CHAPTER 1

NATIONAL TRANSPORTATION NETWORKS AND INTERMODAL SYSTEMS

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1.1 INTRODUCTION

Transportation systems of regional and national extent are composed of networks of interconnected facilities and services. It follows that nearly all transportation projects must be analyzed with due consideration for their position within a modal or intermodal network, and for their impacts on network performance. That is, the network context of a transportation project is usually very important. Thus, it is appropriate to begin a volume on transportation engineering with a chapter on national transportation networks.

The subject of national transportation networks may be approached from at least two different perspectives. One approach, common to most introductory transportation textbooks, describes the physical elements of the various transport modes and their classification into functional subsystems. A second approach focuses on the availability of national transportation network databases and their use for engineering planning and operations studies. The latter approach is emphasized in this chapter, with the aim of providing the reader with some guidance on obtaining and using such networks. In describing these network databases, however, some high-level descriptions of the physical networks are also provided.

The modal networks considered are highway, rail, waterway, and pipeline and their intermodal connections. Airports and airline service networks are deliberately excluded, as air transport is markedly different in character from the surface transportation modes. Likewise, urban highway networks and bus and rail public transportation networks are not covered, since the emphasis is on national and state-level applications. For reasons of space and focus, only transportation networks in the United States are included, although the general concepts presented apply to any national or regional transportation network.

The chapter begins with a general consideration of the characteristics and properties of national transportation networks and the corresponding network databases. The modal networks are then described, followed by a section on multimodal networks and intermodal connections. The concluding section discusses national and local applications of network databases for practical planning studies.

1.2 NATIONAL TRANSPORTATION NETWORK DATABASES

1.2.1 The U.S. Transportation Network

Table 1.1 indicates the broad extent of the U.S. surface transportation system. The national highway network (FHWA 2001) includes nearly 4 million miles of public roads, and total lane-miles are more than double that, at 8.2 million miles. The vast majority of the total highway mileage, 77.6 percent, is owned and operated by units of local government. States own 19.6 percent and the federal government owns only 3 percent. The interstate highway system, consisting of 46,677 miles, accounts for only 1.2 percent of total miles but carries 24 percent of annual vehicle-miles of travel. Another important subsystem is the National Highway System (NHS), a Congressionally designated system that includes the interstate highways and 114,511 miles of additional arterial roadways. The NHS includes about 4 percent of roadway miles and 7 percent of lane miles but carries over 44 percent of total vehicle-miles of travel. Highways are by far the dominant mode of passenger travel in the United States, and trucks operating on the vast highway system carry 29 percent of domestic freight ton-miles (BTS 2003).

The class I railroad network in the United States presently consists of 99,250 miles. This mileage has been decreasing over the past 40 years; in 1960 the class I railroads owned 207,334 miles of track (BTS 2002). Railroad mergers, rail line abandonment, and sales to short-line operators account for the decrease. While this mileage is limited, the rail mode continues to provide vital transportation services to the U.S. economy. For example, railroads carry 38 percent of domestic freight ton-miles, which exceeds total truck ton-miles, and Amtrak provides passenger service over 23,000 miles of track (BTS 2002).

The other modes of transportation listed in Table 1.1 are probably less familiar to the average citizen. The inland waterway system includes 26,000 miles of navigable channels. Of this total, about 11,000 miles are commercially significant shallow-draft waterways (BTS 2002), consisting primarily of the Mississippi River and its principal tributaries (notably the Ohio River system and the Gulf Intracoastal Waterway). To this could be added thousands of miles of coastal deep-draft shipping routes serving domestic intercoastal shipping (e.g., routes such as New York to Miami) and providing access to U.S. harbors by international marine shipping. Nearly totally hidden from view is the vast network of oil and gas pipelines. In fact, at 1.4 million miles, gas pipelines are second in extent only to the highway network. The water and oil pipeline modes each carry about 16 percent of domestic freight ton-miles (BTS 2002).

1.2.2 National Transportation Network Model Purposes and Uses

Motivating the development of national transportation network databases has been the need to consider broad national and regional policies and strategies, and projects for meeting

TABLE 1.1 U.S. Transportation Network

Transportation mode	Statute miles in the U.S. (2002)
Highways	3,936,229
Class I rail	99,250
Inland waterways	26,000
Crude petroleum pipeline	86,369[a]
Petroleum products pipeline	91,094[a]
Natural gas pipeline	1,400,386

[a] Data for year 2001.
Source: BTS 2002.

critical needs for mobility and economic development. Assessing the benefits of such projects often requires considering their role within the national transportation infrastructure. For example, consider the new highway bridge crossing the Potomac River on I-95, under construction near Washington, DC. When this project was nearing a critical funding decision, the question arose as to how much of the traffic using the existing bridge and other regional crossings was interstate truck traffic versus local traffic. Local modeling based on historical truck counts simply could not provide the requisite information. Answering this question (BTS 1998) required a regional or national network model of broad enough scope to capture a diverse set of commercial truck trips (BTS 1997).

Other examples of national network modeling are numerous. An early use of national rail networks was for analyzing the impacts of railroad mergers. The initial proposal to impose a diesel fuel tax on domestic inland waterway transportation was analyzed, in part, with a waterway system network model (Bronzini, Hawn, and Sharp 1978). Subsequent to the energy crisis of the mid-1970s, USDOT used national rail, water, highway, and pipeline networks to examine potential bottlenecks in the movement of energy products (USDOT/USDOE 1980). The potential impacts of spent fuel shipments from nuclear power plants to the proposed waste repository in Nevada have been estimated with the aid of rail and highway network models (Bronzini, Middendorf, and Stammer 1987). Most recently, the Federal Highway Administration (FHWA) has developed the Freight Analysis Framework (FAF), which is a network-based tool for examining freight flows on the national transportation system. Information on the FAF may be found at http://www.ops.fhwa.dot.gov/freight/. Examples of state and local uses of network models are covered at the end of this chapter.

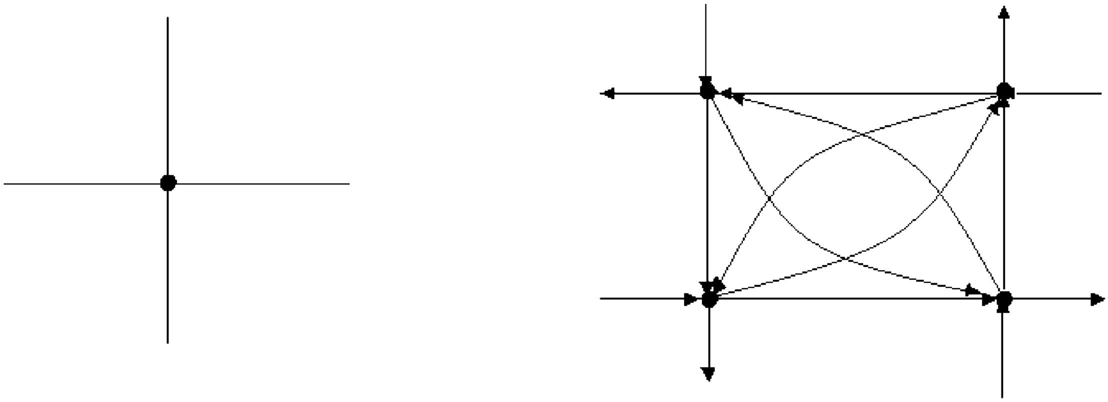
What these examples have in common is that the demand for using specific segments of the transportation system arises from a set of geographically dispersed travelers or shippers. Likewise, the impacts of improving or not improving critical pieces of the network are felt by that same set of diverse network users. Building network models for these types of applications used to be a daunting prospect, due to the lack of available network data. As will be seen later, much of this impediment has been overcome.

1.2.3 Characteristics of Large-Scale Transportation Networks

A network model of the transportation system has two basic analytic requirements: (1) it must be topologically faithful to the actual network; and (2) it must allow network flows along connected paths. A network model that included every mile of every mode would obviously be very unwieldy. Constructing the initial database would be very time-consuming, the quality of the data would likely be compromised, and maintaining and updating the model would be equally difficult. Hence, no such undertaking has yet been attempted, at least not for a model that fulfills both analytic requirements. Topographic databases, as used for mapmaking, do not satisfy the second requirement and hence are not entirely useful for computer-based transportation analyses.

Since the entire system cannot be directly represented in the network model, some judgment must be exercised in determining the model's level of detail. This is referred to as the granularity of the model, which is a relative property. A particular network model can only be characterized as coarser or finer than some other model of the same network, i.e., there is no accepted "granularity scale." Figure 1.1 displays two possible models of a simple highway intersection. In panel (a) the intersection is represented as four links, one for each leg of the intersection, meeting at one node. In panel (b) each direction of travel and each movement through the intersection is represented as a separate link. (In fact, many different types of detailed intersection network coding have been proposed.) The level of granularity adopted will depend upon whether the outcome of the analysis is affected by the details of the within-intersection traffic flows and upon the capabilities of the analytical software to be used in conjunction with the network database.

Related to network granularity is the granularity of the spatial units that contain the socioeconomic activity that generates transportation demands. It is customary to divide the



(*a*) Single node (*b*) Turning movement coding

FIGURE 1.1 Representation of intersections in network models.

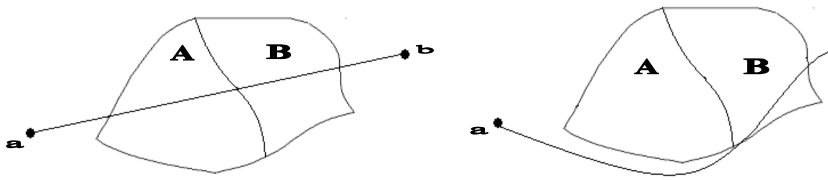
analysis area into zones or regions and to connect these regions with the transportation network model so as to allow analysis of the flows between the zones. For example, in a statewide model the spatial units could be counties and cities. Obviously, the zones and the network must have complementary degrees of granularity.

1.2.4 Typical Network Data Elements

Transportation networks inherently have a node and link structure, where the links represent linear features providing for movement, such as highways and rail lines, and the nodes represent intersections. Thus, the principal data content of a node is its name or number and location. Links usually have characteristics such as length, directionality, number of travel lanes, and functional class. Flow capacity, or some characteristics enabling ready estimation of the capacity, are also included. Of course, the whole assemblage of nodes and links will also be identified with a particular mode.

Another representational decision to be made is whether the network links will be straight lines or will have "shape points" depicting their true geography. Early network models were called "stick networks," which is topologically accurate but lacking in topographic accuracy. For many types of analyses this is of no concern; a software system that deals only with link-node incidences, paths, and network flows will yield the same answer whether or not the links have accurate shapes. For producing recognizable network maps and for certain types of proximity analysis, however, topographically accurate representations are needed (see Figure 1.2). Hence, most large-scale network models currently utilize shape points. This comes at a price, in that much more data storage is required, and plots or screen renderings are slowed. Fortunately, advances in computing power and geographic information systems (GIS) software have minimized these drawbacks to a large extent.

The idea of link capacity was mentioned above. In some networks this is stated directly for each link, in units such as vehicles per hour or tons per day. In others the functional class of a link points to an attribute table that has default capacity values. In the case of an oil pipeline, for example, the diameter of the pipe could be used to estimate flow capacity for various fluid properties. Nodes seldom are modeled as capacity-constrained, but in principal can be (and have been) treated in the same way as links.



(*a*) Yes (*b*) No

FIGURE 1.2 Does link *ab* enter region *A*?

1.3 EXAMPLES OF NATIONAL MODAL NETWORKS

The principal source of national transportation network data in the public domain is the National Transportation Atlas Database (NTAD), developed and distributed by the USDOT Bureau of Transportation Statistics (BTS). Information on the NTAD may be obtained at http://www.bts.gov/gis/. As stated there: "NTAD is a set of transportation-related geospatial data for the United States. The data consist of transportation networks, transportation facilities, and other spatial data used as geographic reference."

Figure 1.3 is a plot of a portion of the U.S. transportation system (excluding pipelines), centered on the state of Ohio, drawn from the NTAD. As could be seen by comparing this figure with state-level highway and rail maps, the NTAD does not contain data for the entire system. In particular, facilities that largely serve local traffic are not represented. Nonetheless, the facilities included carry the great bulk of intercity traffic, hence the networks have proven valuable for conducting national and regional planning studies.

1.3.1 Highway Networks

For the highway mode, the NTAD includes the National Highway Planning Network (NHPN), shown in Figure 1.4, which is a comprehensive network database of the nation's major highway system. Data for the NHPN are provided and maintained by the Federal Highway Administration (FHWA). The NHPN consists of over 400,000 miles of the nation's highways, including those classified as rural arterials, urban principal arterials, and all NHS routes. Functional classes below arterial vary on a state-by-state basis. The data set covers the 48 contiguous states plus the District of Columbia and Puerto Rico. The nominal scale of the data set is 1:100,000 with a maximal positional error of ±80 m. The NHPN is also used to keep a map-based record of the NHS and the Strategic Highway Corridor Network (STRAHNET), which is a subnetwork defined for military transportation purposes.

Highway nodes are labeled with an identification number and located by geographic coordinates, FIPS code, and other location identifiers. Links are designated by the nodes located at each end, a scheme common to all of the databases discussed in this section, and also have identifiers such as a link name or code, sign route, and street name. Other link attributes include length, direction of flow permitted, functional class, median type, surface type, access control, toll features, and any special subnetworks (such as the NHS) to which the link belongs. Each link also has a shape point file.

The NHPN originated at Oak Ridge National Laboratory (ORNL), which has gone on to develop further and maintain its own version of a national highway network database, the Oak Ridge National Highway Network. This is nearly identical in structure and content to the NHPN. For details see http://www-cta.ornl.gov/transnet/Highways.html. Like the NHPN, this database is in the public domain.

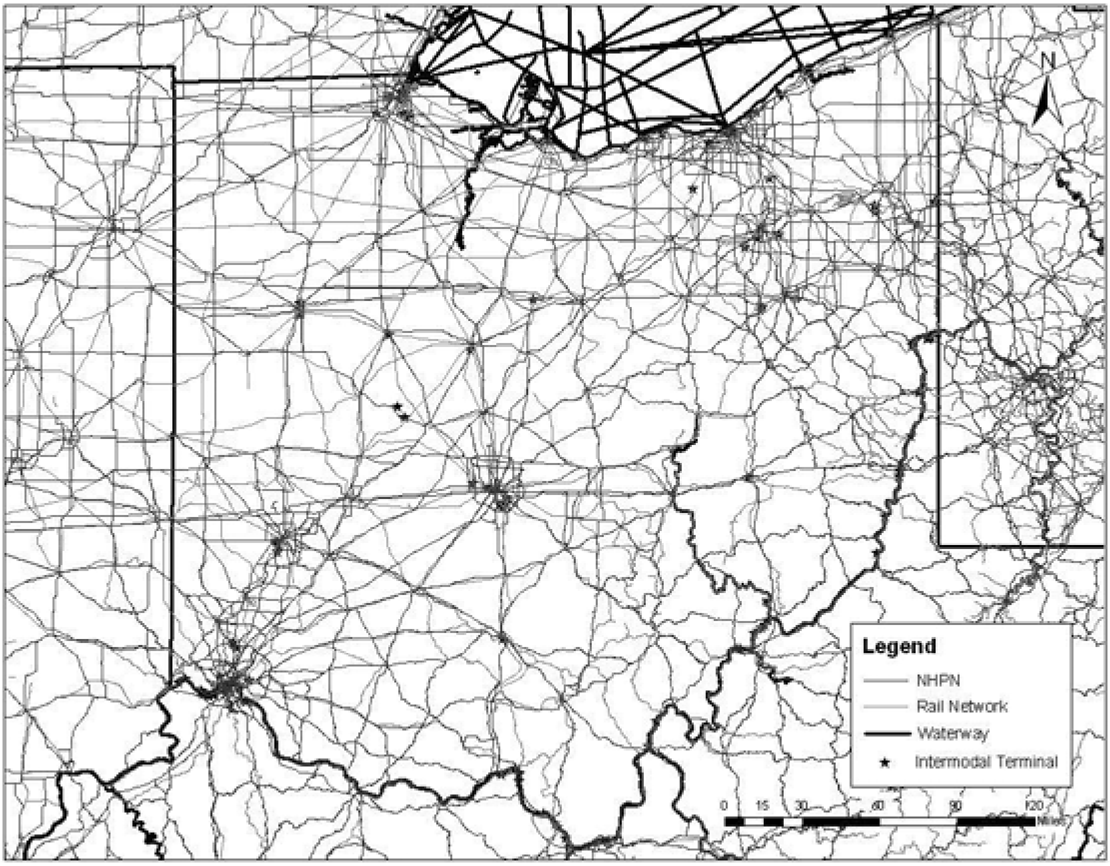


FIGURE 1.3 Extract from the National Transportation Atlas Database (2002).

1.3.2 Rail Networks

The Federal Railroad Administration (FRA) has developed and maintains a national rail network database. The BTS compiled and formatted the rail network data for release as part of NTAD 2002. The rail network (Figure 1.5) is a comprehensive data set of the nation's railway system at the 1:2,000,000 scale. The data set covers the 48 contiguous states plus the District of Columbia. Nodes and links are identified and located in the usual fashion. Link attributes include the names of all owning railroads and all other railroads that have trackage rights, number of main tracks, track class, type of signal system, traffic density class for the most recent year of record, type of passenger rail operations (e.g., Amtrak), and national defense status. FRA is also working on developing a 1:100,000 scale network, but that version has not yet been released.

As in the case of highways, ORNL also maintains and makes available its own version of the national railroad network database. This network is an extension of the Federal Railroad Administration's national rail network. In addition to the network attributes listed above, the ORNL rail network includes information on the location and ownership (including ancestry) of all rail routes that have been active since 1993, which allows the construction of

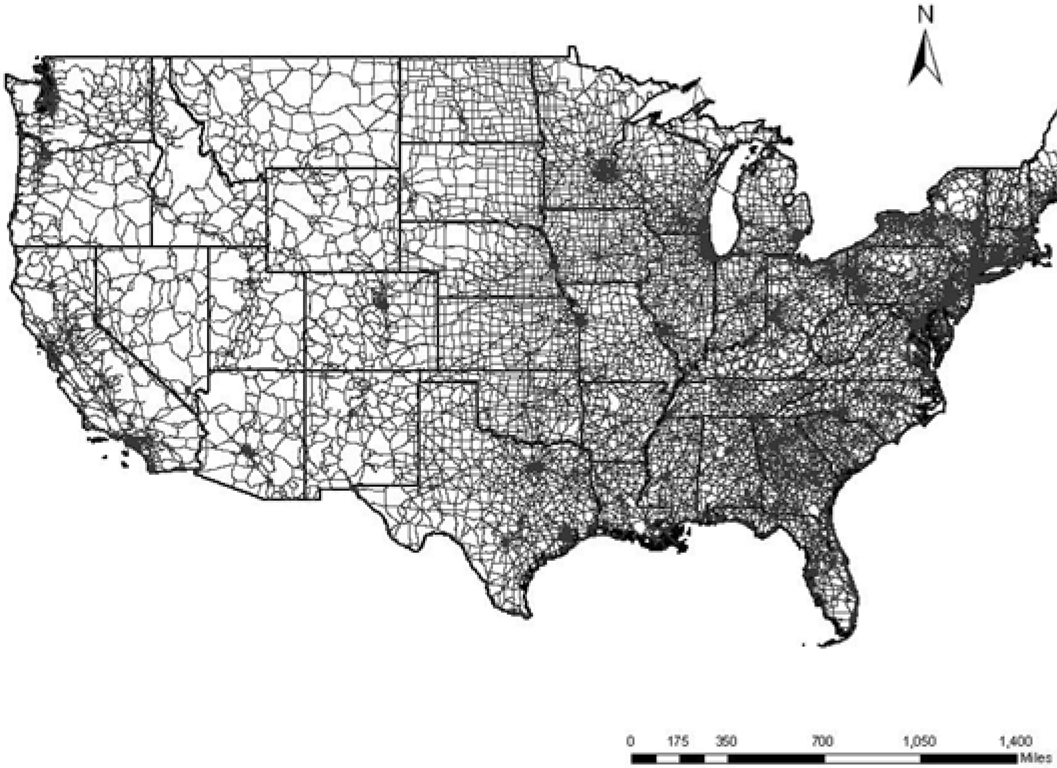


FIGURE 1.4 National Highway Planning Network (2002).

routable networks for any year since then. The geographic accuracy of this network is generally 100 m on active lines.

1.3.3 Waterway Network

The National Waterway Network is a comprehensive network database of the nation's navigable waterways. The data set covers the 48 contiguous states plus the District of Columbia, Puerto Rico, ocean routes for coastwise shipping, and links between domestic and international ocean routes and inland harbors. The majority of the information was taken from geographic sources at a scale of 1:100,000, with larger scales used in harbor/bay/port areas and smaller scales used in open waters. Figure 1.3 shows segments of the National Waterway Network database in and around the state of Ohio.

Links in the waterway network represent actual shipping lanes or serve as representative paths in open water where no defined shipping lanes exist. Nodes may represent physical entities such as river confluences, ports/facilities, and intermodal terminals, or may be inserted for analytical purposes. Approximately 224 ports defined and used by the U.S. Army Corps of Engineers (USACE) are geo-coded in the node database.

The National Waterway Network was created on behalf of the Bureau of Transportation Statistics, the USACE, the U.S. Census Bureau, and the U.S. Coast Guard by Vanderbilt

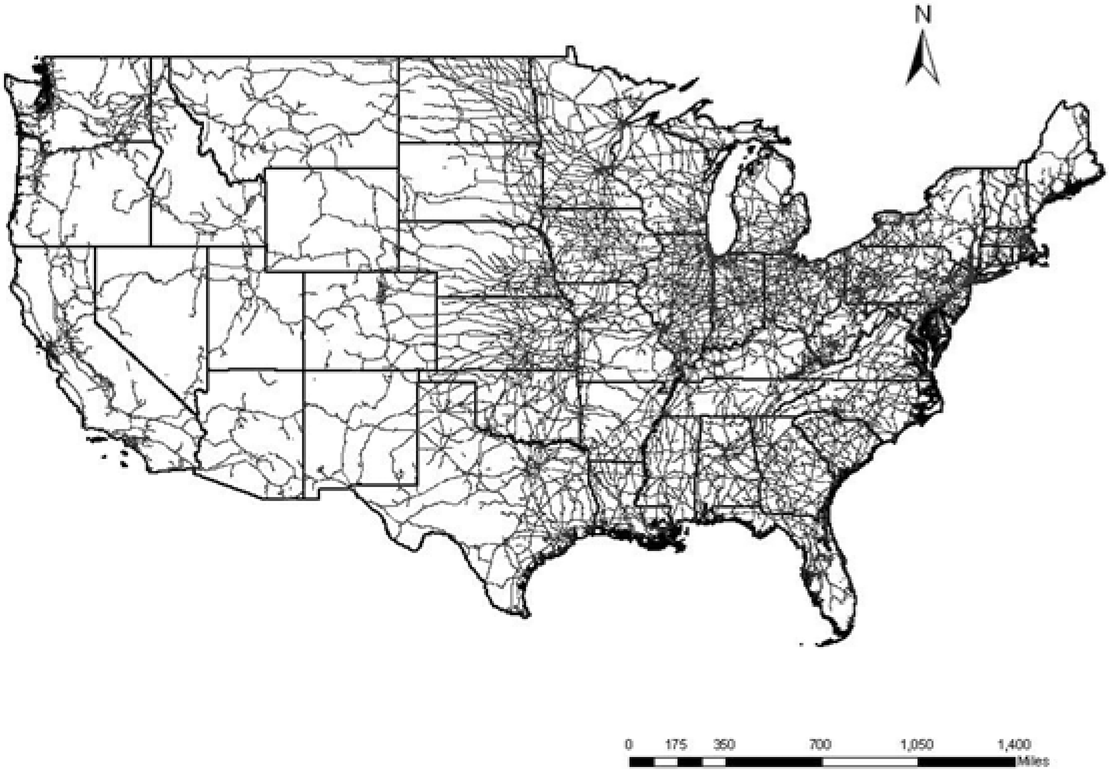


FIGURE 1.5 National rail network (2002).

University and Oak Ridge National Laboratory. Additional agencies with input into network development include Volpe National Transportation Systems Center, Maritime Administration, Military Traffic Management Command, Tennessee Valley Authority, U.S. Environmental Protection Agency, and the Federal Railroad Administration. In addition to its general uses, the network is used by the USACE to route waterway movements and compute waterborne commerce ton-miles for its *Waterborne Commerce* of the United States publication series.

1.3.4 Pipeline Networks

Pipeline network data are available from PennWell MAPSearch, an information provider to the oil, gas, electric, and related industries. Information is published as paper map and CD-ROM products, or licensed in either GIS or CAD formats. The oil and gas database provides pipeline logistical information, including diameter, owner/operator, direction of flow, storage terminals, gas processing facilities, refineries, truck loading/unloading, compressor/pump stations, marketing hubs and other facilities related to crude oil, LPG/NGL, natural gas, refined products, petrochemicals/olefins, and other petroleum-related commodities transported by pipeline. Further information is available at http://www.mapsearch.com/home.cfm.

The USDOT Office of Pipeline Safety (OPS) has underway a joint government-industry effort called the National Pipeline Mapping System. However, at this juncture it appears that the OPS project will not provide a public domain pipeline database, at least not in the near future.

1.4 MULTIMODAL NETWORKS AND INTERMODAL CONNECTORS

There are many applications of national network models that require consideration of traffic that uses more than one mode of transportation for travel between origin and destination areas. In most cases the exact routes and transfer locations of the individual movements are unknown, and hence a multimodal network model must be used to estimate these results. A good example is the processing system used to estimate ton-miles of traffic by commodity and mode for the national commodity flow surveys (CFS) conducted by the USDOT and the U.S. Census Bureau. The procedures used are described by Bronzini et al. (1996). The CFS collected information from shippers about specific intercity freight shipments, including the commodity, origin, destination, shipment size in tons, and the mode or modes of transportation used. Shipment distance by mode was not collected, so a multimodal network model was used to find routes through the U.S. freight transportation network, thereby allowing estimation of mileage by mode for each shipment in the survey. To allow for multimodal routings, the separate modal networks were connected at appropriate locations using intermodal transfer links.

Establishing analytically correct intermodal transfer links for a multimodal network is not a simple undertaking. To a first approximation, one could use GIS software to find nodes of different modes that are within some threshold distance of each other, and simply establish mode-to-mode connectors at all such locations. This, however, ignores the investment cost and special-purpose nature of intermodal transfer facilities, and tends to overestimate the number of intermodal connectors.

To assist with these types of applications, the NTAD includes a file called the Intermodal Terminal Facilities data set. The Oak Ridge National Laboratory developed the intermodal terminal facility data from which this database was derived. This database contains geographic data for trailer-on-flatcar (TOFC) and container-on-flatcar (COFC) highway-rail and rail-water transfer facilities in the United States. Attribute data specify the intermodal connections at each facility; i.e., the modes involved in the intermodal transfer, the AAR reporting marks of the railroad serving the facility, the type of cargo, and the direction of the transfer. These latter two attributes are extremely important. Even though two modes may have an intermodal connection at a given point, it does not follow that all commodities carried by the two modes can interchange there. Typically, each such connector handles only one commodity or type of commodity. For example, a coal terminal will not usually handle grain or petroleum products. Further, the transfer facility may serve flows only in one direction. A waterside coal transfer terminal, for example, may allow dumping from rail cars to barges but may not provide facilities for lifting coal from barges into rail cars. These examples illustrate why a simple proximity analysis method is unlikely to yield correct identification of intermodal connector links.

Attribute data for the Intermodal Terminal Facilities data set were extracted from the Intermodal Association of North America (IANA) 1997 Rail Intermodal Terminal Directory, the Official Railway Guide, the TTX Company Intermodal Directory, the Internet home pages of several railroads, the U.S. Army Corps of Engineers Port Series Reports, Containerization International Yearbook, the 1996 Directory of the American Association of Port Authorities (AAPA), and various transportation news sources, both in print and on the Internet. Attribute data reflect conditions at TOFC/COFC facilities during 1995–96 and are subject to frequent change. The database does not include TOFC/COFC and marine container facilities known to have been closed before or during 1996. However, because of the frequent turnover of this type of facility, some of the terminals included in the database may now be dormant or permanently closed.

The locations of TOFC/COFC facilities were determined using available facility address information and MapExpert, a commercial nationwide digital map database and software package, and recording the longitude/latitude of the approximate center of the facility. Facility locations are not bound to any current or previous highway, railway, or waterway network models. This is an advantage in that the facility locations in the database will be unaffected by changes in the other networks. Figure 1.3 shows some of the intermodal terminals that are included in the NTAD.

Further work for the CFS has validated the use of modal and multi-modal networks for national and regional commodity flow studies. A recent paper by Qureshi, Hwang, and Chin (2002) documents the advantages.

1.5 NETWORK MODEL APPLICATIONS

Section 1.2.2 briefly described use of transportation network models for national-level studies, an area of activity that dates back more than 20 years. Recent transportation studies carried out by states and Metropolitan Planning Organizations (MPOs), however, demonstrate that this type of analytical work is now within the reach of engineers and planners at those levels.

The prototypical use of network modeling at the state level is for statewide transportation planning. Horowitz and Farmer (1999) provide a good summary of the state-of-the-practice. Statewide passenger travel models tend to follow the urban transportation planning paradigm, using features such as separate trip generation and trip distribution models, and assignment of traffic to a statewide highway network. Michigan has one of the most well-developed statewide passenger models (KJS Associates, Inc. 1996). Statewide freight models also tend to follow this paradigm, with a focus on truck traffic on highways. Indiana (Black 1997) and Wisconsin (Huang and Smith 1999; Sorratini 2000) have mature statewide freight models, and Massachusetts (Krishnan and Hancock 1998) recently has done similar work.

Sivakumar and Bhat (2002) developed a model of interregional commodity flows in Texas. The model estimates the fraction of a commodity consumed at a destination that originates from each production zone for that commodity. The model includes the origin-destination distances by rail and truck, which were determined using the U.S. highway and rail networks that are included in TransCAD.

Work by List et al. (2002) to estimate truck trips for the New York City region is representative of freight network analysis activity at the MPO level. The model predicts link use by trucks based on a multiple-path traffic assignment to a regional highway network composed of 405 zones, 26,564 nodes, and 38,016 links. The model produced an excellent match between predicted and observed link truck volumes ($R^2 > 95\%$).

Switching back to the national level, Hwang et al. (2001) produced a risk assessment of moving certain classes of hazardous materials by rail and truck. They used national rail and highway network routing models to determine shipping routes and population densities along the routes for toxic-by-inhalation chemicals, liquid petroleum gas, gasoline, and explosives. Their work is fairly representative of network-based risk assessment methods. They assessed the routing results as follows: “Although the modeled routes might not represent actual routes precisely, they adequately represented the variations in accident probability, population density, and climate that characterize the commodity flow corridors for each hazardous material of interest.” A similar statement could be made about most transportation network analysis results.

1.6 ACKNOWLEDGMENT

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1.7 REFERENCES

Black, W. R. 1997. *Transport Flows in the State of Indiana: Commodity Database Development and Traffic Assignment, Phase 2*. Transportation Research Center, Indiana University, Bloomington, IN, July.

Bronzini, M. S., S. Chin, C. Liu, D. P. Middendorf, and B. E. Peterson. 1996. *Methodology for Estimating Freight Shipment Distances for the 1993 Commodity Flow Survey*. Bureau of Transportation Statistics, U.S. Department of Transportation.

Bronzini, M. S., A. F. Hawn, and F. M. Sharp. 1978. ''Impacts of Inland Waterway User Charges.'' *Transportation Research Record* 669:35–42.

Bronzini, M. S., D. P. Middendorf, and R. E. Stammer, Jr. 1987. ''Analysis of the Transportation Elements of Alternative Logistics Concepts for Disposal of Spent Nuclear Fuel.'' *Journal of the Transportation Research Forum* 28(1):221–29.

Bureau of Transportation Statistics (BTS). 1997. *Truck Movements in America: Shipments From, To, Within, and Through States*. BTS/97-TS/1, Bureau of Transportation Statistics, U.S. Department of Transportation, Washington, DC, May.

———. 1998. *Truck Shipments Across the Woodrow Wilson Bridge: Value and Tonnage in 1993*. BTS/98-TS/3, Bureau of Transportation Statistics, U.S. Department of Transportation, Washington, DC, April.

———. 2002. *National Transportation Statistics 2002*. BTS02-08, Bureau of Transportation Statistics, U.S. Department of Transportation, Washington, DC.

———. 2003. *Pocket Guide to Transportation*. BTS03-01, Bureau of Transportation Statistics, U.S. Department of Transportation, Washington, DC.

Federal Highway Administration (FHWA). 2001. *Our Nation's Highways 2000*. FHWA-PL-01-1012, Federal Highway Administration, U.S. Department of Transportation, Washington, DC.

Horowitz, A. J., and D. D. Farmer. 1999. ''Statewide Travel Forecasting Practice: A Critical Review.'' *Transportation Research Record* 1685:13–20.

Huang, W., and R. L. Smith, Jr. 1999. ''Using Commodity Flow Survey Data to Develop a Truck Travel-Demand Model for Wisconsin.'' *Transportation Research Record* 1685:1–6.

Hwang, S. T., D. F. Brown, J. K. O'Steen, A. J. Policastro, and W. E. Dunn. 2001. ''Risk Assessment for National Transportation of Selected Hazardous Materials.'' *Transportation Research Record* 1763: 114–24.

KJS Associates, Inc. 1996. *Statewide Travel Demand Model Update and Calibration: Phase II*. Michigan Department of Transportation, Lansing, MI, April.

Krishnan, V., and K. Hancock. 1998. ''Highway Freight Flow Assignment in Massachusetts Using Geographic Information Systems.'' 77th Annual Meeting, Transportation Research Board, Washington, DC, January.

List, G. F., L. A. Konieczny, C. L. Durnford, and V. Papayanoulis. 2002. ''Best-Practice Truck-Flow Estimation Model for the New York City Region.'' *Transportation Research Record* 1790:97–103.

Qureshi, M. A., H. Hwang, and S. Chin. 2002. ''Comparison of Distance Estimates for Commodity Flow Survey; Great Circle Distances versus Network-Based Distances.'' *Transportation Research Record* 1804:212–16.

Sivakumar, A., and C. Bhat. 2002. ''Fractional Split-Distribution Model for Statewide Commodity Flow Analysis.'' *Transportation Research Record* 1790:80–88.

Sorratini, J. A. 2000. ''Estimating Statewide Truck Trips Using Commodity Flows and Input-Output Coefficients.'' *Journal of Transportation and Statistics* 3(1):53–67.

USDOT/USDOE (1980). *National Energy Transportation Study*. U.S. Department of Transportation and U.S. Department of Energy, Washington, DC, July.