, rail to a terminal and truck from the terminal to the consumer.
- Rules (described in the next section) were established for each chemical to identify the mode or modes used to deliver shipments to each consumer. Using these rules, the amount of each chemical moving by truck to each consuming plant was estimated.

Gravity Model

A gravity model was developed to assign product flows between producers and consumers. A standard gravity equation was initially used to develop the model, although adjustments were made to make the model appropriate to the specifics of the analysis. Because there were no data available for model calibration, standard coefficients were applied, as described later.

Basic Model

The underlying theory of a gravity model in transportation is similar to Newton's law of universal gravitation, which states that the attractive force between two bodies is proportional to the product of their masses divided by the square of the distance separating them. This model subjectively conforms to the general notion of how one might consider cargo flows to be apportioned between producers and consumers. The shorter the distance between an origin-destination pair, the greater the likely cargo flow between them. Also, the larger the industrial activity in the origin-destination pair, the greater the likely cargo flow between them. This is a widely applied and accepted model and has been shown to be a fairly good predictor of movements (*4*).

To demonstrate how gravity models work, consider chemical production sites, $p(i)$, and a series of consumption plants (sites), $a(j)$. Furthermore, assumed that distance, cost, or some other measure of impedance between Locations i and j is available and termed $r(i, j)$. The basic premise of the gravity model is that the flow from Origin i to Destination j will be proportional to

$$\frac{p(i) * a(j)}{r(i, j)^2} \tag{1}$$

More specifically, the flow, $f(i, j)$, from Origin i to Destination j is given by

$$f(i, j) = K * \frac{p(i) * a(j)}{r(i, j)^2} \tag{2}$$

where K is the proportionality constant. Often K is computed as an appropriate normalizing factor to make the double sum of the $f(i, j)$ equal to some already known total flow.

When historical data are available, the gravity model is often generalized to the form

$$f(i, j) = K * \frac{p(i)^L * a(j)^M}{r(i, j)^N} \tag{3}$$

where the exponents L, M, and N together with the factor K are calibrated from historical data using a least-squares approach. Unknown future flows can be estimated using the right-hand side of Equation 3. In addition, a normalization is usually required, effectively replacing K in Equation 3 by the quantity $K' * K$, where K is derived from the least-squares calibration and K' from normalizing the double sum of the $f(i, j)$.

Most practical implementations of the gravity model differ somewhat from Equation 3, and the implementation used in this study is no exception. In particular,

- Each $p(i)$ is equal to net production available for truck shipments at Plant i;
- Each $a(j)$ is set equal to the estimated demand for the chemical delivered by truck at Plant j;
- Because historical data on hazardous chemical shipments are not available, the standard practice was used of assuming that L and M equal 1 and N equals 2 (*5*);
- The impedance relation, $r(i, j)$, was initially taken as the distance between the plants, but was subject to further modifications, as explained later in this section; and
- The normalization was done individually for each consuming plant, changing the value of K in Equation 3 into $K(j)$.

Captive Consumers

Adjustments were made to the model to reflect captive consumers, that is, consuming plants owned by the same parent company as producing plants. The modification affects the impedance function, $r(i, j)$. For plants owned by the same company, the impedance between the two points was multiplied by an affinity factor, C, where $0 < C < 1$. Because $r(i, j)$ is squared, the affinity factor effectively increased the attractiveness between two plants owned by the same company by a factor of $1/C^2$. Using $C(i, j)$ as the affinity factor to adjust the impedance function, replacing K with $K(j)$, Equation 3 becomes

$$f(i, j) = K(j) * \frac{p(i) * a(j)}{[C(i, j) * r(i, j)]^2} \tag{4}$$

For this study, the affinity factor, $C(i, j)$, was set equal to ⅓ when origin Plant i and destination Plant j were owned by the same company, and equal to 1 when they were not.

Terminals

Distribution of one of the chemicals analyzed involved terminal facilities. A producer may serve a consumer with direct

shipments from the production facility or by shipments from a terminal. To account for terminals, the model was adjusted as follows: each consumer was allowed to be served by each producer, but the method of service from the producer was based on the "least-cost" impedance. To compute the least-cost impedance, the total rail miles from the producing plant to each terminal was obtained. The rail miles were converted into truck-equivalent miles by using a conversion factor of 40 percent. That is, each rail mile costs about 40 percent of a truck mile. This estimate was based on the results of telephone discussions with railroads and trucking companies involved in transporting chemicals. If a producer had, for example, two terminals, the effective impedance to a consumer was calculated for direct truck shipments from the plant and for transshipments through each of the two possible terminals. For shipments directly from the producing plant, the impedance was simply the road mile distance; for the terminals the impedance was the truck-equivalent miles from the producing plant to the terminal plus the actual road miles from the terminal to the consuming plant. The smallest of these impedances was selected for use by the gravity model to calculate the flow matrix. All flow from Producer i to Consumer j was assumed to move only through this minimum impedance route; flows from the producer's other terminals to this consumer were set to zero. The formula for determining the $r(i, j)$ component of impedance then became

$$r(i, j) = \min[d(i, j); e(i, 1) + d(1, j); e(i, 2) + d(2, j) \ldots] \quad (5)$$

where $d(i, j)$ denotes the highway mileage between the production plant or Terminal i and consumption Plant j, and $e(i, k)$ denotes the truck-equivalent miles (calculated as 40 percent of railway miles) between the production plant and Terminal k.

Normalization To Satisfy Constraints

The origin-destination flow matrix was doubly constrained:

- The sum of each column must equal the amount consumed by destination Plant j, or $\Sigma_i f(i, j) = a(j)$.
- The sum of each row must be less than or equal to the amount available at origin Plant i, or $\Sigma_j f(i, j) \leq p(i)$.

The initial flow matrix $f(i, j)$, denoted $f^I(i, j)$, was originally completed using Equation 4 with all $K(j)$ set equal to 1 (i.e., no normalization, and impedance as defined by Equation 5). Next, a normalization algorithm was applied that attempted to ensure that the matrix's double sum equaled total consumption, that is,

$$\sum_i \sum_j f^P(i, j) = \sum_j a(j) \quad (6)$$

where $f^P(i, j)$ denotes the postnormalization flow matrix. This calculation is done by normalizing individually each column to $a(j)$ to reduce or limit to a single column the distortions any extremely short distance would otherwise produce within the entire matrix. Thus, the normalization constraint in Equation 6 can be restated as

$$\sum_i f^P(i, j) = a(j) \quad (7)$$

and the normalizing factor, $K(j)$, for Column j in Equation 4 is

$$K(j) = \frac{a(j)}{\sum_i f^I(i, j)} \quad (8)$$

As indicated, $\Sigma_j f^I(i, j)$ does not need to equal $p(i)$ because the row sums are only constrained to be less than or equal to available production. In general, the sum of the $p(i)$ usually exceeds the sum of the $a(j)$. However, after the normalization conforming to Equation 8 has been performed, the following additional constraint is checked:

$$\sum_j f^P(i, j) \leq p(i) \quad (9)$$

Because the sum of the $p(i)$ was usually larger than the sum of the $a(j)$, the constraint in Equation 9 was often satisfied for all i without the need for any further adjustments. However, if for any i, Equation 9 was not satisfied, an additional normalization was conducted for that row. This row normalization was analogous to the column normalization. The procedure was followed by a series of iterations normalizing in turn by column and by nonconforming row until a convergence observing constraints imposed by both Equations 7 and 9 was achieved or until an iteration limit was reached.

Truncation

The unaltered gravity model has a tendency to assign at least a small increment of flow to all $f(i, j)$. In reality, such small commodity flows do not occur. The model, therefore, has a provision to truncate all $f(i, j)$ below a minimum threshold value and set the cell value to zero. For the applications contained in this paper, the minimum value was set equal to 20 tons per year (or one average-sized bulk truckload per year). The truncation was applied after the completion of all normalizations. To return the remaining flows to balance and conformance with constraints, the normalization algorithm was executed again. Note that, if an $f(i, j)$ was zero, all normalization operations left it unchanged.

Special Cases

During discussions with chemical producers, it was discovered that some consuming plants, as a matter of policy, do not purchase from specified companies regardless of price. For these cases, the appropriate $f(i, j)$s were set equal to zero.

Model Results

The gravity model was applied to the three sample chemicals.

Dodecene-1 (Propylene Tetramer)

Dodecene-1, with an estimated 1987 U.S. production of 200,000 short tons, is in the middle third of the list of 147 chemicals. It is a high-boiling liquid classified as propylene tetramer in Guide 27 (fire explosion and health hazard) in the *Guidebook*. The supply of this chemical is principally from four sources in Texas. (Exports account for about half of U.S. production of dodecene-1), and these shipments move directly from producing plant to oceanborne carrier.) Consumption of dodecene-1 is primarily for the production of branched dodecylbenzene, tridecyl alcohol, and dodecylphenol.

No entries for dodecene-1 under any of its names were available from the 1 percent Waybill sample. However, it was learned that there are rail shipments; because of the small size of these shipments, they may have been missed in the sample or included in an "all other" category.

Discussions with industry representatives indicated that shipments of dodecene-1 move by rail, ship, pipeline, and barge. Eight of the 13 consumers of dodecene-1 were identified as locations receiving truck shipments, but truck shipments account for only about 25 percent of domestic shipments.

Table 3 gives the input data on producing and consuming plants used for the gravity model, and Table 4 gives the resulting flow matrix for dodecene-1.

Of the estimated 11,616 ton-mi of dodecene-1 moved by truck in 1987, nearly 20 percent occurred in Texas, a major consuming and producing state (see Table 5). About 10 percent of ton-miles occurred in Ohio, which has a production facility and a consuming plant that receives 15 percent of the estimated truck shipments of the chemical. About 14 percent of ton-miles occurred in Pennsylvania, a state that has neither production nor major consumption facilities of dodecene-1. Other states with neither production nor consumption facilities that have relatively large percentages of ton-miles include Alabama, Louisiana, Mississippi, Oklahoma, Tennessee, and Virginia. Because the volume of production and consumption of dodecene-1 is relatively small, terminal facilities have not been established to offset the cost of some truck movements.

TABLE 3 GRAVITY MODEL INPUT FOR DODECENE-1

Hazardous Chemical Distribution Gravity Estimation Model—Run Title: DODECENE-1

Parameters for use in this run...
NDIGTRT = 2 (Iteration control and no. digits right of decimal points in flow printouts)
DISTMIN = 1.000 (Distances below this value set to this in gravity equation)
FLOWMIN = 0.020 (Predicted flows below this value truncated to zero)
SAMECOF = 3 if Producer and Consumer same company
PRODEXP = 1.000 (Exponent on production in gravity equation)
CNSMEXP = 1.000 (Exponent on consumption in gravity equation)
DISTEXP = 2.000 (Exponent on distance in gravity equation)

Identifier	Company	Plant Location	ZIP Code	Baseline Impedance	Net Product Availability (Thousands of Tons)
CHV1	Chevron	Houston, TX[a]	77015	0.0	150.00
COA1	Coastal	Corpus Christi, TX	78403	0.0	10.00
SUN1	Sun	Toledo, OH	43693	0.0	23.00
UNO1	Unocal	Beaumont, TX	77704	0.0	10.00
Total Available for Off-Site Consumption					193.00

Identifier	Company	Plant Location	ZIP Code	Consumption (Thousands of Tons)
BUF1	Buffalo	Buffalo, NY	14240	0.60
DIX1	Dixie	Bayport, TX	77062	0.60
GAF1	GAF	Calvert City, KY	42029	1.00
HUM1	Humphrey	North Haven, CT	06473	0.60
LUB1	Lubrizol	Painesville, OH	44077	2.20
MIL1	Milliken	Inman, NC	29349	0.60
MON1	Monsanto	Kearny, NJ	07032	6.00
PHI1	Phillips	Borger, TX	79007	3.50
Total Consumption				15.10

[a] This is a terminal, not a plant. The plant is in Richmond, CA, and the product is shipped by water to the Houston terminal, and from there to customers.

Source: SRI International

TABLE 4 ORIGIN-DESTINATION MATRIX FOR TRUCK MOVEMENTS OF DODECENE-1

IDs		BUF1	DIX1	GAF1	HUM	LUB1	MIL1	MON	PHI1
	Sums	0.60	0.60	1.00	0.60	2.20	0.60	6.00	3.50
CHV1	7.63	0.12	0.60	0.69	0.27	0.13	0.41	2.41	2.99
COA1	0.35	0	0	0.02	0	0	0	0.13	0.19
SUN1	6.66	0.48	0	0.23	0.31	2.07	0.15	3.27	0.15
UNO1	0.45	0	0	0.05	0.02	0	0.04	0.19	0.16

Source: SRI International

1-Butanol (n-Butyl Alcohol)

1-Butanol, which appears in the top one-third of Table 1, is a low-boiling liquid classified in Guide 26 (fire or explosion and health hazard) in the *Guidebook*. The chemical is principally used directly as a solvent and for the production of methacrylate esters, glycol ethers, and butyl acetate.

U.S. production of 1-butanol in 1987 was estimated to have been 575,000 short tons, of which 450,500 short tons was available for shipment to off-site consumers. All production was in the Texas-Louisiana region, whereas consumption of the chemical was concentrated in the Chicago, New Jersey, and Los Angeles areas. Six producers (five of which have terminals) and 67 consuming plants were identified.

Once production and consumption data were collected, shipments by modes other than truck were eliminated. These other means of shipment were determined to be rail and barge through examination of the rail 1 percent Waybill sample, waterborne commerce data, and discussions with producers and consumers of 1-butanol.

On the basis of conversations with major producers and consumers, it was determined that most of the large-volume shipments of 1-butanol are made primarily by barge using inland and coastal waterways. These interviews verified our belief that waterborne shipments are very important in the delivery of 1-butanol to the largest consumers, whose plants are located near navigable waterways. It was also learned that the companies using 1-butanol as a solvent had it delivered by truck in mixed shipments via compartmented tankwagons (cargo tank trucks). However, many of the tankwagon shipments originated from terminals located near major consuming centers, including the Newark, New Jersey, Chicago, Illinois, and San Francisco–Oakland, California, metropolitan areas, and in South Charleston, West Virginia, and Kingsport, Tennessee. 1-Butanol is generally shipped by rail to these terminals and distributed by truck from the terminals to final customers.

Although this study excluded overland movements of international shipments, the levels of exports and imports of

TABLE 5 TRUCK SHIPMENTS OF DODECENE-1 BY STATE, 1987

State Identifier	State Name	Ton-Miles (Thousands)
AL	Alabama	871.9
AR	Arkansas	338.0
CT	Connecticut	34.2
GA	Georgia	139.5
IL	Illinois	23.8
IN	Indiana	33.4
KY	Kentucky	199.4
LA	Louisiana	991.8
MD	Maryland	33.2
MO	Missouri	64.5
MS	Mississippi	509.6
NC	North Carolina	13.2
NJ	New Jersey	428.1
NY	New York	58.2
OH	Ohio	1,145.0
OK	Oklahoma	919.8
PA	Pennsylvania	1,664.0
SC	South Carolina	36.6
TN	Tennessee	791.4
TX	Texas	2,264.4
VA	Virginia	987.1
WV	West Virginia	78.8
Total		11,615.9

Source: SRI International

1-butanol during 1987 were estimated. Imports were negligible (5 short tons). Although 93 thousand short tons of 1-butanol were exported, 93 percent of these shipments departed directly from ports in the Houston-Galveston area. Thus, it is unlikely that a significant amount of 1-butanol is shipped by truck to the ports.

The preceding information and analysis of the rail shipment data led to the conclusion that consumers near navigable waterways received barge shipments. Rail shipments were used for large-volume movements not located along waterways and for movements from production to terminal facilities. Truck movements are generally limited to short-haul (e.g., from a terminal to the end user) or small-volume shipments in drums. Consequently, most 1-butanol moved by rail or barge—only about 20 percent of 1-butanol, measured by tonnage, moved any distance by truck. Furthermore, most truck shipments originated at terminals rather than at the producing plant; only about 12 percent of total truck movements were estimated to originate at the producing plant. Consequently, total ton-miles of 1-butanol truck shipments, estimated at 30,243 in 1987, tended to be minimized through market forces seeking least-cost solutions. As a consequence of the use of terminals, most of the highway miles of truck transport of 1-butanol occurred in either producing or consuming states. There were a few exceptions: for example, Arizona, New Mexico, and Indiana, where truck movements occurred because of transshipment from a producing state or terminal to a consumer. Table 6 gives the estimates of highway miles and ton-miles of 1-butanol moved by truck in each state.

Phosphorus Pentasulfide

Phosphorus pentasulfide, with an estimated U.S. production of 70,000 short tons in 1987, is representative of a chemical in the lower third by size of production of the chemicals given in Table 1. It is a high-melting solid classified in Guide 41 (may ignite in presence of moisture and produce poisonous gas) in the *Guidebook*. Phosphorus pentasulfide is used primarily for production of pesticides and lubricating oil additives. Production occurs in four plants, and there are 13 major consuming plants, widely distributed from the Northeast to the Southeast.

Few shipments were recorded on the 1 percent Waybill sample, and all of these shipments were from the producers to Bayway, New Jersey, or Houston, Texas. No sufficiently detailed data on waterborne commerce of this chemical were available.

Phosphorus pentasulfide was shipped directly from producing plants to consumers by rail and truck. Some specific information was obtained that was used to adjust the input to the gravity model: one of the four producers did not sell phosphorus pentasulfide on the merchant market, one consuming plant receives shipments only by rail, and one plant does not obtain any phosphorus pentasulfide from the closest producing plant.

The model results indicated that about 88 percent of the shipments of phosphorus pentasulfide moved by truck. Because of the dispersed nature of production and consumption and the heavy reliance on trucks, an estimated 27,472 ton-mi of phosphorus pentasulfide moved by truck in 1987 (see Table 7). Nearly a quarter of the ton-miles are in Pennsylvania, a state with a production plant. Other states with about 10 to 15 percent of ton-miles are Ohio, Illinois, Indiana, and Missouri. Most of these states have either a production or consumption facility (see Table 7).

CONCLUSIONS

The primary objective of the research was to determine whether secondary data sources can provide estimates of truck move-

TABLE 6 TRUCK SHIPMENTS OF 1-BUTANOL BY STATE, 1987

State Identifier	State Name	Ton-Miles (Thousands)
AL	Alabama	1,019.1
AR	Arkansas	81.6
AZ	Arizona	1,061.7
CA	California	7,292.4
CT	Connecticut	187.3
DC	District of Columbia	23.3
DE	Delaware	182.2
FL	Florida	39.8
GA	Georgia	440.3
IA	Iowa	30.5
IL	Illinois	1,280.8
IN	Indiana	1,678.3
KS	Kansas	57.4
KY	Kentucky	240.6
LA	Louisiana	1,611.5
MA	Massachusetts	10.2
MD	Maryland	355.3
MI	Michigan	2,319.4
MO	Missouri	139.0
MS	Mississippi	553.9
NC	North Carolina	1,753.8
NJ	New Jersey	671.6
NM	New Mexico	442.6
NY	New York	56.0
OH	Ohio	867.8
OK	Oklahoma	92.0
PA	Pennsylvania	121.7
SC	South Carolina	241.4
TN	Tennessee	363.1
TX	Texas	3,202.0
VA	Virginia	2,077.4
WI	Wisconsin	114.8
WV	West Virginia	1,634.1
Total		30,2242.7

Source: SRI International

ments of hazardous materials within the United States, and, if so, the relative degree of accuracy of these estimates. On the basis of the study results for the three chemicals evaluated, we determined that secondary sources can provide reasonable estimates of truck moves.

- The 147 large-volume chemicals that constitute at least 80 percent of truck movements of hazardous chemicals in the United States were identified.
- The total volume of shipments for each of the 147 chemicals by all modes of transportation within the United States can be estimated from secondary sources.
- The number of producers for the three chemicals evaluated ranged from 4 to 6, and the number of consuming plants ranged from 13 to 67. Therefore, it was possible to contact many of the major producers and consumers with a minimum of difficulty.
- On the basis of experience with the three chemicals evaluated, we believe that the origins (producers) and destinations (consumers) of the 147 chemicals can be determined for all but minor consumers. That is, for the three chemicals evaluated, we were able to identify a very high percentage (about 80 to 90 percent) of the consumption of the chemicals by specific plant location. For one chemical, dodecene-1, there was considerable international trade that was not evaluated in this research.
- The modal split for each chemical was estimated using an approach that reflects the specifics of the chemical, locations of production and consumption facilities, and size of shipments. Data to estimate modal split were obtained from the ICC 1 percent Waybill sample, other secondary sources, and interviews with producing and consuming companies.
- When producers or consumers are concentrated in one or a few areas, the volume of ton-miles moving through various states is not significantly affected by the allocation of flows by the gravity model. For 1-butanol and dodecene-1, most of the supply is from Texas, and plants are situated close to each other. Consequently, the same highway routes would be used to move chemicals to consuming plants in the Northeast or Midwest, irrespective of producer.
- The use of terminals can significantly reduce the ton-miles of chemicals transported by truck, especially in states that are neither producers nor consumers of the chemicals.
- As indicated in Table 8, the percentage of production moved by truck is negatively correlated with volume of production for the three chemicals studied. Whether this is true for all 147 chemicals is unknown, although it seems likely.
- Table 8 also indicates the average net consumption of plants using truck transport compared with other modes. Truck deliveries are significantly lower for the two chemicals evaluated with the largest volume of production (1-butanol and dodecene-1).

TABLE 7 TRUCK SHIPMENTS OF PHOSPHORUS PENTASULFIDE BY STATE, 1987

State Identifier	State Name	Ton-Miles (Thousands)
AL	Alabama	449.8
AR	Arkansas	333.4
DE	Delaware	37.5
GA	Georgia	20.8
IL	Illinois	3,156.4
IN	Indiana	2,800.4
KS	Kansas	871.0
KY	Kentucky	38.0
LA	Louisiana	914.1
MD	Maryland	153.0
MO	Missouri	3,254.3
MS	Mississippi	1,514.5
NJ	New Jersey	996.0
OH	Ohio	4,484.7
OK	Oklahoma	344.1
PA	Pennsylvania	6,356.4
TN	Tennessee	412.6
TX	Texas	647.8
VA	Virginia	461.9
WV	West Virginia	225.8
Total		27,472.4

Source: SRI International

• The volume of production and consumption may not be accurate guides for estimating ton-miles of the chemical transported by truck because the mid- to larger-volume chemicals tend to be handled by modes other than truck, whereas the smallest-volume chemicals of the 147 evaluated may rely almost exclusively on truck transportation. For example, consumption of 1-butanol was nearly 7 times the volume of phosphorus pentasulfide in 1987, but truck ton-miles of phosphorus pentasulfide nearly equaled truck ton-miles of 1-butanol. (Because of its very hazardous nature, special handling is necessary.)

TABLE 8 TRUCK AND NONTRUCK PRODUCTION AND TRANSPORTATION BY CHEMICAL

	1-Butanol	Dodecene-1	Pentasulfide
Off-site consumption (000's tons)	401.7	59.5	59.4
Truck transportation (000's tons)	83.2	15.1	52.5
Percent truck (percent)	21	25	88
Plants receiving chemical by barge or rail transportation			
Number	13	5	1
Average annual consumption (000's of short tons)	50.38	20.08	less than 10
Plants receiving chemical by truck transportation			
Number	54	8	12
Average annual consumption (000's of short tons)	1.54	1.89	4.37

Source: SRI International

• The approach presented in this paper provides valuable information on truck movements of hazardous chemicals in the United States. If all 147 chemicals are evaluated, the data base will be able to provide (*a*) estimates of total ton-miles of large-volume hazardous chemicals moving in the United States by mode; (*b*) estimates of large-volume chemical truck ton-miles moving through each state; (*c*) information on whether terminal facilities reduce truck ton-miles of specific chemicals through intermediate (nonproducing or consuming) states; and (*d*) a listing of producers, consumers, and types of transportation used to serve markets.

FUTURE WORK

The results indicated that the procedure developed is worth further study. Over the next year, the authors plan to conduct the following research:

• Develop a graphics package to display model results visually,

• Test the results against known incident and spill data as a means of verifying reasonableness of the estimates, and

• Apply the methodology to additional chemicals to further refine the general results.

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