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Foreword

Issues related to providing access for certain types of trucks on the basis of their size and weight characteristics are discussed in the first two papers in this Record. The other four papers deal with the impact of trucks on traffic congestion and safety.

In northern states, spring freeze and thaw conditions make many roads susceptible to damage from heavy trucks. To minimize this damage, some states, including Minnesota, impose spring weight restrictions to reduce truck loads. However, these restrictions can increase costs and lower productivity for shippers and producers. With authorization from the state legislature, the Minnesota Department of Transportation has established a market artery system to eliminate spring weight restrictions on those state highways most important to economic and shipping activities. Bloom and Kreideweis describe methodology used for identifying the routes to be included in the market artery system as well as additional commercial access routes.

Enactment of the Surface Transportation Assistance Act of 1982 introduced major changes in the authorized sizes of tractor-semitrailer combinations that could be operated on designated truck routes within each state. Because these designated routes initially were designed for smaller trucks, the Wisconsin Department of Transportation was concerned with the adequacy of its intersection designs to accommodate longer trucks. Truby et al. describe a study of the dimensions and turning characteristics of tractor-semitrailer combination vehicles negotiating four rural interchange ramp intersections in Wisconsin. The study found that Wisconsin's intersection design standards are adequate for existing trucks but are only marginal for the new, longer trucks. The study also concluded that the California Department of Transportation (Caltrans) turning templates adequately described the turning path of the most common size truck observed operating at low speeds.

The next three papers in this Record were submitted in response to a request by the Committee on Urban Goods Movement, which had found that documentation on the effect of truck restrictions on the economics of urban goods movement and on the economics of the urban region was generally lacking. In addition, the effectiveness of various truck restriction strategies in reducing urban congestion had not been adequately recorded.

Grenzeback et al. report on the Urban Freeway Gridlock Study, undertaken for Caltrans at the direction of the state legislature. This study was prompted by concerns about freeway congestion and proposals to regulate large-truck traffic on freeways to reduce congestion. The study focused on freeway systems in three large metropolitan areas in California and addressed the impacts of large trucks, strategies to reduce congestion, and the economic effects of such strategies. Although the volume of large trucks on freeways does not have a significant effect on peak-period congestion, truck-involved incidents and accidents do have a significant effect. Large trucks contribute to congestion only on those few highly congested freeways where truck volumes exceed 10 percent of total vehicular traffic.

Jovanis et al. analyze a series of traffic regulations imposed in New York City on two crosstown streets and the effects of these restrictions on travel times. Comparisons of measured travel times before and after the restrictions were implemented indicate wide changes in congestion patterns. These variations may have resulted from the unprecedented combination of tactics that were simultaneously implemented at the site and the ensuing uncertainties in identifying the causes for travel time changes. An attempt to isolate the effect of curb restrictions from other factors suggests that measures other than restrictions on curbside loading and unloading may be more effective in providing priority for selected road users.

Reilly and Hochmuth examine the effects of currently imposed truck restrictions on transportation demand estimates, the mix of trucks in congested traffic, and truck travel times and trip length. Their analysis shows that truck restrictions negatively affect the transportation industry by causing longer truck travel times and trip lengths. Moreover, such restrictions do not appear to be effective in reducing overall congestion in selected locations.

The concept of imposing certain restrictions on truck operations on multilane highways has been identified as a means of reducing the negative effects of increased truck operation on safety and traffic flow on interstate and primary highways. Garber and Gadiraju describe their study of the nature and extent of the impacts on traffic flows, speeds, headways, and accident patterns of such truck strategies as restricting trucks to specific lanes or imposing a lower speed limit for trucks. Simulation techniques were used to study these effects on multilane highways. The study results did not indicate any safety benefits from these strategies but suggested that a potential for increased accident rates would be created, particularly on highways with high traffic volumes and a high percentage of trucks.

Developing a Market Artery System To Identify Priority Commercial Truck Routes

JON A. BLOOM AND JONETTE R. KREIDEWEIS

In northern states, spring freeze and thaw conditions make many roads susceptible to damage from heavy trucks. To minimize this damage, some states, including Minnesota, impose spring weight restrictions to reduce truck loads. In 1986 legislation authorized the Minnesota Department of Transportation to establish a market artery system to eliminate spring weight restrictions on those state highways most important to economic and shipping activities. Criteria for population, retail and wholesale sales, and manufacturing employment were used to identify significant centers. Nearly 4,800 mi of state trunk highway market artery routes was identified to connect centers that represent at least two-thirds of the state's population and economic activities. These routes carry more than 80 percent of the state's five-axle truck travel. In addition, about 2,800 mi of commercial access routes was identified to connect other important commercial centers to the market artery system. The market artery and commercial access systems will be used to determine future road-strengthening priorities. Study results are also applicable to other activities, such as the designation of routes for the national truck network and highway system. In addition, Minnesota's market artery methodology may be useful to others in addressing trucking and shipping needs in their areas.

Trucks have become predominant players in the nation's efforts to increase productivity and compete more effectively in the global marketplace. In recent years, there has been a phenomenal growth in travel by larger and heavier tractor-semitrailer combinations. The use of heavier trucks has resulted in larger payloads, reduced trips for shippers, and cost savings for producers and consumers. However, heavier trucks have also created added stress on highway pavements. This stress has the potential to accelerate pavement deterioration and increase roadway repair costs. These effects are particularly important for many of the nation's older highways, which were not designed to carry the heavier loads of today's vehicles.

Moisture in subgrade soils from thawing frost and spring rains leaves roadbeds in their weakest condition. This weakness in the soils reduces stability and strength in highway pavements. Heavy trucks traveling over these pavements increase the possibility for accelerated deterioration and pavement breakups.

To reduce the possibility of damage caused by heavier trucks, the Minnesota Department of Transportation (Mn/DOT) imposes spring weight restrictions on structurally weak highways under its jurisdiction. These weight restrictions are generally in effect from March 15 to May 15 of each year. Spring weight restrictions can cause difficulties for shippers and producers. Using smaller trucks or shipping less-than-full loads to comply with posted spring weight restrictions results in higher operating costs for shippers. These restrictions also could diminish the state's attraction for new business development.

In Minnesota, the maximum gross vehicle weight permitted for five-axle, tractor-semitrailer truck combinations on state trunk highways (those highways under the jurisdiction of Mn/DOT) is 10 tons per single axle or 80,000 lb per truck. In 1984 only about 18 percent (2,160 mi) of Minnesota's 12,100-mi state trunk highway system was open year-round to maximum five-axle truck gross vehicle loads of 80,000 lb. Table 1 presents state trunk highway mileage distribution among the various weight restriction categories in the spring of 1984.

Mn/DOT began reassessing its weight management policies in 1984. A number of actions were implemented to support state economic development objectives and improve shipping productivity. For example, the number of weight restriction categories was reduced. More important, a risk management philosophy was implemented to decrease spring weight restrictions and expand the number of miles open all year to gross vehicle loads of 10 tons per single axle or 80,000 lb. Under this philosophy, spring weight restriction signs were removed from many highway segments in response to public and shipper comments. These actions were taken despite pavement strength testing data that showed many of these routes to have inadequate structural capacity to carry heavier loads. Mn/DOT reserved the right to impose weight restrictions again, if necessary, to prevent significant deterioration.

Removing weight restriction signs without strengthening highways to allow them to carry additional weight is not an acceptable long-term solution. Many of these roads are not structurally designed to accommodate heavier trucks. Therefore, they will experience accelerated deterioration and possible roadway failures. On the other hand, the cost of upgrading all 12,100 mi of the state's trunk highway system to carry

TABLE 1 MN/DOT TRUNK HIGHWAY SYSTEM MILEAGE BY SPRING WEIGHT RESTRICTION CATEGORIES: 1984

Weight per Single Axle (tons)	Miles
5	1,310
6	720
7	1,830
8	90
9	5,980
10	2,160
Total	12,090

Minnesota Department of Transportation, Transportation Building, St. Paul, Minn. 55155.

80,000-lb truck loads is prohibitive. In 1985 an Mn/DOT report estimated that the short- and long-term costs of establishing a statewide trunk highway system capable of carrying 80,000-lb loads would be over $32 million per year just for road strengthening (*1*). To put this into context, Mn/DOT spent about $35 million in 1988 to address total reconstruction needs on the 12,100-mi state trunk highway system. Road strengthening needs of this magnitude would require diverting funding resources away from other high-priority highway and bridge improvement needs.

MARKET ARTERY LEGISLATION

Discussion of truck weight management activities and the desirability of opening more roads to year-round 80,000-lb gross vehicle loads was a frequent topic in the state legislature in the 1980s. In 1986 the legislature determined that insufficient resources were available to eliminate spring weight restrictions on all highways in the state. The result was the passage of legislation authorizing Mn/DOT to establish a market artery system (Minnesota Statutes, Chap. 169.832, Subdivision 13, 1986).

The market artery legislation provided more focus and direction to the management of spring truck axle weight restrictions. For example, the legislation was applied only to highways under the jurisdiction of Mn/DOT; county, city, and township roads were excluded. In addition, the legislation included specific language to help Mn/DOT identify market artery routes most important to trucking and shipping activities.

In the legislation, market arteries were identified as state trunk highways that

- Connect significant centers of population or commerce,
- Connect highways that connect significant centers of population or commerce,
- Provide access to transportation terminals, and
- Provide temporary emergency service to particular shipping or receiving points on market arteries.

Mn/DOT was required to notify the legislature of any spring weight restrictions on designated market artery routes. The law further specified that notices must include plans showing how improvements would be made within 3 years so that the restrictions would no longer be necessary on these routes.

The passage of the market artery legislation triggered an extensive study identifying state trunk highway routes most important to population and commercial activity centers. It also initiated a process to enhance the sensitivity of Mn/DOT's trunk highway project programming process to road strengthening needs throughout the state. The market artery study represented the department's first comprehensive attempt to base statewide truck weight management decisions on economic activities rather than on pavement conditions or strength testing data.

IDENTIFYING MARKET ARTERIES—STUDY APPROACH AND METHODOLOGY

The steps taken to define the levels of population and commercial activities that warrant year-round unrestricted truck service are defined and how market artery routes were identified to connect significant centers in Minnesota, surrounding states, and Canadian provinces is explained. In addition, information is included outlining Mn/DOT's philosophy for managing spring weight restrictions on market arteries, other important commercial access routes, and low-volume local and regional access routes. The information obtained from the study will be used to identify future roadway-strengthening priorities for highways under the jurisdiction of Mn/DOT. Study findings and results will also be applicable to other Mn/DOT highway planning activities.

Step 1—Reviewing Available Data and Information

The 1986 legislation specified that the market artery system be made up of routes that connect significant centers of population and commerce. To determine appropriate market artery route connections, criteria had to be identified for defining which cities fit this specification. Two key studies provided background information on the evolution and growth of important trade centers in Minnesota. These studies also provided valuable information on accepted guidelines for measuring the relative importance of metropolitan areas and regional centers. The first study (*2*), conducted in 1963 by John Borchert at the University of Minnesota, identified a hierarchy of trade centers in the Upper Midwest. The classification system developed by Borchert was based on the theory that urban places are arranged in a hierarchical order according to the size and diversity of wholesale and retail functions. Borchert measured diversity specialization by the number of wholesale and retail establishments and the dollar value of annual wholesale and retail sales.

In the second study (*3*), conducted in 1970, Borchert noted that settlement patterns in the Upper Midwest were evolving into urban clusters. He suggested that in future years most of the population in the Upper Midwest would be concentrated in the Minneapolis–St. Paul metropolitan area and other low-density urban clusters located throughout Minnesota. The number and diversity in retail and wholesale activities were used to establish a relative ranking of urban clusters.

The activities of other state transportation departments were also consulted as a part of Mn/DOT's study. For example, a priority commercial network (PCN) has been identified in Michigan to help establish highway project priorities. A production and attraction gravity model uses data on wholesale sales, manufacturing, tourism, and forestry to identify priority commercial routes, which carry products to the most likely attraction, user, or processor sites (*4*).

In Iowa, a commercial and industrial highway network has been identified as part of the Iowa Transportation 2000 investment package. The 2,000-mi network provides a high standard of service to all regional growth centers with 20,000 or more people located in the center of 30-min to 1-hr commuter sheds. According to the Iowa Department of Transportation, routes included in the commercial and industrial network generally carry approximately 3,000 average vehicles and 250 tractor-semitrailers each day.

Pennsylvania has established a 12,000-mi PCN made up of the state's most important commercial routes for the movement of materials and manufactured products. An agricultural access network has also been identified to provide service for lumber, milk and poultry products, feed mills, and fertilizer plants. These networks will guide future Pennsylvania roadway improvement decisions (*5*).

The Michigan, Iowa, and Pennsylvania studies were particularly useful in helping Mn/DOT identify the specific types of economic activities and population levels believed to be most important to trucking and shipping activities. To obtain information on existing economic conditions and emerging shipping trends in Minnesota, Mn/DOT personnel met with geographers, regional planners, and representatives from the Minnesota Department of Trade and Economic Development. These discussions were useful in deciding how study results from other states could be applied to conditions in Minnesota.

With information from studies and interviews, Mn/DOT staff began a comprehensive review of the census data available for cities regarding population, business, and economic development activities. These efforts revealed four significant trends.

First, the data reaffirmed the dominance of the Minneapolis–St. Paul metropolitan area in overall state population and business activities. About 50 percent of the state's 4.2 million people live in the seven counties that make up the Twin Cities metropolitan area.

Second, the data showed ongoing growth, prosperity, and concentration of economic activities in the state's other major urbanized areas. Urbanized areas with populations of over 50,000, such as the cities of Duluth, Rochester, St. Cloud, and Mankato, are expanding their service areas and becoming major regional centers for retail, service, and educational activities.

The third trend was the predictable decline of many small town retail and service functions. Population losses have occurred in more than half of the 616 cities in Minnesota's nonmetropolitan counties during the 1980s, and many main street retail trade centers in small towns are fading away (*6*).

The fourth and most surprising trend revealed by the data was the large number of significant small-town manufacturing and wholesaling establishments scattered throughout the state. This trend was recently discussed in an article (*7*) by John Fraser Hart of the University of Minnesota. Hart noted that much of the population increases in midwestern small towns since World War II are the result of expanded manufacturing employment in nonmetropolitan areas. He suggests that the future of small towns depends on their ability to adapt from agricultural service functions to manufacturing. Further evidence of this trend was reported in a recent newspaper article, which stated that employment in manufacturing was growing twice as fast in areas outside the Twin Cities metropolitan area as inside the area (*8*).

The evidence of the large number of dispersed small-town manufacturing and wholesale establishments caused Mn/DOT to reassess its thinking about population and business centers. Population alone was not a reliable indicator of the need for year-round heavy-truck service. The following examples reflect the trucking and shipping needs of several selected small-town businesses in Minnesota:

- The city of Warroad (population 1,200), located in far northwestern Minnesota, is the home of Marvin Windows, a national producer of window and specialty glass products, which employs over 3,000.
- In southwestern Minnesota, the town of Round Lake (population 480) is the home of Sathers, Inc., a major nationwide wholesale producer and distributor of cookies, candies, and bakery products, with estimated annual revenues in excess of $102 million (*9*, p. 347).
- The unincorporated city of Bongards, west of the Twin Cities metropolitan area, is the location of one of the largest dairy operations in the world.
- In western Minnesota, the town of Frazee (population 1,284) has nearly 2,200 persons employed in poultry processing.

The presence of businesses scattered throughout the state made it clear that a flexible definition of significant centers of population and commerce was needed to address their important trucking and shipping needs.

Step 2—Involving the Public in the Market Artery Study

The market artery study elicited considerable interest among shippers, producers, and county and local government officials concerned with the effects of state weight management activities.

A public involvement process was established early in the study to explain study goals and objectives and solicit comments and opinions from the public and the county and local governments. Minnesota's active Regional Development Commissions (RDCs) provided a logical forum for coordinating these activities. With the help of the RDCs, 12 public meetings were held throughout the state. Attendees included nearly 270 highway users and representatives of manufacturing, retail trade, shipping, agriculture, and county and local government. The comments and opinions helped refine Mn/DOT criteria for defining significant centers of population and commerce. In addition, the input helped department staff recognize important trucking and shipping needs missed by traditionally reported census and manufacturing directories. Public comments also identified the need for comprehensive truck weight management strategies that addressed the total state highway system in addition to market artery connections between significant centers.

Step 3—Choosing Criteria To Define Significant Centers

On the basis of the analysis undertaken and the comments received, significant centers of population and commerce were defined as

- Cities in Minnesota that meet any one or more of the following criteria:
  - Population of 5,000 or more,
  - $50 million or more in annual retail sales,
  - 450 or more manufacturing employees, or
  - $50 million or more in annual wholesale sales.
- Cities in surrounding states or Canadian provinces that have populations of 50,000 or more.

The numerical values were based on logical breaks in the distribution of data for each of the criteria. It was also determined that numerical values should be selected on the basis of their ability to encompass roughly two-thirds of the state's total population and commercial activities.

The definition of significant centers of population and commerce permits cities to be identified as significant centers if they meet any one of the criteria for population, retail sales, manufacturing employment, and wholesale sales. This liberal definition was adopted for two reasons. First, it became apparent that there was considerable legislative, public, and business support for a definition that would ensure access to a market artery route and year-round unrestricted service for an optimum number of economic activity centers. Second, economic trends supported the development of a flexible definition that relied on more than one measure of a city's economic activity.

This liberal definition permitted Mn/DOT to address the shipping needs of many smaller towns with significant manufacturing and wholesale activities. As a result, when the data for all the cities in Minnesota meeting the criteria were added together, approximately 64 percent of the state's population, 82 percent of annual retail sales, 78 percent of manufacturing employment, and 88 percent of annual wholesale sales were represented.

The population and economic censuses prepared by the U.S. Department of Commerce, Bureau of the Census, were used as the primary sources of data to determine whether cities met the criteria. These sources were chosen because they provide the most readily available and consistently reported data on city population and commercial trends. The censuses, however, had several major shortcomings.

First, much of the data were old—population information dated back to 1980 and data on economic activities were last reported in 1982. Another drawback was the lack of information available on cities with fewer than 2,500 persons. Data privacy provisions also resulted in the withholding of information on specific business activity levels in cities with a single major employer. These shortcomings were overcome by using supplementary directories of business activities and by contacting the RDCs, company representatives, chambers of commerce, and local units of government. The following paragraphs summarize the reasons for selecting the criteria used to define significant centers of population and commerce.

Population

Population was used as a criterion because it was identified in the legislation. In addition, population is generally considered a reliable measure of the importance and relative economic strength of cities. The numerical value for populations was set at 5,000 or more persons. This value was selected because it has historically been used for other transportation programs in Minnesota. For example, current state law requires that 9 percent of the net revenues of the Minnesota Highway User Tax Distribution Fund be paid to the municipal state aid street fund. Municipal state aid street fund revenues, in turn, may only be spent on state aid streets in cities with more than 5,000 persons (Minnesota Statutes, Section 12.09, 1986). The population value of 5,000 or more is also used to define urban areas in federal highway regulations (*Code of Federal Regulations*, Part 470.103, Subdivision (b)(1), p. 99, rev. April 1, 1988).

Retail Sales

The retail sales criterion came from the legislation, which defined significant centers of population and commerce as all cities that had total retail sales of at least $50 million as reported in the 1982 Census of Retail Trade of the U.S. Department of Commerce.

Manufacturing and Wholesaling

Criteria for manufacturing and wholesaling were added to the definition of significant centers because these activities are good indicators of the need for heavy-truck service. For example, manufacturing includes the state's food and kindred products, lumber and wood products, paper printing and publishing, chemicals, primary metals, fabricated metals, machinery, electric and electronic equipment, and transportation equipment industries. Wholesaling includes all establishments that sell goods, such as groceries, furniture and home furnishings, lumber and construction materials, and farm product raw materials to industrial, commercial, institutional, or professional users; to government; or to farmers for farm use.

The number of manufacturing employees was selected as a reasonable measure of the need for heavy-truck service. This assumption is based on the traditional view of manufacturing as a labor-intensive activity with a strong positive correlation between the volume of goods produced and the number of production workers employed. The numerical value of 450 manufacturing employees was chosen because it is the smallest unit reported in the Census of Manufactures. The dollar value of annual wholesale sales was selected as an appropriate indicator for measuring business size and associated shipping levels.

Other indicators of a city's economic diversity, such as service industries or tourism, were not used to define significant centers because there was no strong evidence of a relationship between these activities and the need for year-round service by large heavy trucks.

Using the four selected criteria, 67 cities in the Minneapolis–St. Paul metropolitan area and 82 cities located outside of the metropolitan area were identified as significant centers of population and commerce.

Step 4—Identifying Market Artery Connections Between Centers

The next step in the study process involved identifying market artery connections between the significant centers. The methodology for connecting centers was based on the assumption that shipments from lower-order centers are most naturally attracted to higher-order centers.

To determine attraction patterns, significant centers were ranked from high to low for each of the four criteria. The four relative ranks for each significant center were then summed and a relative ranking was established of all the cities identified as significant centers. The result was a composite ranking that listed places with the largest populations and highest levels of economic activity at the top and those with the smallest populations and least economic diversity at the bottom.

Starting at the top of the list, the Minneapolis–St. Paul metropolitan area was connected to other major urbanized areas in surrounding states and Canada. Using the ranking, all other significant centers in Minnesota were connected to higher-order centers. Connections were made following state trunk highways that showed the strongest patterns of interaction and attraction, primarily on the basis of five-axle truck traffic counts. If centers showed relatively equal attractions in multiple directions, more than one route was chosen. Further minor adjustments were made to provide logical interconnections within the network once a skeletal system was identified. Using this methodology, approximately 4,800 mi of state trunk highway market artery routes was identified for connecting the significant centers throughout the state.

ADDRESSING OTHER IMPORTANT COMMERCIAL ACCESS NEEDS

As the effort to identify a market artery system progressed, it was apparent that the system would only resolve weight management issues on a limited number of state trunk highways. Public comments and business concerns suggested that shipping requirements on additional state trunk highways needed to be addressed. As a result, three categories were identified to define route functions and describe the appropriate weight management philosophies applicable to all roadways under the jurisdiction of Mn/DOT. Definitions and management philosophies adopted for each of these categories follow.

Category 1—Market Artery System

The market artery system will provide guaranteed, year-round, unrestricted service between significant centers of population and commerce on nearly 40 percent of Minnesota's state trunk highway system. These highways carry over 80 percent of the five-axle heavy commercial travel in Minnesota. Market artery routes have been identified as priority routes for the elimination of truck axle weight restrictions in the spring. Mn/DOT's highway improvement programming process is currently being adjusted so that the routes with load-carrying capacity deficiencies are given special consideration in future investment decisions.

Category 2—Commercial Access Routes

Commercial access routes make up the second category of Mn/DOT's weight management approach. These routes connect important commercial places to the market artery system. Commercial places do not have the economic diversity or strength of significant centers. Nonetheless, they represent important activity areas for the state's economy.

For this study, commercial places were defined as cities in Minnesota with one or more of the following economic activities:

- Manufacturing (more than 100 employees);
- Major dairies with multiple processing operations (cheese, milk, and butter);
- Large grain elevators with permanent storage capacity of more than 670,000 bushels; and
- Major log and timber processors.

Commercial places identified in Minnesota that were not already served by market artery routes totaled 160. Connections between commercial places and the market artery system were based on an assessment of truck traffic patterns and an evaluation of where Mn/DOT was most willing to risk access for the anticipated heavier-truck traffic. Commercial access routes were also designated to serve as supplemental linkages between significant centers of population and commerce. Alternative connections between significant centers were designated as commercial access routes if they carried at least one-half of the five-axle commercial traffic on the designated market artery route. Approximately 2,800 mi of state trunk highway commercial access routes were designated.

To minimize or eliminate weight restrictions, Mn/DOT's management philosophy for commercial access routes authorizes district offices to take risks beyond those suggested by strength-testing data. The Mn/DOT highway programming process will be modified to incorporate commercial access routes in overall project ranking decisions.

Category 3—Local and Regional Access Routes

Local and regional access routes make up the third category in Mn/DOT's weight management approach. These highways primarily serve individual land holdings, such as farms, residences, and pulp-cutting sites. They provide for the first haul of agricultural, forest, or other products to local processing plants or storage facilities. They are also used for the last haul of fertilizer, feed, seed, and other products from distribution sites to farm or home use. These routes have low traffic volumes. Local and regional access routes are managed to preserve the life of the roadway by minimizing damage from heavy vehicles. This means that spring weight restrictions will continue to be imposed if pavement strength testing data warrant their use. Because of limited financial resources, local and regional access routes do not compete well for improvement dollars against more heavily traveled routes with higher-priority needs.

On local and regional routes, shippers are responsible for deciding how to manage loads during spring weight restriction periods. They may ship in advance of or after the weight restriction periods, or they may haul products during unrestricted periods and stockpile commodities at sites next to market artery or commercial access routes. Shippers may also ship in smaller, more divisible loads that comply with posted weight restrictions.

CONCLUSION

The Mn/DOT market artery study represented the department's first comprehensive attempt to base state truck weight management decisions on economic activities rather than on pavement conditions or strength-testing data. This paper describes the extensive data analysis and public involvement process that was used to identify economic activity areas and route connections important to trucking and shipping in Minnesota.

The road and weight management philosophies that resulted from the market artery study were implemented in 1989. Significant progress has already been made to improve shipping

TABLE 2 COMPARISON OF MN/DOT TRUNK HIGHWAY MILEAGE WITH SPRING WEIGHT RESTRICTIONS: 1984 AND 1989

Weight per Single Axle (tons)	Miles 1984	Miles 1989
5	1,310	540
6	720	0
7	1,830	2,320
8	90	0
9	5,980	0
Total restricted mileage	9,930	2,860
10	2,160	9,210
Total mileage	12,090	12,070

productivity on state trunk highway market artery and commercial access routes. Table 2 shows the progress that has been made since 1984 to reduce spring weight restrictions and increase the number of miles of trunk highway open year-round to 10-ton-per-axle or 80,000-lb gross vehicle loads.

The Mn/DOT market artery study will primarily be used to determine future state trunk highway road strengthening priorities. However, the study process produced a wealth of information on state economic activities that will be useful in a variety of other transportation planning studies and programs, including

- Managing requests for additions to Minnesota's National Truck Network,
- Identifying candidate routes for the proposed Highway System of National Significance,
- Evaluating the need for expanded four-lane highway connections to economic centers,
- Determining appropriate detour routes for scheduled highway construction projects, and
- Continuing communication with highway users, business interests, and local government officials.

The market artery study will be updated every 2 years. Hence, future changes in economic activities and shipping patterns can be incorporated into Mn/DOT weight management decisions.

Market artery study results, together with the significant reductions in spring weight restrictions, have met with considerable legislative, business, and community support. Concerns continue to be expressed regarding trucking needs on local and regional routes under the jurisdiction of Mn/DOT and on other roads in the state that are under the jurisdiction of counties and local units of government. Mn/DOT is working with state legislators and others to reassess transportation needs and develop a consensus on adequate, stable, and predictable highway funding to address these and other important transportation needs in Minnesota.

Transportation is the lifeline that links farms and cities and connects products with markets. The strength of a state's transportation system can determine its competitive advantage in the national and global marketplace. The market artery study reaffirmed the important role of state transportation agencies in enhancing economic development opportunities. Designated market artery and commercial access routes will permit Mn/DOT to target resources to highways that are most important to Minnesota businesses while maximizing the state's ability to address overall transportation needs.

The market artery study process described in this paper may be of use or interest to other state highway and transportation departments that are involved in identifying trucking, shipping, or economic networks.

REFERENCES

1. *Truck Weight Action Group Report.* Minnesota Department of Transportation, St. Paul, Jan. 1985.
2. J. R. Borchert. *The Urbanization of the Upper Midwest: 1930–1960.* Urban Report No. 2, Upper Midwest Economic Study. Geography Department, University of Minnesota, 1963.
3. J. R. Borchert and D. D. Carroll. *Minnesota Settlement and Land Use.* Minnesota State Planning Agency, St. Paul, 1970.
4. *Methodology for Determining Michigan's Priority Commercial Network.* Michigan Department of Transportation, Lansing, May 1985.
5. *Pennsylvania Agri-Access Network Statewide Report.* Pennsylvania Department of Transportation, Harrisburg, April 1985.
6. B. Von Sternberg and R. Meador, eds. Fading Away. *Star Tribune*, Section A, Part II, Oct. 30, 1988, pp. 29A–34A.
7. J. F. Hart. Small Town Manufacturing. *The Geographical Review*, Vol. 78, No. 3, July 1988, pp. 272–287.
8. C. Strouse. Rural Manufacturing Jobs Up Sharply. *Minneapolis/St. Paul City Business*, Oct. 31, 1988, pp. 1 and 22.
9. Engler-Budd & Company Inc. *Corporate Fact Book, 1988 Edition.* MCP Inc. Publishers, Dec. 1987.

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Operational Considerations Relating to Long Trucks in Rural Areas

Mark W. Truby, Dennis D. Hoagland, Philip H. DeCabooter, Clinton E. Solberg, and Wayne L. Ristau

Much effort has been devoted to the theoretical aspects of truck turning characteristics, but little has been done to test these theories by observing actual trucks turning. This study focused on the dimensions and turning characteristics of combination tractor-semitrailer vehicles negotiating four rural interchange ramp intersections in Wisconsin. An attempt was made to determine the adequacy of Wisconsin's intersection and ramp terminal design standards and to evaluate the ability of the California Department of Transportation (Caltrans) theoretical turning templates to describe the actual paths of turning trucks. It was found that Wisconsin's intersection design standards are adequate for existing trucks but only marginal for the new, longer trucks (such as Wisconsin's WB-62, which has an overall wheelbase of 61.7 ft). Also, the Caltrans turning templates adequately described the turning path of the most common truck observed operating at low speeds.

It is standard engineering practice to base the design of a proposed highway facility on the needs of a predetermined design vehicle. This is especially critical at intersections where these design vehicles are likely to turn.

Early research on the turning characteristics of various design vehicles was conducted by the Society of Automotive Engineers and the Western Highway Institute (*1*). Later, the University of Michigan Transportation Research Institute (UMTRI) developed a series of equations that became the basis of a computer program designed to describe the paths of turning vehicles. The California Department of Transportation (Caltrans) adapted and enhanced the UMTRI program to develop mainframe computer software that creates theoretical turning templates for a variety of possible design vehicles (*2*). This study was conducted, in part, to field validate the Caltrans model.

Before 1982, rural highways in the United States were designed to accommodate tractor-semitrailer combinations with overall wheelbases of either 40 ft (WB-40) or 50 ft (WB-50). The Surface Transportation Assistance Act (STAA) of 1982 introduced major changes. It authorized even longer tractor-semitrailer combinations to operate on a system of designated truck routes within each state. In Wisconsin this longer vehicle is known as a WB-62. Because the designated routes were for smaller trucks, the Wisconsin Department of Transportation (WisDOT) became concerned that its intersection designs were inadequate for longer trucks.

M. W. Truby, D. D. Hoagland, and C. E. Solberg, Central Office Design, Wisconsin Department of Transportation, P.O. Box 7916, Madison, Wis. 53707. P. H. DeCabooter and W. L. Ristau, Applied Research Section, Wisconsin Department of Transportation, 3502 Kinsman Boulevard, Madison, Wis. 53704.

This paper documents the efforts that WisDOT made to evaluate rural intersections and ramp terminals in Wisconsin. In this study, rural sites were differentiated from urban sites by their relatively lower traffic volume and their lack of signalized control. These conditions allow many truckers to execute their turns without coming to a complete stop. They also increase the likelihood that trucks will encroach on adjacent lanes.

An evaluation of urban-type intersections was addressed by DeCabooter and Solberg (*3*).

DATA COLLECTION

There were two main objectives in this study:

1. To evaluate the ability of existing rural intersections to accommodate larger trucks, especially at ramp terminals, and
2. To determine how well the Caltrans turning templates describe the low-speed maneuvers of actual trucks.

Because both of these objectives involved actual truck operational characteristics, data collection and analysis were a major part of the study.

Site Selection

This effort began with the review of a previous WisDOT report that identified those interchanges on the state system of designated truck routes that had the highest probability of operational problems. Interchange ramp terminals were selected as the best places to collect truck turning data. Because they are near controlled-access highways, they carry significant amounts of truck traffic. In addition, the geometrics of these sites are deliberately restrictive to discourage wrong-way traffic on ramps.

A multidisciplinary engineering team studied aerial photos of these sites to identify those intersections with the most restrictive geometrics. The team chose small median opening as the key restrictive geometric element. Finally, the most likely sites were inspected for signs of vehicle encroachment in their medians.

Actual volume of truck traffic was not used as a major criterion for site selection. The study team believed truck volume would be adequate for sampling along the entire designated system. Furthermore, the methods of data collection chosen rendered many high-volume traffic sites unsuitable.

The team finally selected four interchanges at which to collect data. They were

1. US-12 with WI-67, Elkhorn;
2. US-51 with I-90/94, Madison;
3. US-14 with I-43, Darien, and
4. US-41 with WI-23, Fond du Lac.

Figure 1 shows their locations, and Figures 2 through 5 show the configurations of the specific sites.

Types of Data

Because the size and location of median openings were considered the controlling geometric elements for truck maneuvers, the team concentrated on collecting data for left turns. Two types of data were collected. The first was dimensions of individual trucks (see Figure 6). The principal dimensions of interest were the effective tractor length (KP-1) and the effective trailer length (KP-2). These were used to classify vehicles and to learn what sizes of trucks are using Wisconsin's roads. To determine these dimensions, the location of the kingpin had to be identified. The location of the fifth wheel was established first. Then, based on previous research, the kingpin location was defined as the center of mass of the fifth wheel. The second type of data collected was the coordinates of key points on trucks as they negotiated through intersections. These were used to define the actual paths of the turning trucks.

Collection Methods

Data were collected by two methods:

1. Photographing trucks from a crane-mounted platform suspended over the intersection and

FIGURE 1 Study of long trucks, rural sites.

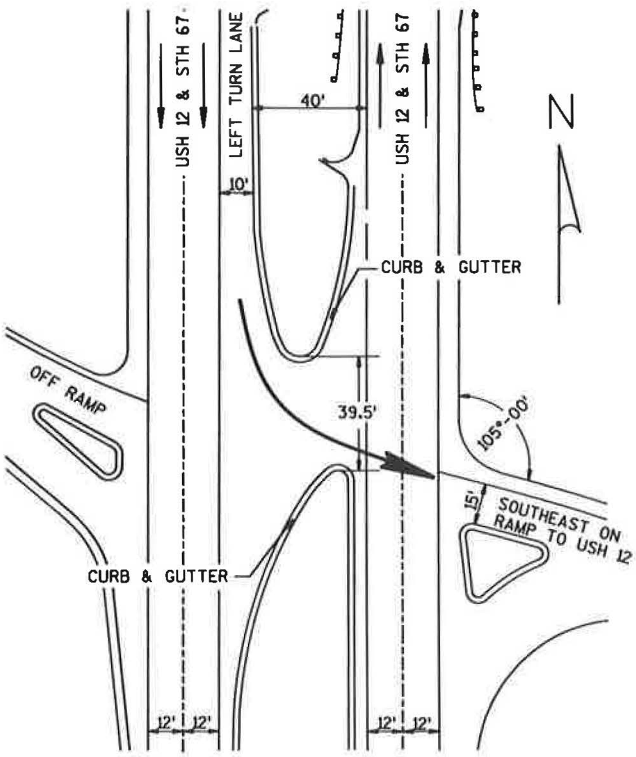

FIGURE 2 US-12 and WI-67, Elkhorn intersection.

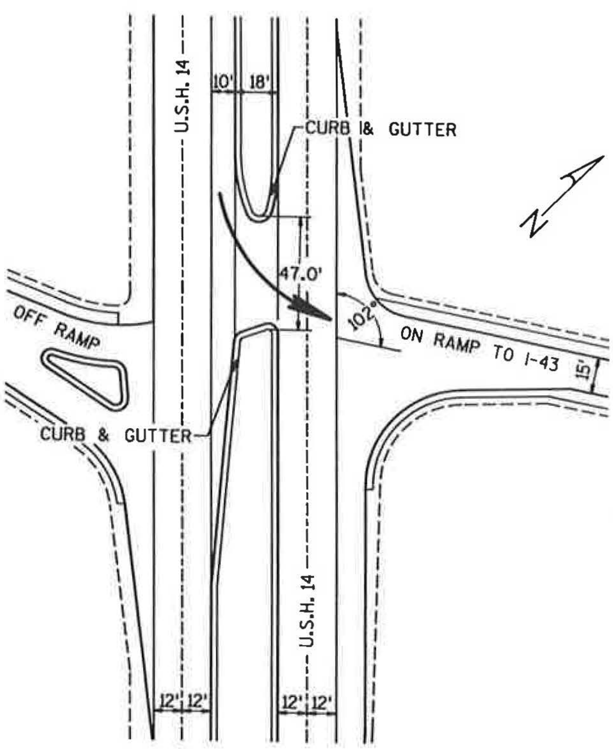

FIGURE 3 US-14 and I-43, Darien intersection.

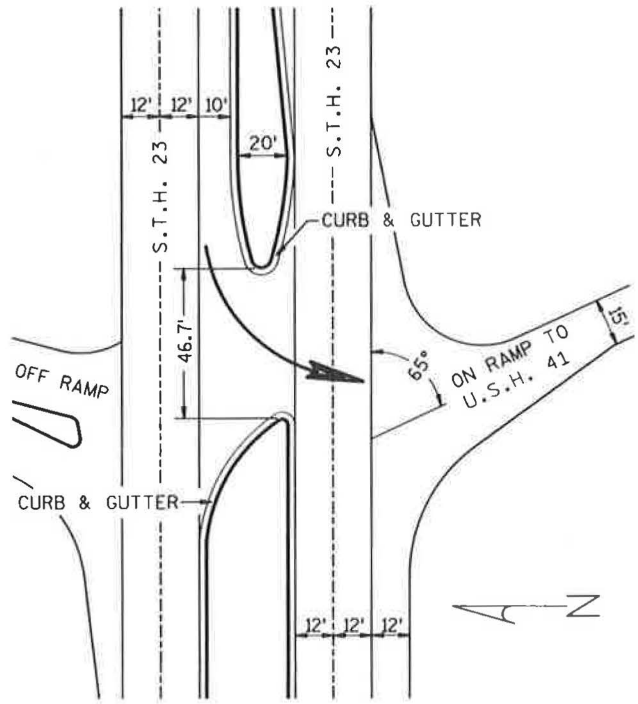

FIGURE 4 WI-23 and US-41, Fond du Lac intersection.

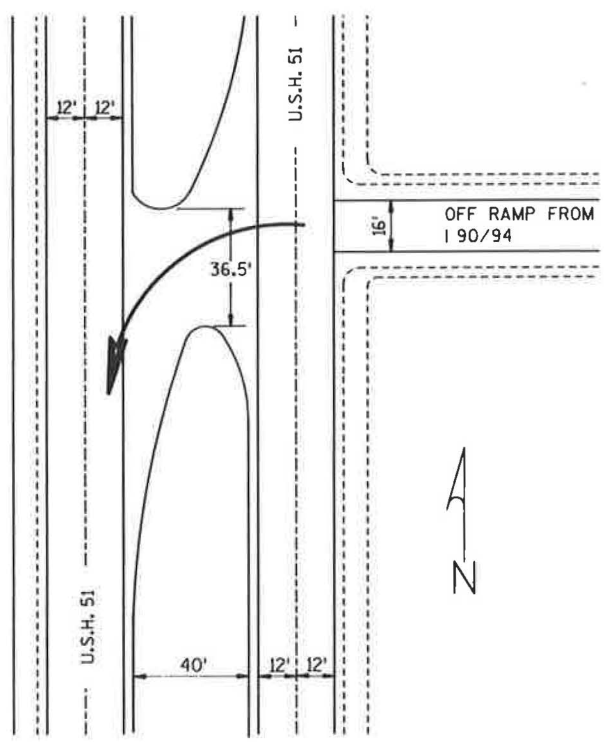

FIGURE 5 US-51 and I-90/94, Madison intersection.

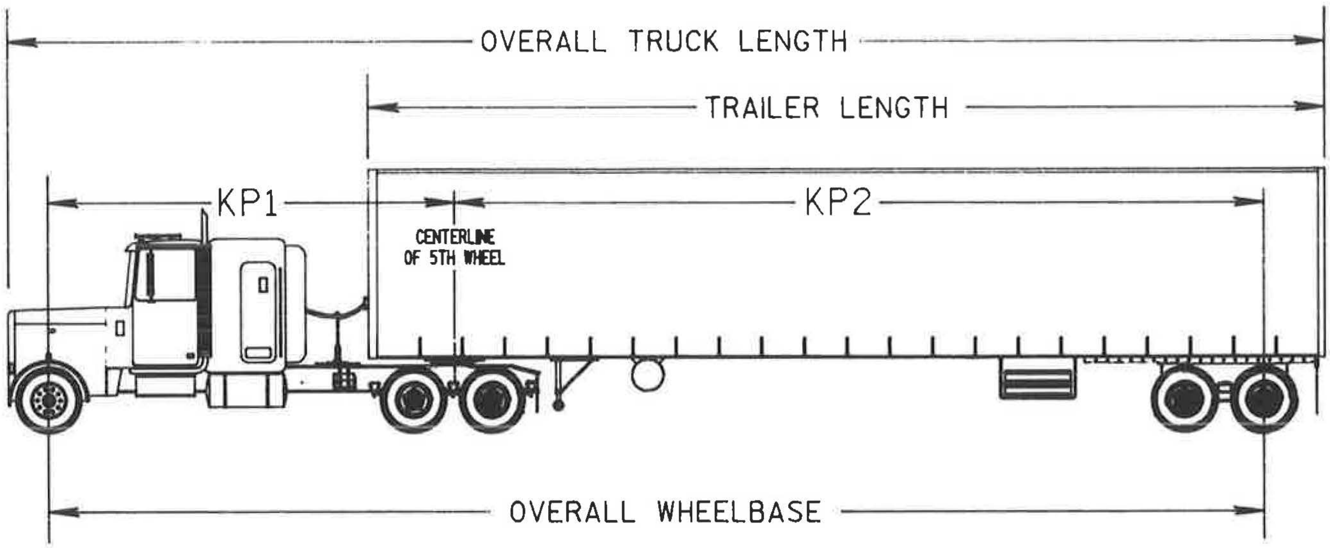

FIGURE 6 Dimensions captured on trucks.

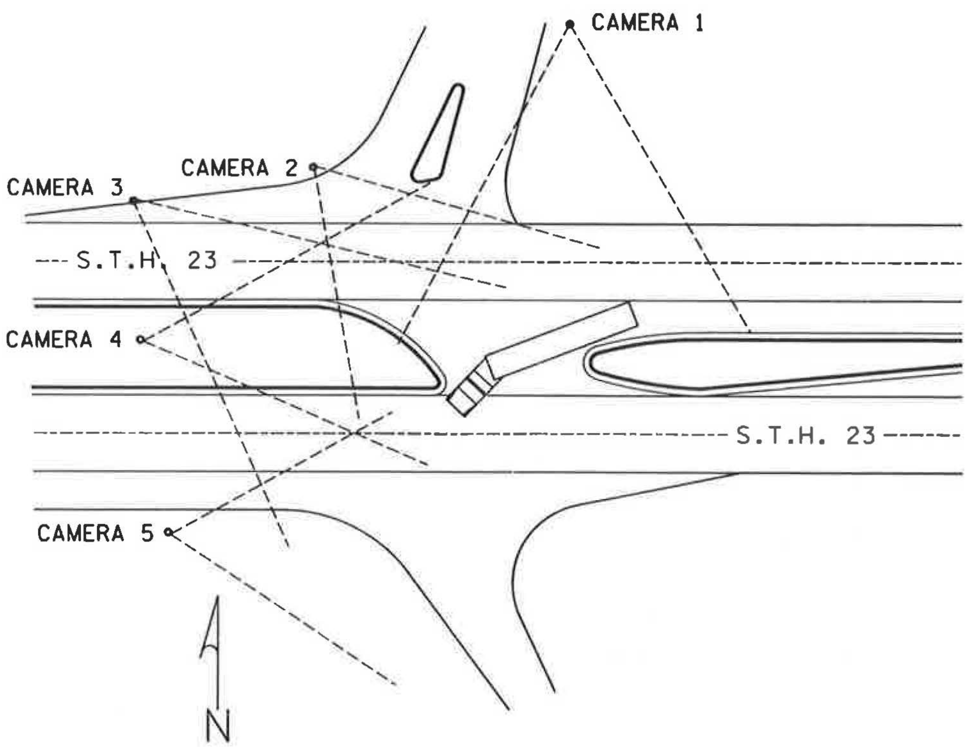

FIGURE 7 Typical camera locations.

2. Phototriangulation of trucks from a series of ground cameras.

The overhead photography method was used successfully at the Elkhorn site. However, this method could not establish the critical KP-1 and KP-2 dimensions by itself, so a second data collection method—phototriangulation—was used in conjunction with overhead photography. Researchers discovered that the overhead photography method was limited by local site conditions. In fact, it could not be used at the other sites due to high fill sections, overhead utility lines, or, in one case, an airport glide path.

The on-ground phototriangulation system developed by University of Wisconsin researchers used a series of nonmetric, single-lens reflex cameras mounted on tripods that were located strategically at the intersections. The cameras were positioned so that turning vehicles were visible within each of their fields of view for the entire turn (see Figure 7). This ensured good geometric strength in the photogrammetric solution obtained.

Simultaneous photographs were taken of each vehicle at five different points within its turning path. Simultaneity was achieved by firing a master switch that was electronically connected to each camera. At the time of photographing, control surveys were performed to support the photogrammetric calculations. Photographic coordinates of vehicle images and control point images were then measured in the University of Wisconsin Photogrammetric Laboratory using a newly developed digital projection system.

Phototriangulation was first tested as a supplement to the overhead photography at Elkhorn. Four cameras were set up, but the control mechanism malfunctioned on one. Therefore, there were problems with the data collected at this site. The fifth wheel location could not be identified for several trucks. Furthermore, three cameras could not provide enough points to define the turning paths adequately. For these reasons, the Elkhorn truck data were not used in this study.

After the Elkhorn experience, the system was redesigned to use five cameras, which all worked at the remaining three sites, significantly increasing the accuracy of the system. The only remaining problem was shadows. The cameras could not identify the fifth wheel location if it was in shadow. This limited the time period during which truck data could be collected. Once the number of cameras was increased and the shadow limitation was recognized, the system collected accurate, useful data.

OBSERVATIONS

Figures 8 through 10 show the truck dimension data for the three remaining sites. These graphs show a broad spectrum of truck sizes on Wisconsin's roads. This diversity is due in part to the number of different sizes that are manufactured, as well as to the variable settings possible for the rear dual axles on a semitrailer. Depending on the situation, the dual axles can be shifted forward or backward over a range of 10 ft. In fact, at the observed sites, none of the trucks fit the AASHTO definitions of a WB-40 or WB-50. Only 19 of the observations were categorized as new, longer trucks allowed by STAA, and these were mostly multiple passes of a special test vehicle at the Elkhorn site.

The wide range of truck sizes observed and the small number of the larger STAA vehicles encountered in this study agree with other data collected at a Wisconsin truck scale in 1985. These findings are also consistent with the data collected in 1987 by DeCabooter and Solberg in their evaluation of long trucks at urban intersections.

The results of the turning maneuver observations are shown in Figures 11 through 13. These figures show a wide variation in the paths taken by individual trucks. The data collection team observed that many truck drivers took advantage of low volumes of opposing traffic to make the most comfortable turn possible. This involved using the farthest possible outside lanes to begin or end their turns. On several occasions, the opportunity to turn without stopping permitted drivers to start or end their turns by encroaching into a lane not intended for that purpose.

Of the four sites observed, the Fond du Lac site offered the most restrictive geometric situation to turning vehicles. In this case, 82 percent of turning trucks started and ended their turns in the proper lanes. For this reason, the following analysis concentrates on that site.

ANALYSIS

Observations of the turning maneuvers at Fond du Lac revealed that most trucks negotiated the intersection without much difficulty. This was true even for the largest trucks. Those

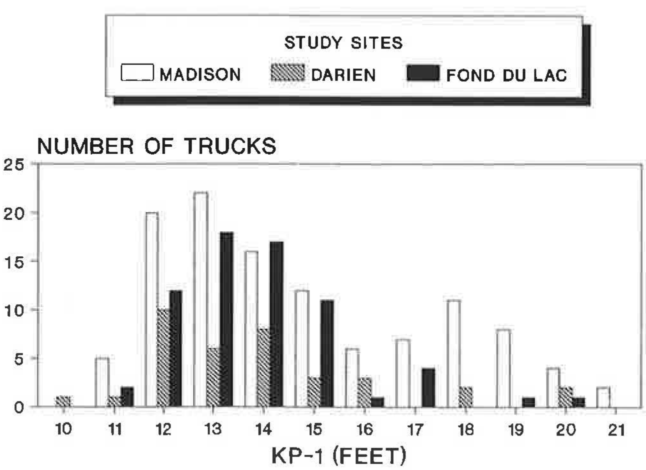

FIGURE 8 Effective tractor lengths (KP-1).

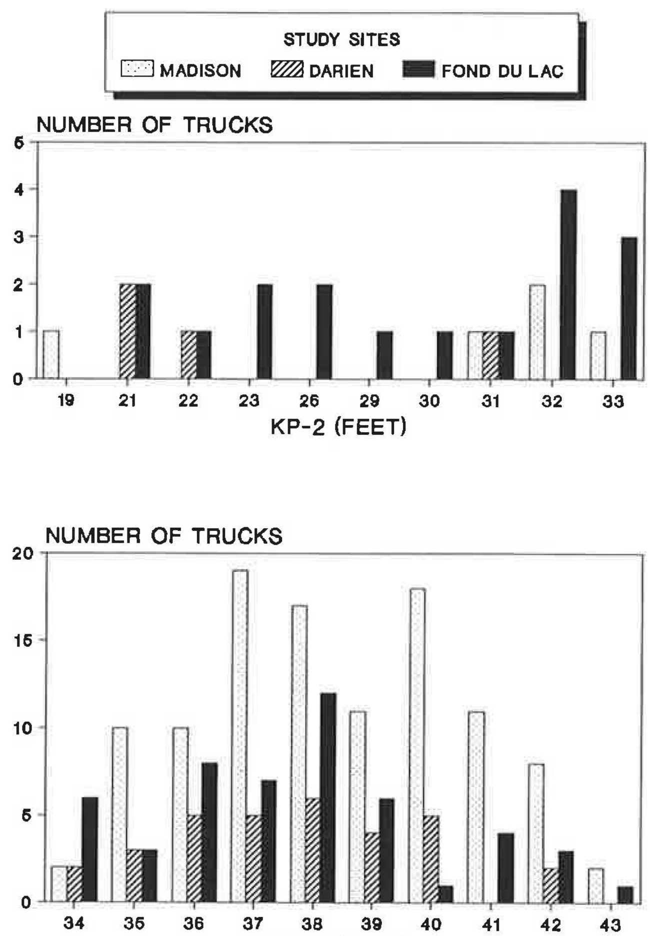

FIGURE 9 Effective trailer lengths (KP-2).

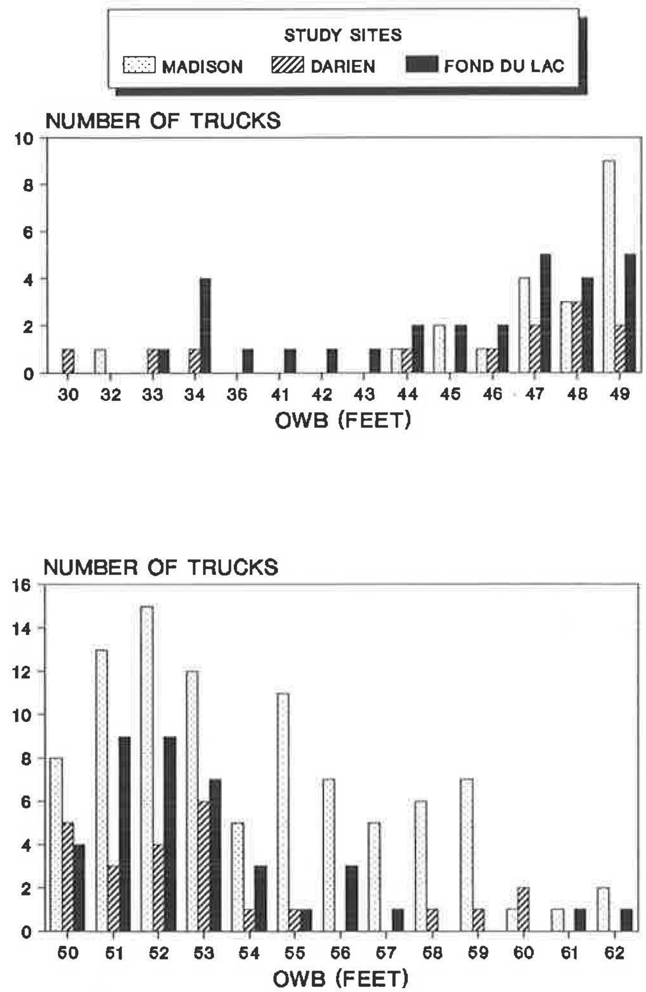

FIGURE 10 Overall wheelbase (OWB).

encroachments that did occur were minimal, and the observers attributed them mainly to driver misjudgment. Unfortunately, only a few of the largest trucks were observed at this site.

Using the Caltrans software, the team generated a hypothetical turning template for one of the larger trucks. The configuration of this vehicle is shown in Figure 14. The vehicle was named WB-62, and its dimensions are those of the largest tractor-semitrailer currently allowed in Wisconsin.

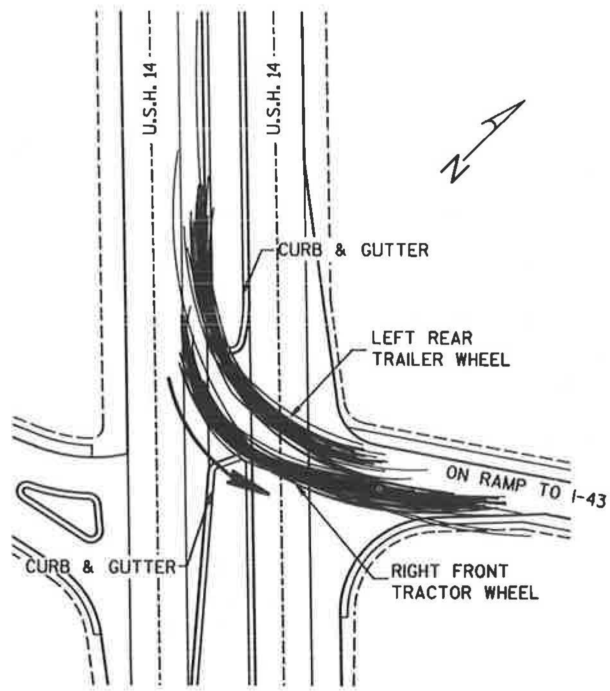

FIGURE 11 Darien intersection, all truck turns.

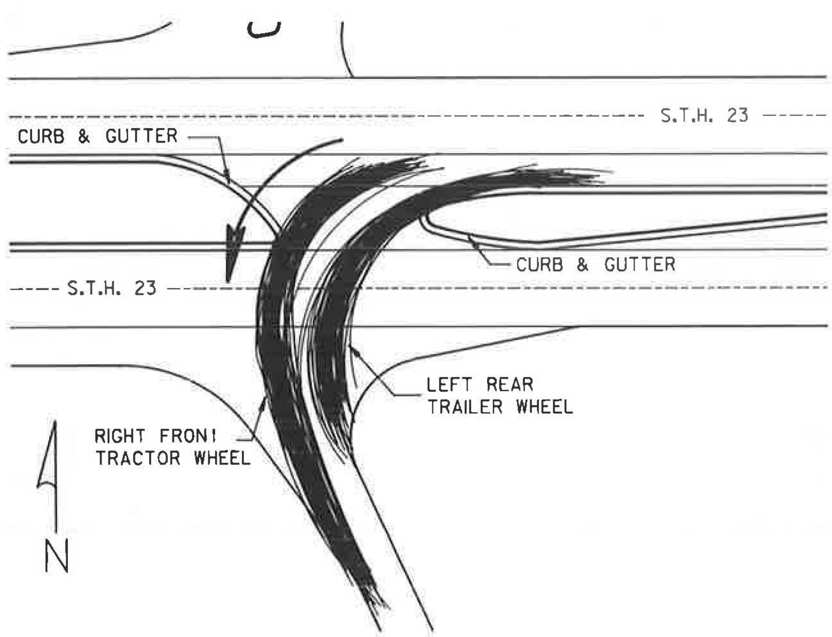

FIGURE 12 Fond du Lac intersection, all truck turns.

When this template is superimposed over the Fond du Lac site (see Figure 15), it appears that a truck of this size could just barely maneuver through the intersection. Even so, there is a high probability that a large truck would either ride over the median curb and encroach onto the shoulder of the on-ramp or initiate the turn from outside the turn lane provided. This agrees with the video evidence and researcher observations at the Elkhorn site. At Elkhorn the WB-62 test truck was only able to turn left if the driver reduced speed significantly.

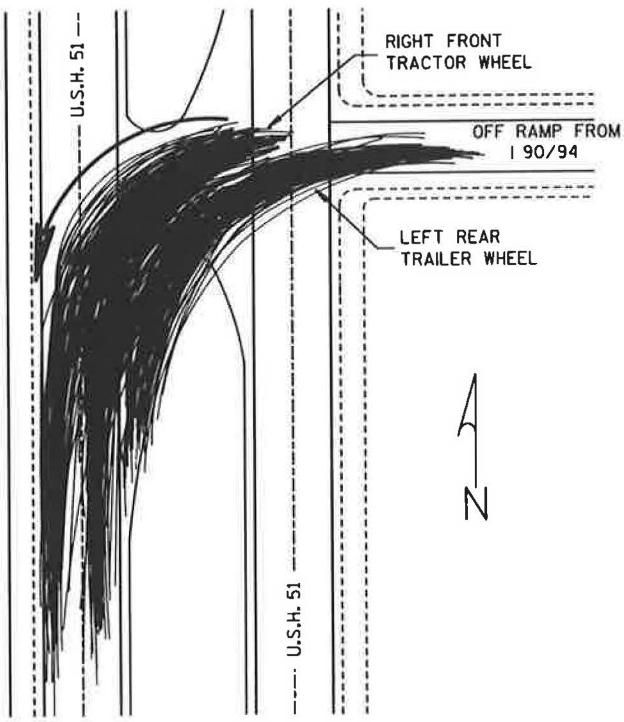

FIGURE 13 Madison intersection, all truck turns.

To evaluate the Caltrans software, the team used it to create a template of the most common truck encountered at the Fond du Lac site. This truck had an effective tractor length (KP-1) of 14 ft and an effective trailer length (KP-2) of 38 ft. The parameters needed by the Caltrans software are given below. It should be noted that the tractor wheelbase is the KP-1 dimension plus the distance from the kingpin to the rear tractor axle (in this case, 3 ft):

Truck Characteristic	*Caltrans Parameter*
Angle of turn	115 degrees
Radius of turn	60 ft
Tractor wheelbase	17 ft
Trailer length (KP-2)	38 ft
Trailer width	8.5 ft
Axle width	8 ft

The template was then compared with a composite of the paths followed by trucks of the same size as they negotiated the intersection. Figure 16 shows that the Caltrans-generated template is reasonably accurate in describing the path of this particular group of trucks.

One of the findings of the Caltrans effort reaffirmed the conclusion of earlier offtracking formulas that the effective trailer length has more of an effect on offtracking than does the effective tractor length. To test this hypothesis, the offtracking of certain vehicles at the Fond du Lac site was plotted against their KP-1 and KP-2 dimensions. Figures 17 and 18 show the results. Figure 17 shows that, for fixed trailer wheelbase, offtracking is stable over a wide range of tractor wheelbases. On the other hand, Figure 18 shows significant variation in offtracking as trailer length changes.

These findings generally agree with the results obtained from the Caltrans modeling.

CONCLUSIONS

- Trucks using Wisconsin's system of routes designated for long trucks vary considerably in size and configuration.

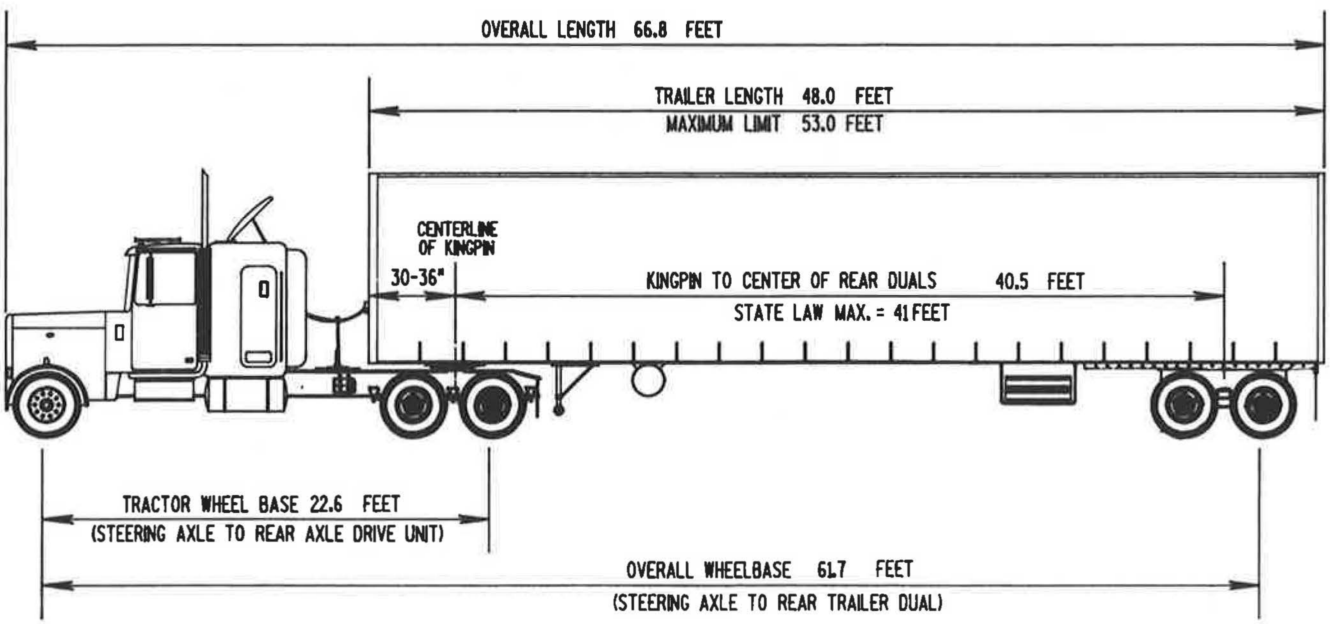

FIGURE 14 Typical Wisconsin WB-62.

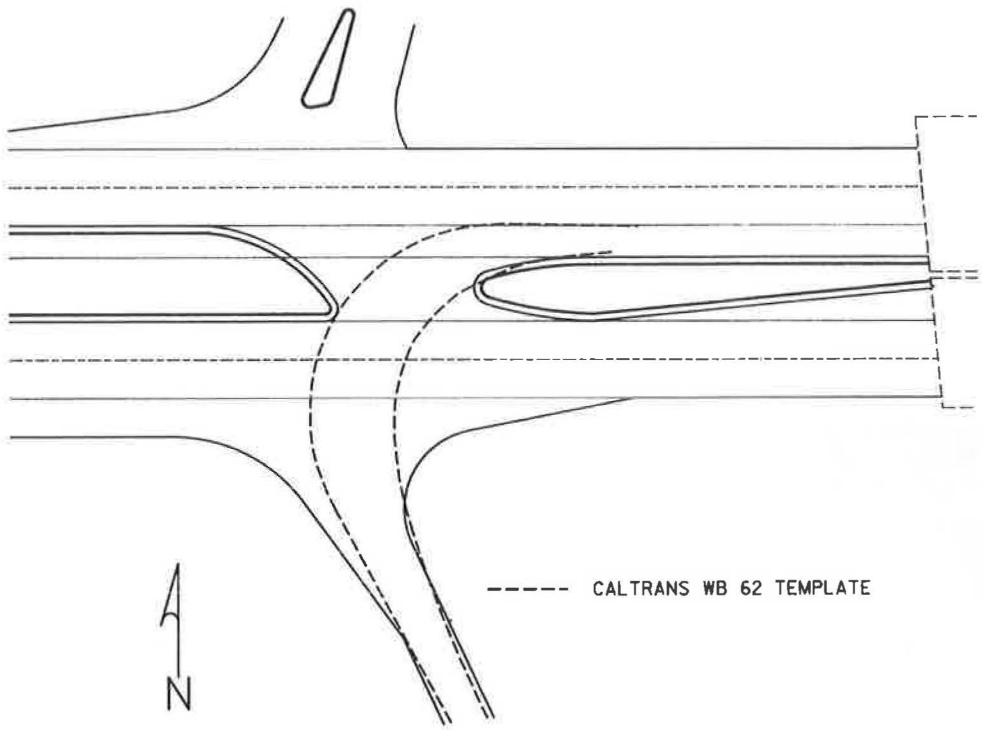

FIGURE 15 WB-62 template comparison.

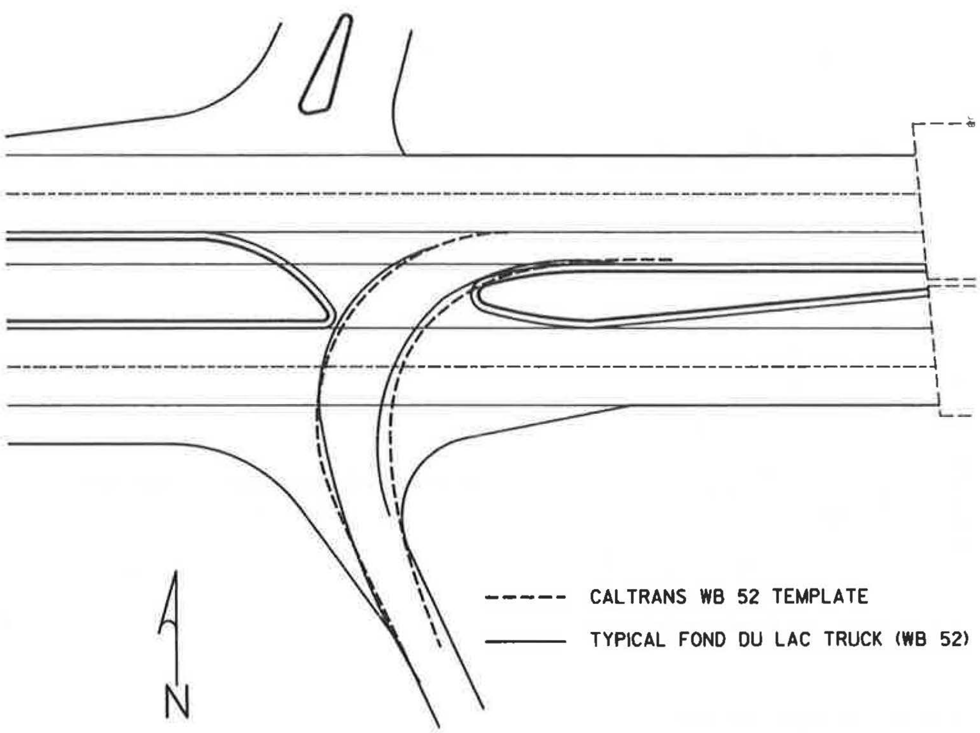

FIGURE 16 Caltrans WB-52 versus actual WB-52.

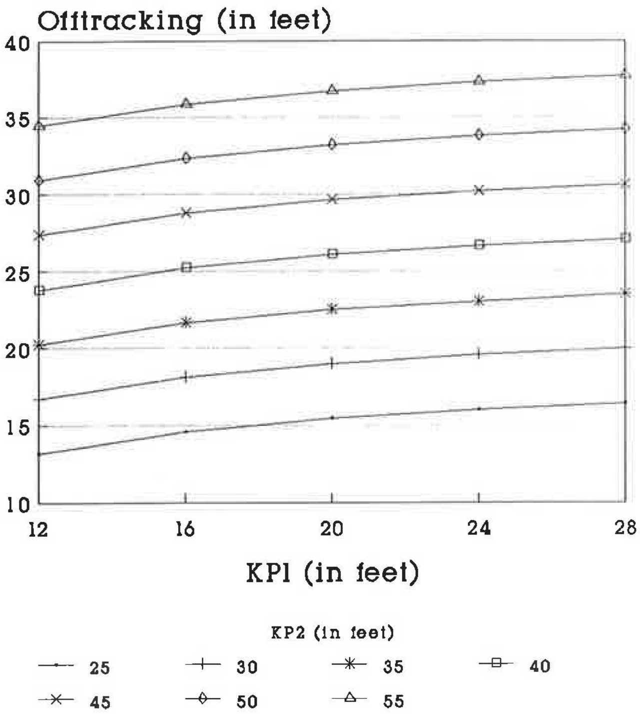

FIGURE 17 KP-1 versus offtracking.

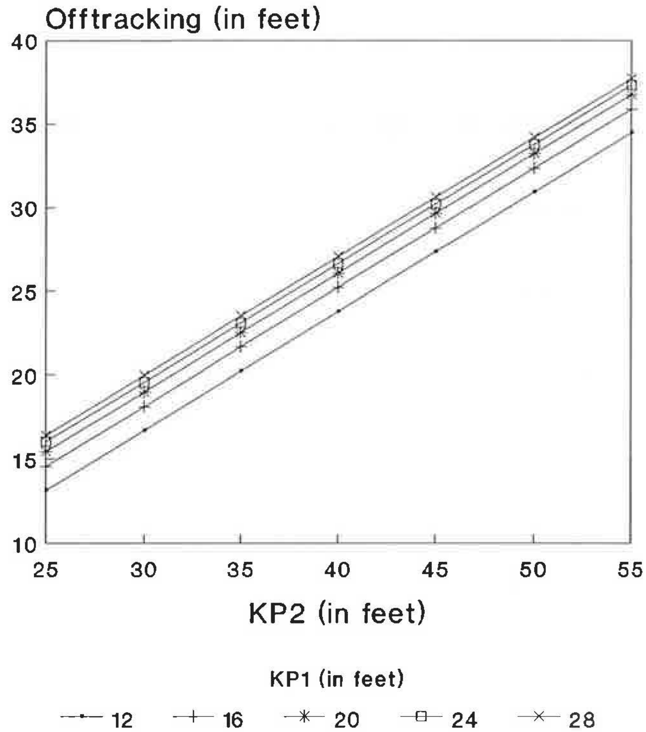

FIGURE 18 KP-2 versus offtracking.

- A significant number of trucks turning at these test sites encroached into lanes not meant for turning traffic. They also avoided coming to a complete stop whenever possible.
- The phototriangulation method of data collection was successful in defining the path of turning trucks.
- In general, intersection design standards in Wisconsin are adequate for the trucks currently using them.
- Theoretically, the new, longer trucks can negotiate intersections designed for smaller vehicles. However, there is little margin for error, and less capable drivers will almost certainly have problems.
- The Caltrans theoretical turning-template software accurately described the low-speed turning characteristics of one type of truck in Wisconsin.

RECOMMENDATIONS

- The Caltrans turning templates should be used when intersections are designed. The software to generate specific templates should be incorporated into the computer-aided design system being used.
- Designers should be more aware of the size of trucks using or likely to use the facility being designed.
- Designers should consider the urban versus rural nature of the intersection location and the volume of traffic to be accommodated. In rural areas, designers should use a turning radius larger than the minimum.
- Further studies should be conducted to determine the actual turning characteristics of the longest legal trucks.

REFERENCES

1. *Observations on the Turning Characteristics of Western Type Trucks and Combinations.* Western Highway Institute, San Bruno, Calif., 1950.
2. *Truck Paths on Short Radius Turns.* Division of Highways, California Department of Public Works, Sacramento, 1972.
3. P. H. DeCabooter and S. E. Solberg. Operational Considerations Relating to Long Trucks in Urban Areas. *In Transportation Research Record 1249*, TRB, National Research Council, Washington, D.C., pp. 5–15.

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Urban Freeway Gridlock Study: Decreasing the Effects of Large Trucks on Peak-Period Urban Freeway Congestion

LANCE R. GRENZEBACK, WILLIAM R. REILLY, PAUL O. ROBERTS, AND JOSEPH R. STOWERS

The Urban Freeway Gridlock Study investigated the effects of large trucks on peak-period urban freeway congestion. The study, undertaken for the California Department of Transportation at the direction of the California legislature, was prompted by concerns about freeway congestion and proposals to regulate large-truck traffic on the freeways. The study focused on the freeway systems in the Los Angeles, San Francisco, and San Diego metropolitan areas. It addressed the effects of large trucks, strategies to reduce congestion (improved traffic management, expanded incident management, mandatory night shipping and receiving, and mandatory peak-period truck bans), and the economic effects of these strategies. It was concluded that the volume of large trucks on the freeways does not have a significant effect on peak-period congestion but that truck-involved incidents and accidents do affect congestion significantly. Truck traffic makes a relatively small contribution to freeway congestion except on those few highly congested freeways where truck volumes exceed 10 percent of total vehicles. It was recommended that the state expand and improve its incident management programs and concurrently expand and intensify its long-term traffic management programs. The state should support a pilot program in Los Angeles to determine whether a cost-effective night shipping and receiving program can be developed. Areawide freeway truck bans should not be pursued; however, time-of-day and lane restrictions should be researched. Finally, it was recommended that the state collect data and improve traffic modeling procedures used to estimate the effects of trucks on air quality.

Portions of the U.S. urban freeway systems are saturated during the peak commute periods. The number of people who want to use the freeways is simply greater than the capacity of the freeways at those times of day, and the result is congestion. Congestion increases travel time, accident rates, and air pollution. These factors force people to travel earlier or later than they would like—a phenomenon called peak-spreading—or to forgo trips. In addition, they force businesses to pay more to move their goods. The problem is greatest in Los Angeles because freeway congestion also contributes substantially to air pollution, which imposes environmental and economic costs on the whole region, not just on commuters and motor carriers caught in freeway congestion.

L. R. Grenzeback, Cambridge Systematics, Inc., 222 Third Street, Cambridge, Mass. 02142. W. R. Reilly, JHK & Associates, 110 South Church Street, Tucson, Ariz. 85701. P. O. Roberts, Transmode Consultants, Inc., 3400 International Drive, N.W., Washington, D.C. 20008. J. R. Stowers, Sydec, Inc., 1601 Washington Plaza, Reston, Va. 22090.

The seriousness of these problems and the degree of public concern are evident in recent proposals that deal with congestion-related issues. The most sweeping of these is the program announced in September 1988 by Los Angeles Mayor Thomas Bradley in which he proposed a multifaceted attack on the problems of freeway congestion and air pollution. The key elements of his plan were (a) a truck-permitting program that would drastically reduce the number of large trucks allowed to operate on the streets of the city of Los Angeles during the morning and evening peak periods, (b) regulations requiring large businesses to stay open longer in the evenings for shipping and receiving, (c) stronger truck safety enforcement, and (d) more rapid accident cleanup.

However, changing travel patterns is difficult and costly because people and businesses are dependent on freeway systems. Freeways serve both personal travel (for work, shopping, and recreation) and urban and Interstate goods movement. Americans have organized much of their lives and businesses around the mobility and access provided by the urban freeway systems: manufacturers depend on just-in-time delivery of components to their assembly lines to reduce inventory costs, retailers depend on overnight delivery of goods to restock shelves, and families depend on a steady flow of food to supermarkets to keep themselves fed.

At issue is how best to manage the freeways at peak periods to minimize congestion and how to do so equitably without major disruption to people's lives and their economy.

The Urban Freeway Gridlock Study was performed by Cambridge Systematics for the California Department of Transportation (Caltrans). It addressed three questions posed by the California legislature:

1. What are the impacts of large trucks on peak-period freeway congestion?
2. Can management techniques reduce congestion?
3. What are the economic costs of these techniques to commuters, motor carriers, business, industry, and the public?

SCOPE OF WORK

The study, which focused on the freeway systems in the Los Angeles, San Francisco, and San Diego metropolitan areas, dealt primarily with the impact of large trucks on these systems. For this study, a large truck was defined as having three or more axles and a gross vehicle weight rating of at least 26,000 lb.

The work was organized around the following five topics.

Current Conditions

Traffic flows at 40 freeway sites in the Los Angeles area, 25 sites in the San Francisco area, and 13 sites in the San Diego area were videotaped and analyzed to determine the number and types of large trucks on the freeways during peak periods. Next, public officials, industry associations, motor carriers, and shippers and receivers were interviewed to evaluate the impact of congestion on freeway and trucking operations. Finally, current research on truck accidents and the effects of trucks on traffic flow was reviewed.

Management Techniques

An extensive list of freeway and truck management techniques was assembled and screened. Four strategies were specified for detailed analysis: (a) traffic management, (b) incident management, (c) night shipping and receiving, and (d) peak-period truck bans.

Implementation Feasibility

California and federal statutes and regulations governing freeways and motor carriers were reviewed. In addition, leading court cases dealing with freeway and truck regulation were reviewed. Federal and state officials were surveyed to determine current experience in implementing and operating freeway and truck management programs.

Economic Impacts

Estimates of the number of truck movements by industry and type of motor carrier were developed to determine which industries generate the most truck traffic. Public agencies, carriers, shippers, and receivers were interviewed to estimate the direct economic effects of freeway and truck management strategies. The indirect economic effects of the strategies on the Los Angeles, San Francisco, San Diego, and California economies were estimated using a regional economic model.

CURRENT CONDITIONS

Large-Truck Travel Patterns

Large trucks account for three-fourths of all medium- and heavy-duty truck travel (excluding travel by pickup and panel trucks) in the Los Angeles, San Francisco, and San Diego areas. Large trucks also account for most of the truck travel on freeways. In Los Angeles it is estimated that large trucks account for 80 to 90 percent of all truck miles on the freeways. Most of these are heavy trucks, typically five-axle, 18-wheel tractor-semitrailers, and most are registered in California. Large-truck travel patterns in the Los Angeles, San Francisco, and San Diego areas are similar to those in other major urban areas except that California has a larger proportion of twin trailer trucks than most other states.

Proportion of Large Trucks in Freeway Traffic

In the Los Angeles and San Francisco areas, it was found that large trucks constitute 4.0 percent of all vehicles during the morning peak and 2.5 percent of all vehicles during the evening peak. The proportions are significantly lower in San Diego: 1.8 percent of all traffic during the morning peak and 0.8 percent during the evening peak. The percentage and absolute number of large trucks are highest during the midday period in all three areas. During that time, large trucks average 5.5 percent of all vehicles in Los Angeles and San Francisco and 2.5 percent of all vehicles in San Diego. These percentages are equivalent to 300 trucks per hour per direction in Los Angeles, 220 trucks per hour per direction in San Francisco, and 100 trucks per hour per direction in San Diego. The averages and observed ranges for each area are presented in Table 1.

Few freeways are highly congested and have a significant proportion (more than 10 percent) of large trucks in the traffic stream. In Los Angeles, such freeways include I-5, I-605, I-710, and SR-60; in San Francisco, I-80, I-880, and I-580.

TABLE 1 LARGE TRUCKS AS A PERCENTAGE OF TOTAL VEHICLES (ONE DIRECTION ONLY)

	Los Angeles	San Francisco	San Diego
A.M. peak (7:00–9:00 a.m.)			
Weighted average	3.8	4.2	1.8
Observed range	0.5–17.2	0.8–13.2	0.7–5.7
Midday offpeak (11:00 a.m. to 1:00 p.m.)			
Weighted average	5.5	5.4	2.5
Observed range	0.7–16.2	0.6–12.1	0.6–4.8
P.M. peak (4:00–6:00 a.m.)			
Weighted average	2.6	2.4	0.8
Observed range	0.2–13.2	0.3–6.8	0.1–1.9

NOTE: Averages are weighted by volume, all sites, and all time.

None of the freeways surveyed in San Diego has more than 6 percent large trucks in the traffic stream. At 60 percent of the survey sites, large trucks compose no more than 3 percent of all vehicles; at 90 percent of the sites, they compose no more than 9 percent of all vehicles.

As a general pattern, highly congested freeway segments tend to have lower truck volumes than do moderately congested freeway segments. An estimated 30 percent of freeway segments in Los Angeles, 20 percent in San Francisco, and 10 percent in San Diego are highly congested. These freeway segments have high traffic volumes, operate at levels of service E and F (stop-and-go traffic averaging less than 35 mph), and have a high rate of fatal and injury accidents per mile. Large-truck volumes on these highly congested segments average 3.5 percent, whereas large-truck volumes on moderately congested freeway segments average 4.2 percent.

Types of Trucks

Of the large trucks on the freeways during the peak periods, 65 percent are tractors hauling a single trailer, 20 percent are tractors hauling double trailers, 12 percent are single-unit straight trucks, and 3 percent are other configurations (such as tractors without trailers). By body type, 55 percent are vans, 25 percent are refrigerated vans, 10 percent are flatbeds, and the remaining 10 percent are predominantly tankers and construction equipment. These proportions are similar across all three metropolitan areas.

Industries Served by Trucks

The industries generating the most truck miles of travel in the Los Angeles area are wholesale trade (37 percent), durable goods manufacturing (28 percent), and nondurable goods manufacturing (19 percent). Together, these three industry groups generate almost 90 percent of all truck miles of travel in the Los Angeles area.

Private truck fleets owned by business and industry account for about half of all truck miles of travel; most of their trips are short-haul trips (less than 200 mi). Common carriers account for the other half of the truck miles of travel; about one-third of their trips are short haul and two-thirds are long haul (over 200 mi).

Effect of Trucks on Freeway Traffic Flow

Trucks affect traffic flow in their lane because they occupy more roadway space than passenger cars and cannot accelerate, decelerate, or maintain speed on upgrades as easily as passenger cars. The magnitude of their effect varies greatly with the type of truck, its weight, the volume of traffic on the freeway, and the roadway grade. On urban freeways where there are fewer than 10 percent trucks in the traffic stream and grades are below 2 percent, which is typical of most freeway segments in the Los Angeles and San Diego areas, the effect of a large truck is usually equivalent to that of 1.5 to 2.0 passenger cars. On long grades, such as those found on some San Francisco area freeway segments, the effect can be substantially more—equivalent to that of 4 to 8 passenger cars.

Trucks also have an effect on traffic flow in adjacent lanes. The headway between passenger cars increases slightly as car drivers pass a truck. The effect is thought to be caused by the truck's size (which restricts the passenger car driver's field of view), noise impacts, and psychological factors. This adjacent lane friction effect increases the impact of trucks by the equivalent of 0.1 passenger cars per adjacent lane.

The perceived effect of large trucks is greater than that calculated by traffic engineers because of the large size of trucks relative to passenger cars and the high visibility of trucks in the traffic stream. These factors contribute to a psychological, if not an actual, barrier to passenger car drivers' entering and exiting the freeway. In California, as in many other states, trucks are restricted to the rightmost lanes and are prohibited from using the leftmost or median passing lanes except where necessitated by left-hand exits and merges. This regulation increases the density of trucks in the rightmost lanes. Where there are large volumes of traffic entering or exiting the freeway, trucks tend to dwell in the second lane to avoid frequent lane and speed changes caused by merging traffic. This practice creates a barrier to merging traffic. Research on this effect is limited and inconclusive but indicates that, when the freeways are saturated during peak periods, trucks and automobiles stay in the acceleration lanes longer than normal, and many merges are forced. It is likely that this condition contributes to sideswipes and rear-end accidents when traffic flow is unstable.

Truck Accidents and Incidents

In the Los Angeles, San Francisco, and San Diego areas, truck accidents (such as collisions and jackknifes) and truck incidents (such as breakdowns, spills, and shifted loads that force trucks to stop on the freeway) cause 19 million vehicle-hours (veh-hr) of delay per year, at a cost of over $200 million. Accidents and incidents involving large trucks during the peak periods are estimated to account for 5 million veh-hr of delay at a cost of over $50 million per year.

It has been estimated that the total delay cost of congestion in Los Angeles is about $1 billion per year. Of this, $500 million is attributed to recurrent congestion (predictable delay caused by the high volume of traffic on the freeways). The other $500 million is attributed to nonrecurrent congestion (unpredictable delay caused by accidents and incidents). Truck-involved accidents are estimated to account for $100 million, about 20 percent of the total cost of nonrecurrent congestion.

Major incidents, which constitute 5 to 10 percent of all truck incidents, are thought to be responsible for about half of the total delay caused by truck incidents. A major incident is defined as an incident or accident that blocks two or more lanes of the freeway for 2 hr or longer. Recker et al. (*1*) estimate that the average duration of a major incident is 3 hr, 39 min; it triggers an average of 2,800 veh-hr of delay on the freeways around it. A few of these major incidents last 10 to 12 hr, triggering 30,000 to 40,000 veh-hr of delay. About two-thirds of major incidents are the result of overturns, spills, and shifted loads. These incidents tend to occur on ramps, and the primary cause is excess speed on the curve. Most major incidents occur before the peak periods—at dawn or during midday when trucks and other vehicles are operating at full freeway speeds before congestion reaches its peak.

Common incidents, which constitute 90 to 95 percent of all incidents, are thought to be responsible for the other half of the total delay caused by truck incidents. The average duration of a common incident is 1 hr, but it triggers an average of 1,200 veh-hr of delay (*1*). Half the common incidents are caused by breakdowns, stalls, broken fan belts, and flat tires, and 27 percent are caused by accidents. Most of the accidents involve sideswipes and rear-end collisions in the travel lanes, and many occur during the peak periods.

Most truck accidents and incidents occur on weekdays during the midday period, which is when truck volumes on the freeways are highest. It is estimated that 90 to 95 percent of all major and common incidents occur on weekdays, 70 to 80 percent during the daytime, and about 50 percent during the midday period.

Truck accidents and incidents are concentrated on a few heavily traveled freeways. In each of the metropolitan areas, three freeways account for nearly 50 percent of the total incidents and vehicle-hours of delay. In Los Angeles, four freeways account for 67 percent of the total number of vehicle-hours of delay caused by truck-involved accidents: I-5 accounts for 29 percent, US-101 for 13 percent, I-405 for 13 percent, and I-10 for 12 percent.

MANAGEMENT STRATEGIES

The study identified and screened a large number of freeway and truck management techniques. Three evaluation criteria were considered: potential to reduce peak-period freeway congestion and truck-involved accidents, applicability of the technique to California freeways, and feasibility. The assessment of feasibility took into consideration technical, legal, and budgetary constraints. The overall assessments were as follows, where + + indicates significant reduction of congestion or accidents, feasible; + indicates moderate reduction of congestion or accidents, feasible; ? indicates feasibility uncertain; and – indicates not technically or legally feasible at this time.

- Truck restrictions
  - – Peak-period bans
  - +? Freeway section bans
  - ? Route diversions
  - + Designated access routing
  - + Hazardous materials route restrictions
  - + Local truck and noise ordinances
- Road pricing
  - – Peak-period permits
  - +? Freeway permits
  - + +? Peak-period tolls
  - + Peak/offpeak rate differentials
- Traffic engineering
  - + Lane designations and restrictions
  - +? Wider lanes
  - + + Continuous merge lanes
  - + + Variable message signs
  - + + Sign placement
  - + Truck advisory signs
  - +? Speed restrictions
- Road design and construction
  - + Capacity and safety improvements
  - + + Improved entry/exit ramps and merges
  - + + Continuous-merge lanes
  - +? Exclusive truck facilities
    Peak-high-occupancy-vehicle (HOV)-only/offpeak truck-only lanes
- Fleet management
  - + Voluntary offpeak operations
  - + Automatic vehicle location/computerized routing
  - + Driver training and management
- Shipper/receiver actions
  - + Voluntary offpeak operations
  - + +? Mandatory offpeak operations
- Incident management
  - + Automated detection
  - + + Site and area surveillance and communications
  - + + Equipment and procedural improvements
  - + Organizational changes
- Inspection and enforcement
  - +? Automated surveillance
  - + Urban truck inspections and enforcement
- Information management
  - +? Highway advisory radio
  - +? Traffic information

Four strategies were developed, incorporating the leading techniques from this list. The strategies were (a) traffic management, (b) incident management, (c) night shipping and receiving, and (d) peak-period truck bans. Although approval for a peak-period freeway truck ban was judged to be unlikely under the provisions of the Surface Transportation Assistance Act of 1982 (STAA), it was included and assessed for the following three reasons:

1. Truck bans are widely perceived by the public and the media as a direct and appropriate response to peak-period congestion.
2. There were no data on the effects of a truck ban on freeway congestion.
3. At the time the strategies were formulated, the city of Los Angeles and the South Coast Air Quality Management District (SCAQMD) were actively considering a peak-period freeway ban.

The city subsequently announced a truck permit program that would restrict the number of large trucks that could use city streets during the peak periods. The street ban was not assessed because (a) adequate data were not available (the city is now collecting the necessary data), (b) the restrictions affect only a portion of the metropolitan area, and (c) the street ban would be difficult for the state to pursue on a regionwide basis.

Although the strategies are evaluated separately, they are not mutually exclusive. An effective freeway and truck management program could use elements from several of these strategies.

TABLE 2 COMPARISON OF FREEWAY AND TRUCK MANAGEMENT STRATEGIES ($ MILLIONS ANNUALLY)

			Economic Impacts(1)					
			Direct:			Indirect:		
Strategy	Feasible	Freeway Congestion Relief	Motor Carriers(2)	Other Vehicles(2)	Shippers/ Receivers(3)	CA Business Sales(4)	Air Quality(5)	Implementation Cost(6)
Traffic Management(7)	Yes	++	$8	$121	+	} $8	+	$20-40
Incident Management(7)	Yes	+	$4	$44	+		+	$3-5
Night Shipping and Receiving(8)	Maybe	+	$3	+	-$2,200	-$913	+	$2-3
Peak Period Ban -- Core Freeways(8,9)	Unlikely	+	-$43	$7	-	-$28	-	$2-3

Notes:

++ Significant positive impact
\+ Modest positive impact
\- Modest negative impact

(1) 1988 Dollars
(2) Time and vehicle operating cost savings (+) or cost increases (-)
(3) Logistics cost savings (+) or cost increases (-)
(4) Changes in volume of business sales (output) in 1988 relative to baseline forecast. Traffic and incident strategies were combined because their individual direct (motor carrier) impacts were too small to be modelled reliably
(5) Not quantified
(6) Ten-year annualized implementation costs
(7) Los Angeles, San Francisco, and San Diego
(8) Los Angeles and San Francisco only
(9) Assumes 80 percent of peak period truck miles of travel are diverted to arterials; 20 percent diverted to offpeak periods (midday or night)

The strategies and their estimated direct and indirect effects are described in the following paragraphs and summarized in Tables 2 and 3.

Traffic Management

A traffic management program could reduce congestion by smoothing the flow of traffic. This result would be achieved by a combination of traffic management and freeway design measures, such as adding continuous-merge lanes at critical locations, redesigning high-accident ramps, providing information to drivers about traffic conditions ahead, regulating speed and lane use, and enforcing safe truck operation. A traffic management strategy would focus on problems related to large trucks, but the traffic and safety benefits would accrue to all freeway users.

Six techniques were identified as having the greatest potential for reducing freeway traffic congestion by addressing the problems unique to large trucks. The first involves sign placement. Drivers have a difficult time detecting and reading directional signs, particularly exit signs, when large trucks block their field of view. This difficulty decreases the time drivers have to anticipate and safely execute lane changes. On congested freeways, it contributes to sideswipe and rear-end collisions. To counteract this problem, additional signs should be placed to the left side of the freeway, on overhead structures, or in the median in advance of difficult exit situations.

The second technique employs variable message signs. Caltrans has installed these signs alongside freeways in several locations in the larger metropolitan areas. Variable message signs are used to alert drivers to accidents, queues of stopped vehicles, severe congestion, and speed restrictions. Through the traffic management program these signs could be installed in many locations and intensive use could be made of individual lane signs to assign trucks to lanes, control traffic flow at merges, and regulate traffic speeds.

The third technique consists of speed restrictions. Many truck accidents occur at ramps because trucks attempt to take the curves at too high a speed. Therefore, ramps could be posted with safe speed limits for trucks. Rear-end collisions are frequently the result of unstable, stop-and-go traffic flows. Variable message speed signs could be used to dampen speed oscillations, giving drivers of large trucks adequate time to brake safely.

Additional lanes and lane restrictions for trucks constitute the fourth technique. Trucks are required to use the rightmost lanes of the freeway, where the pavements have been strengthened in anticipation of heavier truck loads. When the proportion of trucks in these lanes is high, it creates a psychological, and sometimes physical, barrier for drivers trying to merge and contributes to sideswipes and rear-end collisions. To mitigate this effect, an additional continuous-merge lane could be constructed along the breakdown lane where traffic volumes warrant and space permits. Large trucks would be excluded from this lane except at entrances and exits.

The fifth technique is improved entrance and exit ramps. On some older freeways, entrance and exit ramps do not provide adequate deceleration and acceleration lanes. In addition, some ramps are not properly banked for today's larger

TABLE 3 COMPARISON OF FREEWAY AND TRUCK MANAGEMENT STRATEGIES: ECONOMIC IMPACTS BY REGION ($ MILLIONS ANNUALLY)

	Economic Impacts by Region					
	Direct(1):			Indirect: Business Sales(2)		
Strategy	Los Angeles	San Francisco	San Diego	Los Angeles	San Francisco	San Diego
Traffic Management(3,5)	$74	$44	$11	} $4.4	2.4	$0.48
Incident Management(3,5)	$28	$16	$4			
Night Shipping and Receiving(4,6)	-$1,450	-$710	n/a	-$580	-$290	-$15
Peak Period Ban -- Core Freeways(4,5)	-$22	-$14	n/a	-16.6	-$10	-$0.35

Notes:
(1) 1988 Dollars
(2) Changes in volume of business sales (output) in 1988 relative to baseline forecast.
Changes for 'all other areas' in CA are not shown in this table. See Table 1 in Chapter III of Summary Report.
Traffic and incident strategies were combined because their individual direct
(motor carrier) impacts were too small to be modelled reliably
(3) Los Angeles, San Francisco, and San Diego
(4) Los Angeles and San Francisco only
(5) Time and vehicle operating cost savings (+) or cost increases (-)
(6) Logistics cost savings (+) or cost increases (-)

and heavier trucks. These problem ramps could be earmarked for an accelerated redesign and reconstruction program.

The last technique involves mobile truck safety inspection teams. The California Highway Patrol (CHP) maintains a network of truck inspection stations on intercity freeways, but there are few urban inspection stations. Land is expensive, truckers can use arterials to avoid the stations, and truck movements in and out of the stations cause congestion. The use of mobile truck safety inspection teams (a concept already being demonstrated by CHP) could be expanded along freeways that have a high proportion of large trucks and accidents.

The traffic management program would focus on the most congested freeways in the core of each metropolitan area: about 150 mi of freeway in Los Angeles, 84 mi in San Francisco, and several dozen miles in San Diego. It is estimated that an aggressive traffic management program in these areas could realize a 15-percent reduction in the vehicle hours of delay caused by recurring congestion (a 25-percent reduction on the core area freeways but less on the outlying freeways). The estimate takes into consideration that these three metropolitan areas already have traffic management programs in place for portions of their freeway systems. The techniques proposed for the traffic management strategy would build on and complement current traffic programs, such as the Los Angeles Smart Streets project for the I-10 corridor, the San Francisco traffic operations center project, and the Heavy-Vehicle Electronic License Plate Program (HELP).

The direct benefits to all highway users, measured in time and vehicle operating cost savings, would be about $74 million per year in Los Angeles, $44 million per year in San Francisco, and $11 million per year in San Diego. The differences in the savings reflect the different sizes of the metropolitan areas; the savings per vehicle would be about the same in each area.

Time savings provide most of the benefits in the traffic management strategy. The calculations assume that the value of time for motor carriers is $20/hr; the weighted average for all vehicles is $10/hr. The benefits from time savings are offset by small increases in vehicle operating costs. Stop-and-go driving on congested freeways is costly: speed oscillates up and down, and wear and tear on tires and engines increases. Smoother traffic flows reduce these operating costs, but the savings are lost as freeway speeds increase. As speed increases, fuel consumption increases significantly, increasing total vehicle operating costs, too. These costs would be small compared with the value of time savings.

The traffic management strategy would have several additional effects that are not quantifiable. A successful program would increase the total volume of peak-hour traffic. By reducing congestion and increasing freeway speeds, the program would make peak-period travel marginally more attractive than it is today. This change would cause some drivers to shift their trips from the shoulders of the peaks into the peak periods, and a few drivers would make more trips during this period than they do now. No attempt has been made to estimate the elasticity of demand for peak-period travel with respect to travel time because little information is available to support the analysis, but the direction of the effect is clear. Finally, although a traffic management strategy would not decrease the number of large trucks in peak-period traffic, it would likely result in modest air quality improvements (by reducing stop-and-go traffic) and significant safety improvements (by reducing hazardous traffic situations).

Incident Management

An incident management program could reduce congestion and delay by significantly reducing the time required to locate and clear incidents and accidents from the freeways. Caltrans and CHP have established an excellent program for managing accidents and incidents; however, the resources allocated to the major incident response teams and system-level traffic management have not kept pace with the growth in traffic and congestion on the freeways. The incident management strategy would recapitalize and expand current programs.

There are four key elements in the incident management strategy. The first is improved surveillance and communication. Incident management, like emergency medical service, is most effective when problems can be diagnosed and stabilized in their early stages. Information about the type of truck, its position, traffic on the freeway, and conditions on parallel arterials is critical. The incident management program could use closed-circuit television and data links (along the freeway or mounted in planes and helicopters) to bring information to incident management teams before they are dispatched to a site so decisions on equipment, personnel, and system-level traffic management could be made in a timely manner.

The second element involves equipment and procedures. Prepositioning of heavy-duty tow trucks; helicopter delivery of emergency equipment and personnel; video recording of accident scenes to speed up documentation for administrative, legal, and insurance reports; and similar techniques could be applied to facilitate work at accident sites.

System operations management is the third element. The incident management program could make extensive use of computers to monitor system traffic flows, test incident management plans, and evaluate the effectiveness of the program.

The fourth element includes organization and coordination. Caltrans and CHP have well-coordinated operations, but major incidents often involve police, fire, and emergency medical personnel; hazardous materials experts; traffic engineers; maintenance workers; and mechanics from different agencies and jurisdictions. The incident management strategy could strengthen the institutional capabilities to coordinate and manage these large teams effectively.

The incident management strategy could reduce the duration of major incidents, which may account for 5 to 10 percent of all incidents, by 50 percent (from an average of 4 hr to an average of 2 hr) and the duration of common incidents, which may account for 90 to 95 percent of all incidents, by 20 percent (from an average of 1 hr to an average of 50 min). These changes would reduce the total number of vehicle-hours of delay resulting from truck-involved accidents and incidents by 25 percent, a savings of about 4.4 million veh-hr of delay per year. The savings would be 2.6 million veh-hr of delay per year in Los Angeles, 1.5 million in San Francisco, and 0.4 million in San Diego. The direct benefits to all highway users would be $28 million per year in Los Angeles, $16 million per year in San Francisco, and $4 million per year in San Diego.

The portion of these costs and benefits that accrues to motor carriers affects the cost of goods movement, which affects the cost of doing business, which in turn affects the competitive position and earnings of businesses and industries in regional, national, and international markets. These changes, which reverberate throughout the economy, can be measured in terms of changes in employment, personal incomes, and business sales or output. The indirect economic effects of the savings generated by the traffic and incident management programs (combined for analysis because the individual savings were small relative to the regional and state economies) would be modest, but positive, on the metropolitan and California economies. Employment and personal income would rise, and it was estimated that total business sales (output) in California would increase by $7 million in 1988 and $31 million by 1995. The traffic management program would account for about two-thirds of these effects and the incident management program for about one-third.

Night Shipping and Receiving Strategy

A night shipping and receiving strategy could reduce congestion by requiring that establishments do most of their shipping and receiving at night. Two segments of the population would be candidates for night operations: large establishments, for which the additional cost would be relatively small and could be spread over many operations, and establishments that normally operate 16 to 24 hr a day (for example, oil refineries, large warehouses, and continuous manufacturing operations). Within these segments, businesses and industries that have their own private fleets and could control shipping and receiving schedules would have the greatest flexibility to shift to night operations. Some, such as supermarket chains, have already done so. Other establishments would be encouraged, but not required, to make this change. For most small manufacturers and retail stores, the labor costs for night operations would be prohibitively high relative to their total labor and operating costs. For others, such as construction firms, night shipping and receiving may be feasible only on large projects where lighting can be installed to ensure safety.

In Los Angeles, 56,000 of 263,000 establishments are large or normally operate at night. An estimated 17,000, or 30 percent, of these establishments would be capable of shifting a significant portion of their shipping and receiving to night operations. (This estimate is based on the authors' professional judgment as well as interviews with shippers and receivers. The full social and economic effects of this strategy are not easily estimated; more industry-by-industry interviews could refine the estimated participation rate.) In San Francisco, 27,000 of 132,000 establishments are large or multishift operations and would be eligible for this change; an estimated 8,000 would be capable of shifting. In San Diego, 8,000 of 42,000 establishments are large or multishift operations and would be eligible, whereas an estimated 2,500 would be capable of shifting. It was assumed, however, that San Diego would not institute a night shipping and receiving program because of the relatively low proportion of large trucks on its freeways.

The truckload movements for these establishments would be the easiest to shift—an estimated 50 to 60 percent could be shifted. Less-than-truckload (LTL) movements would be more difficult to shift because their schedules are determined by the demands of many shippers and receivers, and LTL carriers are dependent on the economies of scale provided by dense pickup and delivery routes. It was estimated that only 10 to 20 percent of LTL movements could be shifted economically to night operations.

The additional cost to shippers and receivers for night operations would be about $75,000 per establishment per year, or $300 per day over a 250-operating-day year. The cost would cover building overhead (heat, light, and power), security (a security guard to protect against theft), management (a portion of a shift supervisor's time), and administration (a portion of a receiving clerk's time). General management and overhead costs would add another $1 per employee in these establishments. There would be considerable variation across establishments and industries, with some firms incurring high costs and others marginal costs. Some firms could offset the additional cost with operational savings, but it is believed that many of the large firms that stand to realize significant savings from night shipping and receiving have already taken steps to capture these benefits. For most firms, mandatory night shipping and receiving would increase the cost of doing business. The total estimated costs to shippers and receivers would be $1.45 billion in Los Angeles and $710 million in San Francisco.

A secondary cost to shippers and receivers would be the cost of delayed shipments. Most firms ship in the afternoon at the end of a day's production with the expectation that the shipment will be delivered the next morning. California's freeway system makes it possible to ship from Los Angeles in the evening and receive in San Francisco the following morning. Many businesses and industries depend on this level of service to keep inventory costs down. If pickups are delayed until night hours, a high proportion would not be delivered in the morning. Most LTL shipments and many truckload shipments between Los Angeles and San Francisco would lose a full day's production time. The cost of such a delay is approximately 0.04 percent of the value of the shipment affected. It is estimated that an aggressive mandatory night shipping and receiving program could affect 20 percent of shipments, at an annual cost of $24 million in Los Angeles and $11 million in San Francisco.

The direct cost impacts of a night shipping and receiving program would vary by the type of carrier and the industry it serves. In general, truckload carriers, both for-hire and private fleets, would realize modest benefits from night operations. Labor and administrative costs would increase, but time savings and operating efficiencies would likely offset these. This would not be the case for LTL carriers. Pickup and delivery operations account for 10 to 30 percent of total transport costs for these carriers. The denser the pickup and delivery operations, the less costly they are to perform. If a significant proportion of shipments were to be picked up or delivered at night, the LTL carrier would have to "plow the same field twice." Preliminary estimates indicate that a two-shift operation for LTL carriers could increase costs 15 to 35 percent. Some of this increase would be offset by service and operational innovations developed in response to a night shipping and receiving program. However, because it is unclear how carriers would adapt to night operations and because the proportion of LTL shipments involved in night operations would likely be modest, no dollar value has been placed on the additional costs for LTL operations.

A night shipping and receiving program would have modest effects on traffic and congestion. The total truck-miles of travel in the metropolitan areas would increase slightly, particularly for LTL operations. Some truck movements would shift out of the peak, but most of the truck movements, particularly the truckload movements, would probably be shifted out of the less congested midday offpeak period. The benefits to commuters on the freeways would be modest. The annual value of time savings would be in the range of $2 to $4 million in Los Angeles and $0.7 to $1.5 million in San Francisco.

The air quality benefits of a night shipping and receiving program would likely be positive, but they were not quantified. Trucks that shifted to night operations would operate at higher average speeds and generate somewhat less air pollution because smaller amounts of the diesel emissions would be exposed to sunlight.

The additional costs to shippers and receivers would change the cost of doing business in Los Angeles and San Francisco. It was estimated that the indirect economic effects of these cost changes would decrease total California employment by 11,300 jobs (−0.1 percent) in 1988 and 31,500 jobs (−0.2 percent) by 1995. Without offsetting savings, total business sales or output would decrease by an estimated $0.9 billion (−0.1 percent) in 1988 and $3.4 billion (−0.3 percent) by 1995.

Implementation of a night shipping and receiving program would depend on the ability of state and local governments to require shippers and receivers to change their operating patterns. The California legislature recently granted SCAQMD the power to regulate shipping and receiving as an indirect source of truck emissions. This power could provide the regulatory basis for the night shipping and receiving strategy. SCAQMD is considering a night shipping and receiving regulation patterned after its ridesharing program, which is targeted at businesses that have a large number of employees. The program involves information programs, mandatory preparation of ridesharing plans, and the threat of enforcement through regulatory actions and fines.

The direct target of a night shipping and receiving program would be shippers and receivers, but the acknowledged objective would be to regulate truck movements to reduce air pollution. This regulation would likely be challenged as interfering with Interstate commerce. Resolution of the two conflicting federal mandates, to achieve clean air standards and to minimize interference with Interstate commerce, will require congressional or judicial action.

Peak-Period Freeway Truck Ban

Peak-period freeway truck bans could reduce congestion by excluding large trucks from core area freeways during the morning (7:00–9:00 a.m.) and evening (4:00–6:00 p.m.) peak periods. In Los Angeles, the ban would affect 150 mi of freeway bounded by the Ventura Freeway and SR-134 on the north, I-605 on the east, and I-405 on the south and west. In San Francisco, the ban would affect 84 mi of freeway in the city, on the San Mateo peninsula, and in the East Bay. A San

Diego ban would affect several dozen miles of freeway at the center of the region.

The ban would force motor carriers to divert to parallel arterials, shift operations to offpeak periods, increase their use of two-axle trucks not embargoed by the ban, and, in a few cases, shift the location of terminals and drop-points. The majority would divert their trips to parallel arterials because their customers would find it too costly to remain open for nighttime shipping and receiving. An estimated 80 percent of truck trips affected by a peak-period ban would be diverted to parallel arterials, and 20 percent would be shifted to offpeak periods (midday or night). Those trips shifted to the offpeak would primarily be truckload operations because the cost of shifting LTL would be prohibitively high for most shipments.

Because of the capital cost and the loss of efficiency, few carriers are expected to switch to two-axle trucks. A two-axle truck is less maneuverable than a three-axle city tractor towing a 28-ft pup trailer. It is also not as cost efficient because it has less cargo space and its cargo must be transferred to a trailer for long-distance line-hauls. A peak-period ban affecting freeways and city streets would make two-axle trucks much more attractive. Extensive use of two-axle trailers would tend to increase the truck miles of travel.

A peak-period freeway truck ban would increase average speeds on the core area freeways. For example, in Los Angeles, average freeway speeds would increase from about 40 to 42 mph during the peak periods. A typical Los Angeles freeway carries 1,700 passenger cars and 50 large trucks (3 percent of total volume) per lane per hour. Because each truck is equivalent to 2.0 passenger cars, the total traffic volume is equivalent to 1,800 passenger cars per lane per hour. At that volume, the average freeway speed is 40 mph. A peak-period freeway truck ban would remove 50 trucks, or 100 passenger car equivalents, decreasing the total volume to 1,700 passenger cars per lane per hour and increasing the average freeway speed to 42 mph. Experience has shown that this gain will be short-lived in a saturated system. As peak-period travel conditions improve, drivers tend to shift from the shoulders of the peak period back into the peak period, shortening queues at bottleneck locations slightly. Most of the congestion relief from a peak-period freeway ban would likely be lost within 6 weeks to 6 months.

In Los Angeles, the value of time saved by all vehicles remaining on the freeways would be $19 million per year. These benefits would be offset by increased costs to motor carriers and to vehicles affected on the arterials. The additional time and operating costs would be $28 million for motor carriers and about $12 million for automobile drivers on the arterials. The net direct cost impacts of a freeway truck ban would be $22 million in Los Angeles and $14 million in San Francisco. These estimates do not include cost changes for the 20 percent of large-truck trips shifted to offpeak periods. These carriers would realize marginal savings from operating under less-congested conditions but would accrue offsetting marginal costs for night operations.

The additional costs to motor carriers would affect the cost of doing business. It was estimated that the indirect impacts of these cost changes would reduce total California business sales (output) by $27 million in 1988 and $118 million in 1995.

A peak-period ban would also have direct impacts on safety and air quality. Accident and incident rates would decrease on the core area freeways but would increase on the parallel arterials due to the diversion of truck travel. Because the road conditions and speeds are different, the types and mix of accidents and incidents would change. Responsibility for these incidents would shift from state agencies to local agencies.

Approval for a peak-period ban on large-truck travel on freeways is unlikely under the provisions of the STAA, the Tandem Truck Safety Act of 1984 (TTSA), and subsequent court decisions. The STAA designated a national network of highways (including most California freeways) and prohibited state restrictions on large-truck operations on these routes unless the Secretary of Transportation finds significant safety problems on Interstate routes or significant safety, environmental, and operational problems on federal-aid primary routes.

A number of states have challenged the STAA. The challenges have included attempts to prohibit doubles, restrict trucks to specified routes, prohibit peak-period operation of large trucks, and require special permits for the operation of large trucks. In these cases, the courts have overruled state attempts to restrict the movement of large trucks that otherwise comply with the STAA and TTSA regulations. In several instances, the courts have been sympathetic to state arguments in favor of restricting large-truck movements on certain highways, but they have consistently ruled that the language of the STAA and TTSA does not permit the states to take these actions. The courts have interpreted the acts as permitting truck restrictions only when substantial safety problems can be demonstrated.

Truck bans on specific, accident-prone freeway segments are possible, but FHWA has approved only one truck ban (of limited duration) since the STAA was enacted. An areawide ban aimed at reducing air pollution has not been tested with FHWA or the courts.

CONCLUSIONS

Large-Truck Impacts on Freeway Congestion

The volume of large trucks on the freeways does not have an inordinate effect on peak-period congestion. Peak-period congestion is created primarily by the high volume of automobile traffic. Truck traffic makes a relatively small contribution to that congestion except on those few, highly congested freeways where truck volumes exceed 10 percent of total vehicles. Removing large trucks from most freeways would increase average speeds by only a few miles per hour.

On the other hand, truck-involved incidents and accidents do have a significant impact on freeway congestion. They account for about 20 percent of the delay accruing from all vehicle incidents and accidents, and they are highly visible to motorists and the public. Major truck incidents, which are of most concern, are few, but their impacts can be catastrophic and can trigger gridlock.

Traffic Management

A traffic management strategy is feasible and can be built on existing programs. Such a strategy would directly address the problem of freeway congestion and would provide positive benefits to freeway users and the economy. A traffic management strategy would not reduce the number of large trucks in peak-period traffic, but it would likely result in modest air quality benefits (by reducing stop-and-go traffic) and significant safety improvements (by minimizing hazardous traffic situations).

Incident Management

An incident management strategy is also feasible and can also be built on existing programs. It would address the public's concern about freeway gridlock and provide positive benefits to freeway users and the economy. An incident management strategy would reduce delay from truck-involved incidents and accidents, but it would not address the problem of recurring congestion. To be most effective, an incident management program should be paired with a traffic management program.

Night Shipping and Receiving

A night shipping and receiving program may be feasible in Los Angeles if it can withstand legal challenge and garner industry support. The California legislature has granted SCAQMD the power to regulate shipping and receiving as an indirect source of truck emissions, but such a program may be challenged as interfering with Interstate commerce. Resolution of the conflicting federal mandates (to facilitate Interstate commerce and reduce air pollution) may require congressional or judicial action. The full social and economic impacts of this strategy are not easily estimated; however, it is clear that the economic impacts will be costly unless the program is directed toward businesses and industries that can find offsetting savings. This will necessitate the strong participation of shippers and receivers in the design and implementation of the program. The strategy would have a modest effect on peak-period congestion, but it may improve air quality by reducing truck emissions during daylight hours. The strategy warrants more detailed study.

Peak-Period Freeway Truck Ban

A peak-period ban on large-truck travel on the freeways would have modest negative impacts on motor carriers, the economy, and air quality (engine emissions would increase as trucks divert to slower arterial routes). Average freeway speeds would increase slightly, but a ban would not provide significant relief from peak-hour congestion. Approval of a peak-period freeway truck ban is unlikely under the provisions of the STAA and subsequent court decisions. The courts, citing the federal supremacy clause, have consistently struck down state laws that have attempted to impose truck bans based on general concerns about congestion and safety. Truck bans on specific, high-accident freeway segments are possible, but FHWA has approved only one ban (of limited duration) since the STAA was enacted. An areawide ban aimed at reducing air pollution has not been tested with FHWA or the courts.

RECOMMENDATIONS

At the conclusion of this study, the following recommendations were made to the state of California.

Programs

• The state should expand and improve its incident management programs in the Los Angeles, San Francisco, and San Diego areas.

As a first step, Caltrans and CHP should undertake a joint review of their current incident management programs. Using this review as a base, they should develop a list of improvements (including those suggested in this paper) in the areas of surveillance, communications, site procedures, organization, and management. The improvements should then be tested and demonstrated to establish their feasibility and cost-effectiveness. Other state and local agencies that are involved in incident management should participate in the development program to encourage innovation and disseminate new techniques as rapidly as possible. The state should continue and strengthen its efforts to prevent accidents and incidents through its licensing, equipment maintenance, and safety inspection programs.

• Concurrently, the state should expand and intensify its traffic management programs in all three areas.

Caltrans should review its current traffic improvement programs to ensure that they give explicit consideration to the needs of large-truck operators and to the effects of these trucks on traffic flow. Special attention should be given to signage, speed controls, and the design of ramps and continuous-merge lanes. Congested freeways with high volumes of large trucks should be assessed and targeted for intensive truck-traffic management. In the San Francisco East Bay area, I-880 (the Nimitz Freeway) should be considered for use as a demonstration site for the truck-traffic management program. It is a congested freeway that carries a high volume of trucks and has a high accident rate. It is already a candidate for traffic management improvements and would provide an early opportunity to evaluate the effectiveness of truck-traffic management actions.

• The state should support a pilot program in Los Angeles to determine if a cost-effective night shipping and receiving program can be developed.

The program should focus on one or two high-truck-volume industries and determine if there are regulatory, tax, or operational changes that could make offpeak shipping and receiving economically attractive to firms. The pilot program should have a working council representing business, industry, motor carriers, and government. The working council should provide a forum for technical work as well as program development. As part of this program, Caltrans should monitor the progress of the night shipping and receiving program proposed by the city of Los Angeles (requiring large shippers and receivers to operate their docks for at least 4 hr between the hours of 8:00 p.m. and 6:00 a.m.).

• The state should not pursue areawide freeway truck bans; however, it should research time-of-day and lane restrictions.

Caltrans should conduct additional research on truck-involved incidents and traffic flow under congested conditions to determine whether there is a safety justification for time-of-day and lane restrictions on specific, high-accident freeway sections.

• The state should collect data and improve traffic modeling procedures used to estimate the impact of trucks on air quality.

The assessment of air quality impacts was not part of the scope of this study, but it is an important element of freeway and truck management strategies for Los Angeles. Available data on truck movements are inadequate, and current traffic models do not adequately distinguish trucks from other vehicles. New data and more responsive analytical tools must be developed.

Policies

This study provided new data and new insights on the relationships between large trucks and urban freeway congestion, and it put California at the leading edge of efforts to develop new solutions to urban freeway congestion. The issues of freeway and truck management are complex, and some solutions have significant social and economic costs. A single study, necessarily, leaves many questions unanswered and many options unexplored. Effective and equitable solutions will require a long-term commitment to research and implementation. As transportation policies are developed, it is recommended that the state.

- Encourage the development and coordination of freeway and truck management programs;
- Develop forums through which business, industry, and government can resolve congestion and urban goods movement problems; and
- Promote research and development of technology for highway and truck management.

ACKNOWLEDGMENT

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REFERENCE

1. W. W. Recker, T. F. Golob, and R. F. Teal. *An Analysis of Truck-Involved Freeway Accidents.* Institute of Transportation Studies, University of California at Irvine, 1988.

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Effect of 49th-50th Street Bus and Taxiway on Traffic Congestion in Manhattan

Paul P. Jovanis, Kambiz Bashar, and Ali Haghani

In March 1986, the New York City Department of Transportation simultaneously imposed a series of traffic regulations along 49th and 50th streets that became known as the 49th and 50th Street Bus and Taxiway. The regulations included a curbside priority lane for buses and occupied taxis, a ban on curbside pickup and delivery during selected midday hours, and a required turn for all nonpriority vehicles at the end of each block. Because the "before" data are limited, a before-and-after experimental design was conducted for priority vehicles (i.e., buses and occupied taxis) only. The findings of a study to assess the impact of these regulations suggest that measures other than curbside loading and unloading restrictions may be more effective in providing priority for selected road users. This conclusion is tempered by the unprecedented combination of tactics that were simultaneously implemented at the site and the ensuing uncertainties in discerning the causes for the observed changes in travel time.

During the middle and late 1980s, urban traffic congestion increased. This increase led to outcries from decision makers and the public at large. Although many tactics have been proposed and implemented, a group targeted frequently for travel restrictions is those involved in the movement of urban goods, in spite of a recent literature review (*1*) that revealed limited empirical assessments of traffic benefits due to truck restrictions. Further, the same review revealed that little is known of the economic consequences of goods movement restrictions on transportation providers, shippers, or customers.

It is legitimate to ask how this state of affairs has evolved. A simplistic response is that people vote and packages do not. Beyond this rationale, it must be assumed that many transportation professionals believe that restricting the delivery of urban goods and services by light trucks and vans is a positive policy option in relieving congestion. The congestion-related effects of a particular restriction on delivery of goods and services formed the focus of this research.

In March 1986, the New York City Department of Transportation (NYCDOT) implemented a series of traffic regulations on 49th and 50th streets, a pair of one-way streets in Manhattan, between 3rd and 8th avenues (Figure 1). These regulations, referred to by NYCDOT as the 49th and 50th Street Bus and Taxiway, are listed below:

- A red zone priority lane was implemented in the right-side curb lane for the exclusive use of buses and loaded taxis.
- Private vehicles and unloaded taxis could use 49th and 50th streets but were required to turn off after traveling one block (shown in Figure 1 as dashed lines at each intersection).
- On-street loading and unloading of vehicles were prohibited on 49th Street from 11:00 a.m. to 2:00 p.m. and on 50th Street from 2:00 to 5:00 p.m., Monday through Friday.

The first two sets of regulations were in effect from 8:00 a.m. to 6:00 p.m., Monday through Friday.

These regulations had a significant effect on traffic patterns on both 49th and 50th streets, as well as on the neighboring streets and avenues. A particular concern was that three traffic control measures were implemented simultaneously: a priority lane, mandatory turns for classes of vehicles, and restrictions on loading and unloading. In evaluating the effectiveness of the bus and taxiway, it is important to understand how each individual regulation affected traffic flows.

Because of a concern for the continued viability of their businesses, a number of companies joined together to form the Business Committee on Midtown Traffic. This organization requested that the Northwestern University Transportation Center submit a proposal for a study that would assess the impacts of the bus and taxiway. The accepted proposal had two major components: (a) a study of traffic impacts and (b) a study of companies' perceptions of how the restrictions affected their operations in the area. This paper reports findings of the traffic impact phase of the research.

OBJECTIVES OF THE RESEARCH

The objectives of the traffic study were

1. To measure the effect of the 49th and 50th street regulations on travel time in the corridor. This included separate measurement of travel time along 49th and 50th streets as well as the nearest adjacent streets, 48th and 51st. Particular emphasis was placed on identifying spatial and temporal changes in travel time. When possible, the magnitude and cause of any changes were determined.
2. To separately estimate the effect of restrictions on loading and unloading along 49th and 50th streets. Because these restrictions were imposed simultaneously with mandatory turns for through traffic, it was important to separate their effects.

The overall intent of the research was to conduct an independent assessment of the effect of the traffic regulations. In developing a study design, emphasis was placed on the ability to statistically test hypotheses concerning these effects.

P. P. Jovanis, Department of Civil Engineering and Transportation Research Group, University of California, Davis, Calif. 95616. K. Bashar, United Parcel Service, 2311 York Road, Timonium, Md. 21093. A. Haghani, Department of Civil Engineering, University of Pittsburgh, 949 Benedum Hall, Pittsburgh, Pa. 15261.

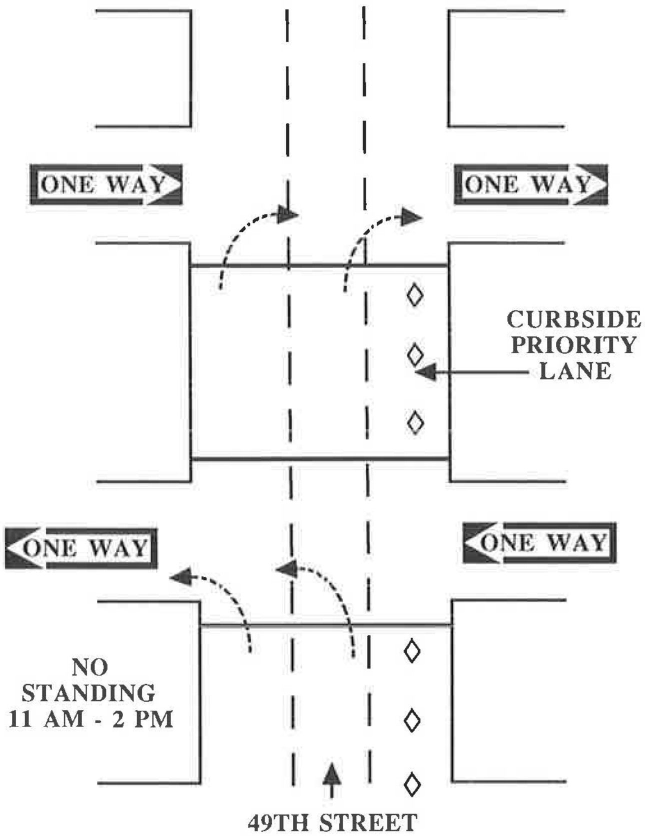

FIGURE 1 Diagram of corridor traffic regulations.

STRUCTURE OF THE ANALYSIS

Although data describing conditions after implementation of the bus and taxiway could be collected easily, the research team had to rely on NYCDOT to provide data describing previous conditions. (Contact was not established between the Business Committee and Northwestern until after the bus and taxiway was implemented.) Preliminary meetings with NYCDOT representatives revealed that travel time data were periodically collected on selected New York City streets during spring and fall. NYCDOT committed to providing available travel time data for affected streets before bus and taxiway implementation. Because limited flow data were available for that period, travel time (or speed) was chosen as the primary measure of effectiveness. A subsequent report by NYCDOT (*2*) indicated that total volumes on 49th and 50th streets had remained nearly the same, although the mix of vehicles had changed dramatically: There were many more taxis and fewer trucks and private automobiles. A before-and-after design was thus undertaken using travel time as the primary measure of effectiveness.

The research team asked NYCDOT to provide copies of individual travel time runs in the study corridor. Summary data containing the means of several runs were initially sent to the researchers, but these were insufficient for statistical inference. After several months of discussion, individual travel time runs were provided to the research team for 49th, 50th, and 51st streets for fall 1985. At this point, the research team had a choice:

1. Conduct limited analyses of summary data provided by NYCDOT (which would consist of comparing two numbers without the ability to statistically test hypotheses unless a variance and sample size were assumed) or
2. Use the more limited set of raw data for fall 1985, but conduct valid statistical tests of hypotheses concerning equality of mean travel times before and after the bus and taxiway was implemented.

As part of these deliberations, Figure 2 was constructed from NYCDOT Speed Books (*3*, *4*), which are a compilation of mean travel times on selected routes for a season and year. The plots indicate that the fall 1985 travel times for 49th and 50th streets were a little higher than previous times. The research team concluded that it was reasonable to use fall 1985 travel times to characterize traffic conditions before the bus and taxiway. Because the fall 1985 travel times were somewhat higher, the decision might have created a bias in the direction of overstated bus and taxiway time savings. Therefore, a *t*-test was used to test the null hypothesis of equal mean travel times for unequal sample sizes and unequal (and unknown) variances. The alternative hypothesis was that the means were unequal.

The analyses of the travel times were complicated by the overlapping of the traffic restrictions. One figure of merit that could have been used was the change in average travel time from 3rd to 8th avenues during the entire day. This measure is useful in determining average efficiency for crosstown travel, but it ignores important differences in the spatial and temporal patterns of corridor use. For example, it is useful to know the changes in travel time for the hours just before the restrictions on loading and unloading, the hours during the restrictions, and those after the restrictions.

The spatial differences are particularly important because of the mandatory turns. After the bus and taxiway was implemented, many vehicles had to approach their destination along the nearest avenue and then turn directly along 49th or 50th street for less than a block. If the destination was along a block that had experienced an increase in travel time, that user would experience an increase in travel time, not a reduction. After serving a customer on one block, a vehicle may have needed to serve another customer on the next block of 49th or 50th Street. An eight-block detour was typically needed in this situation because of the mandatory turns and the one-way grid street pattern. Separate analyses were therefore conducted of block-by-block changes, identifying road sections that experienced travel time increases or no significant changes as well as those that experienced travel time reductions.

DATA COLLECTION

Overview

NYCDOT collected travel time data using department vehicles during fall 1985. These were the only New York City data used in the analysis. Inspection of the completed data forms indicated that the city used a technique similar to one in the *Transportation and Traffic Engineering Handbook* (*5*). Unfortunately, data were only provided for through vehicles on 49th, 50th, and 51st streets; no analysis of 48th Street

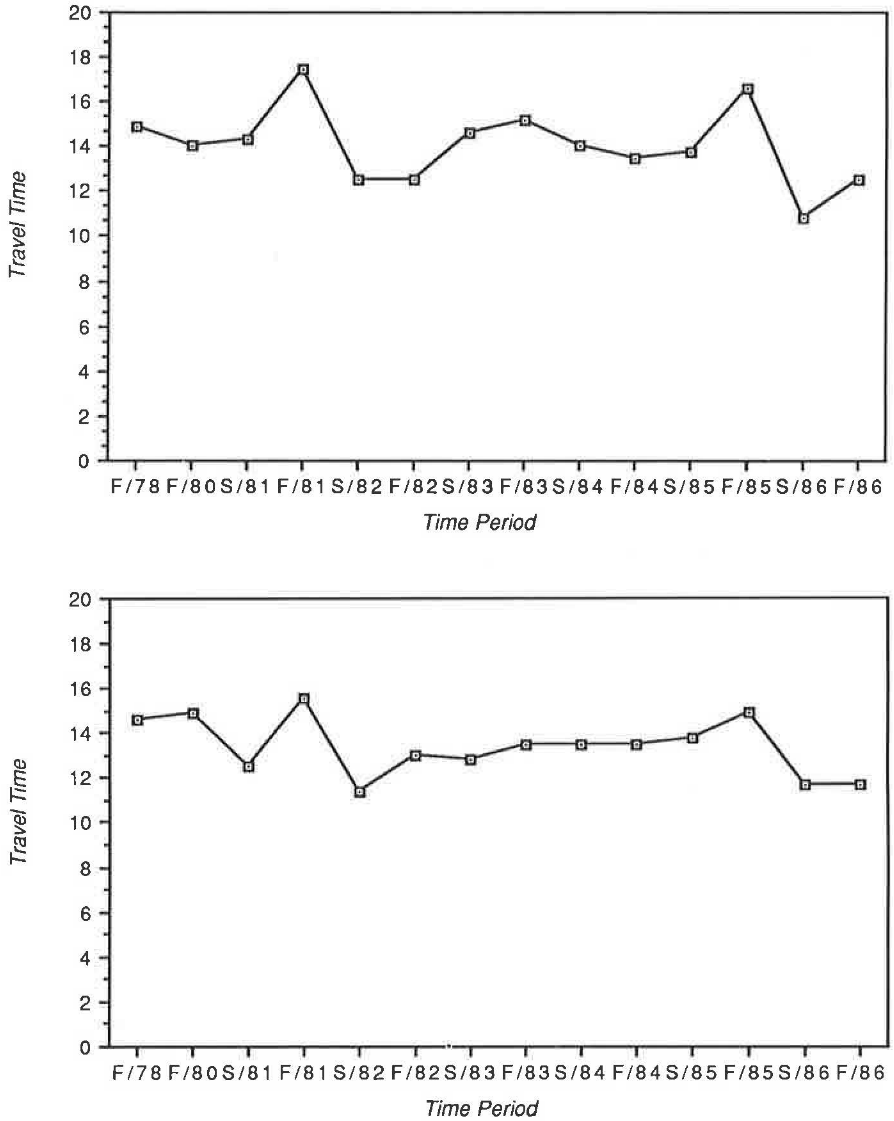

FIGURE 2 Historical travel times: (*top*) 49th Street and (*bottom*) 50th Street.

was possible nor was it possible to assess travel time changes for travelers turning off the subject streets because of the mandatory turns.

Travel times after implementation of the bus and taxiway were collected by the research team. Several visits were made to Manhattan during late summer 1986 to plan and design the data collection activity. Data were collected on Tuesday and Thursday from September 30 through October 9 between 8:00 a.m. and 6:00 p.m. The streets studied were 48th through 51st between 3rd and 8th avenues. Because of the vehicular restrictions on 49th and 50th streets, Medallion taxis with New York cab drivers were used as the data collection vehicles.

Travel time and stopped delay data were collected using the "moving vehicle" method (*5*). There were two observers in the data collection vehicles. One recorded the elapsed time between each intersection and the other, the duration of the delays and their causes. The drivers of the vehicles had no role in observing and collecting data. They were specifically asked to drive as they normally would so the data would reflect actual taxi travel times in the corridor. Thus, travel times are reflective of priority vehicle travel in the corridor. Nonpriority vehicles experienced much longer travel times.

In addition to the usual data collected in such a study, additional data were collected to discern the effect of the curb use restrictions on travel time. One observer recorded the number of vehicles illegally parked at the curb during the restricted hours and their location along the block. Parked vehicle travel times were compared with the travel time data collected when no vehicles were parked at the curb during the same period. These data were used as part of a field simulation to provide a more detailed assessment of the effect of the restrictions on loading and unloading.

Comment on Travel Time Estimates

Travel times in an urban street corridor are affected by a wide variety of factors. Driver perceptions of the value of time can be conceptualized to be balanced against operating costs and safety level; an outcome is the driver's desired travel time or speed. The presence of other traffic and pedestrians because of urban economic activity may cause congestion or accident risk, further constraining this travel time choice. As each of these factors changes (as they did in the bus and taxiway), travel times change.

This conceptualization makes it easier to see how each factor was considered during the data collection study design. In concept, direct measurement of the effect of the three road traffic controls implemented on 49th and 50th streets, the exclusive lane for buses and taxis, the restrictions on loading and unloading during midday, and the mandatory turns at each intersection for all vehicles other than buses and loaded taxis would be desirable. The level of enforcement necessary to ensure compliance with the restrictions is implicitly included in the assessment. During visits to the site, it appeared that enforcement at the intersections was fairly strict; traffic agents were typically posted at each intersection. Enforcement of the restrictions on loading and unloading was more erratic, as shown by the illegal curb use. Thus, the travel time measurements captured the collective effect of changes in lane use (the bus lane), parking (loading and unloading restrictions), turns, and enforcement.

It was assumed that several factors would not change significantly in the 1-year time period between the before-and-after studies. These included the driver's value of time and the perception of fuel, insurance, and vehicle maintenance costs. The road design itself did not change in the corridor during the year nor did the handling and braking characteristics of the vehicles. It was assumed that the level of other street use (e.g., for construction) had not appreciably changed during the year. Given the intense level of building and restoration activity in Manhattan, this did not seem an unreasonable assumption. It was also unlikely that signal timing changes were implemented because of the dense grid that characterizes the Manhattan street system and the current lack of central computer control in Manhattan.

Because the data collection and analysis were constructed to compare data from two consecutive fall seasons, there were controls for fluctuations in traffic (pedestrian and vehicular) that were due to seasonal economic cycles. Implicitly, there were also controls for broad patterns in weather and hours of daylight and darkness. By waiting until fall 1986 to collect the data, users were allowed over 6 months to change their operations in response to the bus and taxiway. The travel times thus reflected what was believed to be a new equilibrium pattern of operations in response to the traffic restrictions. This experimental structure allows the use of a variety of statistical procedures to test whether differences in travel times were due to chance or whether they were lasting effects. Further details of the data analysis and summaries of raw data are contained in the technical report of the study (*6*).

These estimates of changes in travel time did not include the time wasted by any vehicle other than a loaded taxi or bus that tried to move more than one block along 49th or 50th Street. Any nonpriority vehicle that attempted to cross an avenue was required to travel an additional eight blocks to reach the intersection entry at the next block (due to the mandatory turns and the largely one-way grid of streets). These circuitous routings had important implications for travel time and air quality that were too difficult to measure in the field. Thus, the estimates of travel time changes should be considered as a best-case scenario biased in favor of the bus and taxiway. The experiences of many users were expected to be somewhat worse.

EMPIRICAL FINDINGS OF TRAVEL TIME STUDIES

Overall Effect

For a crosstown trip along 49th Street from 3rd to 8th Avenue between 8:00 a.m. and 6:00 p.m., the average travel time savings was significant for any user. Before the restriction, the average travel time on 49th Street was 15.1 min. Afterward, travel time was 9.2, a drop of 5.9 min. On 50th Street, however, a trip from 8th to 3rd Avenue that previously took 10.1 min took 9.7 min after the restriction—a difference of only 0.4 min. After implementation of the restrictions, travel times on 51st Street increased by 22 percent, from an average of 10.1 min to an average of 12.3 min. Only the 49th and 51st street changes were statistically significant. Further, the temporal and spatial patterns indicated clear patterns of response to the 49th and 50th street restrictions.

Temporal Distribution of Travel Times

The three traffic control measures that made up the bus and taxiway were not all implemented during the same time period. The priority lane and mandatory turns were imposed on weekdays from 8:00 a.m. to 6:00 p.m. Curb use was restricted from 11:00 a.m. to 2:00 p.m. on 49th Street and from 2:00 p.m. to 5:00 p.m. on 50th Street. It was expected that the three control measures would alter usage patterns along 49th and 50th streets and result in complex patterns of travel time changes throughout the day and along streets in the area as users responded to the restrictions.

Figures 3 and 4 show travel times by hour for crosstown travel between 3rd and 8th avenues on 49th and 50th streets, respectively. Average travel times before the bus and taxiway (fall 1985) and after implementation (fall 1986) are plotted separately, and differences attributable to the bus and taxiway are highlighted with diagonal lines. The crosshatched areas represent a qualitative estimate of the travel time savings that may be attributable to the loading and unloading restrictions in effect only during these time periods on each street. The area was determined by extrapolating travel time changes at the beginning of the loading and unloading restrictions (i.e., 11:00 a.m. on 49th Street and 2:00 p.m. on 50th Street) to those existing at the end of the restrictions (after 2:00 p.m. and 5:00 p.m., respectively). The line connecting the beginning and end points can be interpreted as a trend line that represents changes that might have occurred in the absence of the loading and unloading restrictions. Sample sizes for the two data sets were quite different: "before" data (collected by NYCDOT) typically contained 2 observations per hour, whereas "after" data (collected by Northwestern) typically contained 10.

Figure 3 shows substantial travel time savings during the midday period (roughly 10:00 a.m. to 3:00 p.m.). The hour from 3:00 to 4:00 p.m. had virtually the same travel time before and after the restrictions as did the 8:00 to 9:00 a.m.

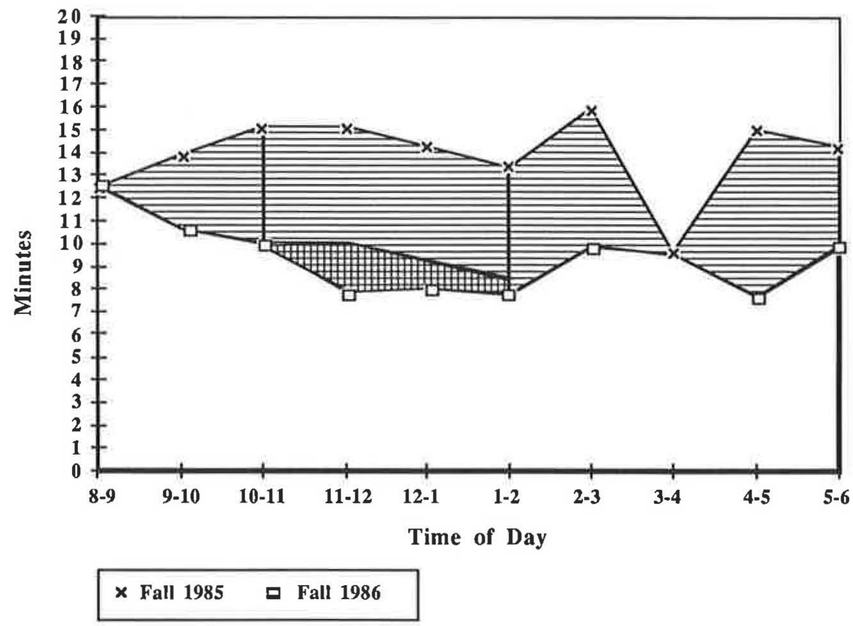

FIGURE 3 Travel time: 3rd to 8th Avenue on 49th Street.

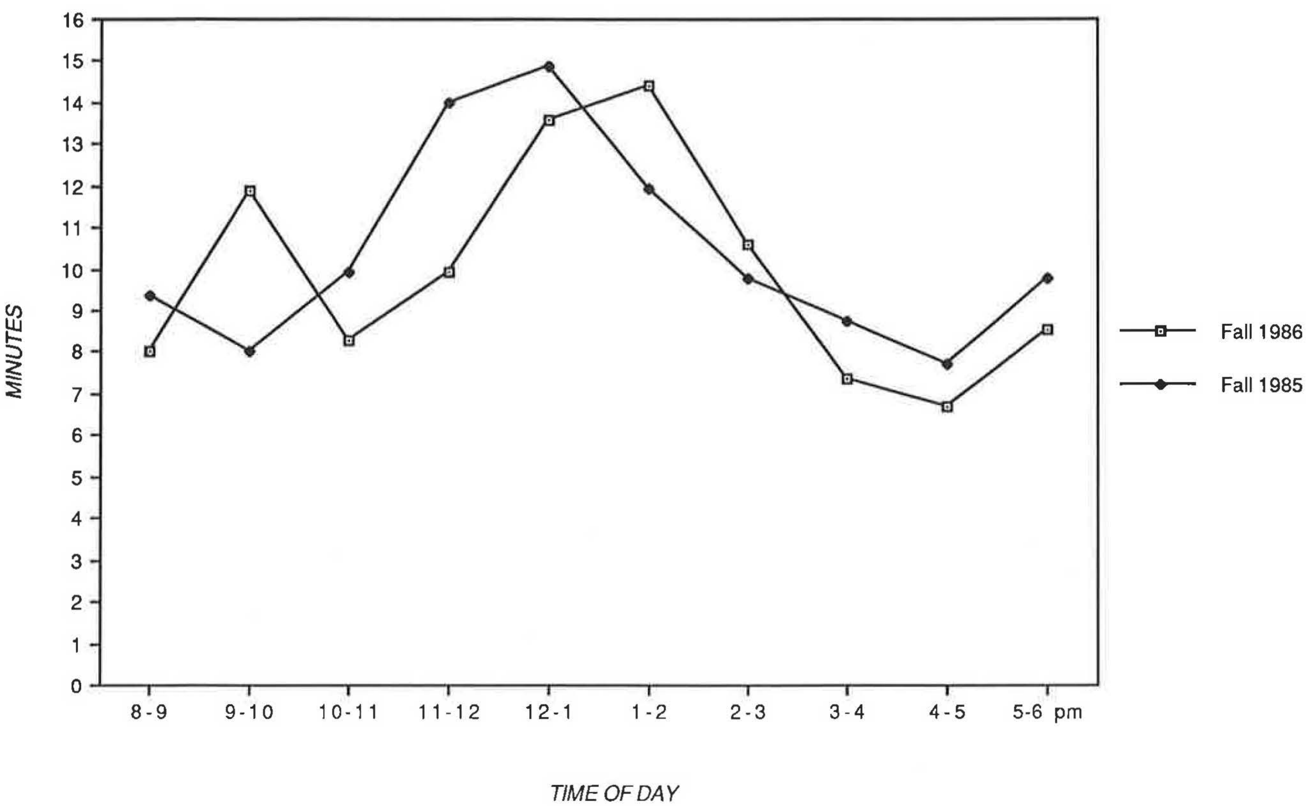

FIGURE 4 Travel time: 3rd to 8th Avenue on 50th Street.

hour. Large savings were also apparent from 4:00 to 6:00 p.m. Figure 4 shows a different set of travel time changes for 50th Street. There were major reductions in travel time from 10:00 a.m. to 1:00 p.m. and from 4:00 to 6:00 p.m. However, there were increases in travel time from 8:00 to 10:00 a.m. and from 1:00 to 3:00 p.m.

To facilitate statistical tests, the 10 hr of the restriction were divided into four time periods: 8:00 to 11:00 a.m.; 11:00 a.m. to 2:00 p.m.; 2:00 to 5:00 p.m.; and 5:00 to 6:00 p.m. These correspond to time blocks just before curb use restrictions, during 49th Street restrictions, during 50th Street restrictions, and after curb restrictions, respectively.

Statistical tests comparing mean travel times on 49th Street supported the earlier qualitative assessments (see Table 1): travel time changes from 8:00 to 11:00 a.m. were 2.5 min, the smallest of any time period. The travel time change for all time periods was also statistically significant.

Statistical tests of travel time change on 50th Street (see Table 1) revealed that there was no significant change in crosstown travel time for any of the four time periods. Although Figure 4 appears to show savings in travel time with the restrictions, the apparent differences in average travel time are overwhelmed by variations in the data. These findings are consistent with the earlier conclusion of no significant travel time change on 50th Street.

Although the pattern of travel time changes was different for the two streets, there is a common conclusion to the analysis: the major factors contributing to time savings appear to be the priority lane and mandatory turns, not the restrictions on loading and unloading.

The travel times on 51st Street, as a function of time of day, are shown in Figure 5 and Table 1. Several clear patterns emerge: travel times from 8:00 to 10:00 a.m. were much higher than before the bus and taxiway, but the result is of marginal

TABLE 1 TRAVEL TIME CHANGES BY TIME OF DAY

	Travel Times (min) by Time of Day			
Street and Time Period	8–11 a.m.	11 a.m.–2 p.m.	2–5 p.m.	5–6 p.m.
49th Street				
Before	13.3	19.2	13.7	14.3
After	10.8	7.8	9.0	9.1
Difference	2.5[a]	11.4[a]	4.7[a]	5.2[a]
50th Street				
Before	9.0	13.4	8.4	9.8
After	9.9	12.0	8.2	8.5
Difference	−0.9	1.4	0.2	1.3
51st Street				
Before	9.2	12.0	10.3	9.0
After	11.2	14.8	12.1	11.1
Difference	−2.0	−2.8[a]	−1.8[a]	−2.1

[a]Implies a statistically significant difference for $\alpha = 0.05$.

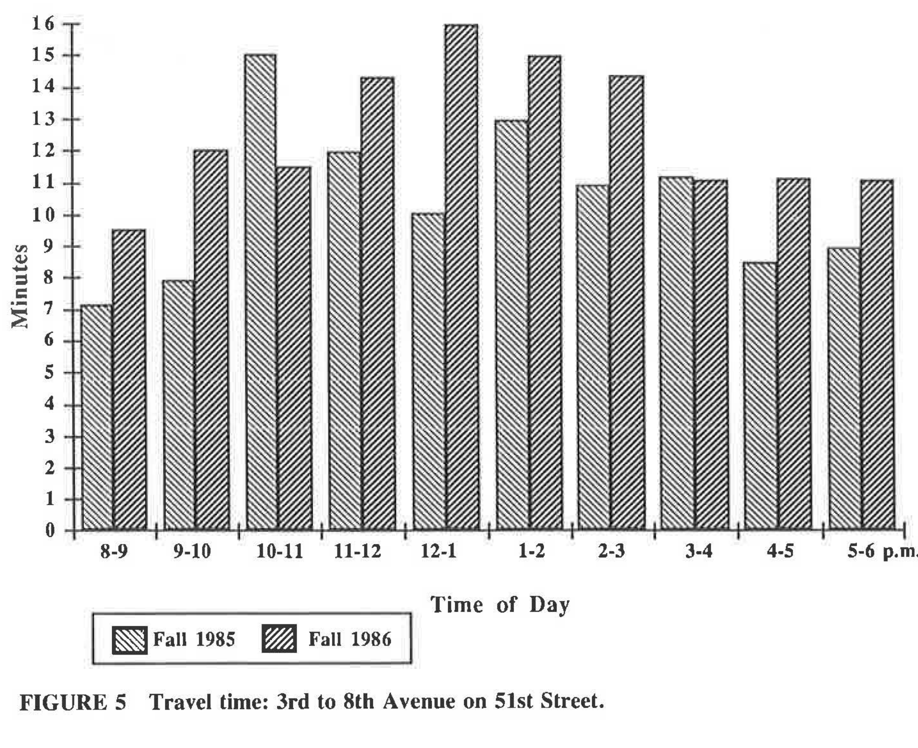

FIGURE 5 Travel time: 3rd to 8th Avenue on 51st Street.

statistical significance. These findings could have been caused by vehicles arriving early in the corridor to avoid the restrictions on 49th Street. There were also large travel time increases from 11:00 a.m. to 2:00 p.m. (when loading and unloading were banned on 49th Street) and from 2:00 to 5:00 p.m. (when 50th Street curb restrictions were initiated). The worst increase occurred from 12:00 to 1:00 p.m., when there were also high pedestrian flows in midtown. The magnitude of these differences was also substantial, with changes frequently exceeding 3 min and occasionally nearing 6 min.

Another observation should be made concerning these travel time trends. To some extent on 49th and 51st streets, but quite clearly on 50th Street, travel times tended to reach a peak during midday both before and after the restrictions. Field observations revealed that this was primarily attributable to the large number of pedestrians that circulated in the corridor and competed with high vehicle turn flows for limited roadway space. During morning and afternoon rush hours, the pedestrian conflicts lessened somewhat, easing turns for vehicles.

This pattern of congestion was quite different from that experienced in many other cities and substantially complicated the identification of causes of congestion. During field data collection, the vast amount of congestion occurred at the intersections. It was simply impossible to observe and identify what was causing the delay: poor signal timing, pedestrian conflicts, the mandatory turns, inadequate capacity, or some combination of these factors. Although it was possible to describe what had occurred, it was more difficult to provide a more detailed attribution of causality.

Spatial Distribution of Travel Times

Figures 6 and 7 show the spatial distribution of travel time changes for 49th and 50th streets, respectively, using mean times from 8:00 a.m. to 6:00 p.m. Figure 5 shows an enormous time savings (nearly 4 min) on 49th Street approaching 7th Avenue and moderate savings (typically 1 min) approaching 6th and 8th avenues. There were small changes at other intersections, including an increase approaching Lexington Avenue. Statistical tests (see Table 2) support these qualitative assessments. Significant travel time savings on 49th Street for the entire day were only observed on the west side approaching 6th, 7th, and 8th avenues. There were scattered travel time savings and increases on other mid-Manhattan and east side streets, but they were not sustained throughout the day. The massive time savings approaching 7th Avenue dominated any other travel time changes along 49th Street.

Findings for 50th Street were again quite different. Figure 7 shows travel time savings approaching Madison and 3rd avenues but increases in travel times approaching 6th and 5th avenues. Statistical tests confirmed these findings. What was gained at 3rd Avenue and Madison was lost on 5th and 6th avenues. The net result for a crosstown trip was no improvement in travel time with the restrictions. On this street, westside users were worse off because of the bus and taxiway, even if circuitous routings were not considered. Only users approaching Madison and 3rd avenues received any benefit throughout the day.

As with other streets in the bus and taxiway area, there were significant spatial patterns to the travel time changes on 51st Street (see Figure 8 and Table 2). Substantial travel time increases occurred approaching Lexington, Madison, and 7th avenues. These increases existed on the Lexington Avenue approach for all time periods except 11:00 a.m. to 2:00 p.m. There were also significant increases in travel time on the 7th Avenue approach, particularly from 11:00 a.m. to 5:00 p.m., when the loading and unloading restrictions were in effect on 49th and 50th streets.

EFFECT OF LOADING AND UNLOADING RESTRICTIONS ON TRAVEL TIME

The effect of the curb use restriction was evaluated by noting the presence of any illegally parked vehicles during the hours restricting loading and unloading. These vehicles effectively

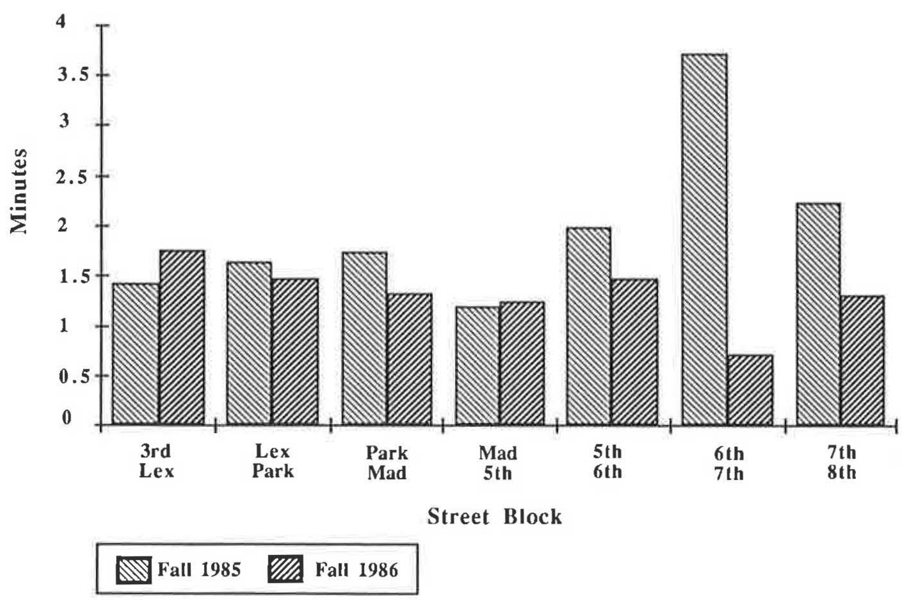

FIGURE 6 Block travel time: 9:00 a.m. to 6:00 p.m. on 49th Street.

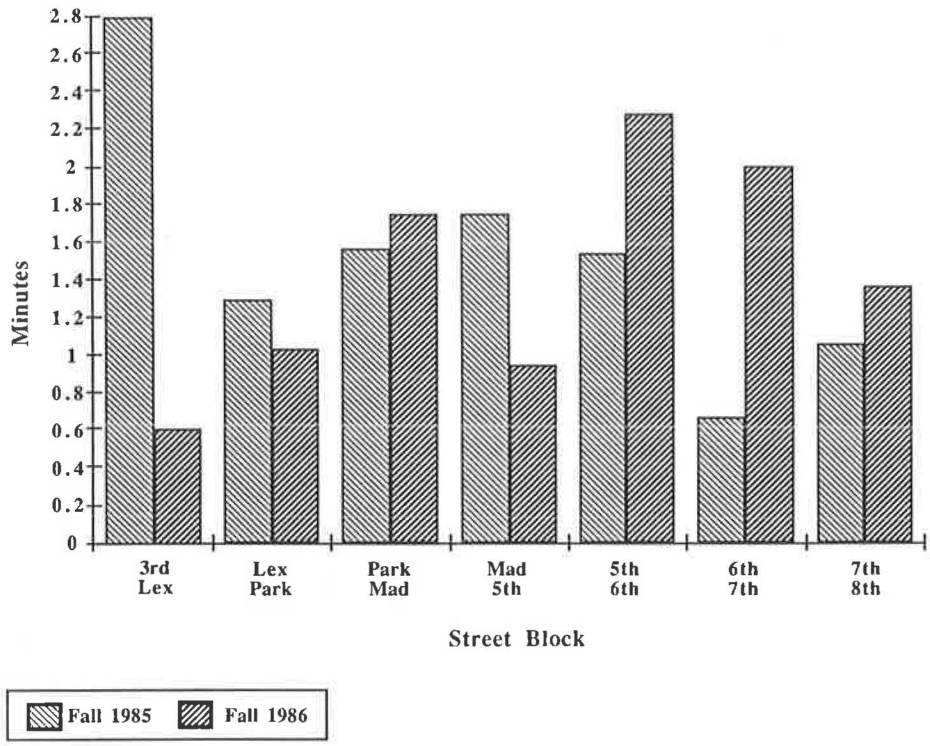

FIGURE 7 Block travel time: 8:00 a.m. to 6:00 p.m. on 50th Street.

TABLE 2 TRAVEL TIME CHANGES ALONG INDIVIDUAL BLOCKS: 8:00 A.M. TO 6:00 P.M.

	Mean Travel Times (min) by Blockface[a]						
Street and Time Period	3rd and Lexington	Lexington and Park	Park and Madison	Madison and 5th	5th and 6th	6th and 7th	7th and 8th
49th Street							
Before	1.6	1.4	1.7	1.3	2.3	4.6	2.2
After	1.7	1.4	1.3	1.2	1.5	0.7	1.3
Difference	−0.1	0.0	0.4	0.1	0.8[b]	3.9[b]	0.9[b]
50th Street							
Before	2.5	1.1	1.6	1.7	1.5	0.7	1.0
After	0.6	1.0	1.7	0.9	2.2	1.9	1.4
Difference	1.9[b]	0.1	−0.1	0.8[b]	−0.7[b]	−1.2[b]	−0.4
51st Street							
Before	1.5	1.2	1.3	1.2	2.3	1.4	1.3
After	2.3	1.4	1.7	1.3	2.1	2.2	1.2
Difference	−0.8[b]	−0.2	−0.4[b]	−0.1	0.2	−0.8[b]	0.1

[a]49th and 51st streets are one way westbound; therefore, vehicles move from 3rd Avenue toward 8th Avenue. 50th Street is one way eastbound; therefore, vehicles move from 8th Avenue toward 3rd Avenue.
[b]Significant difference in travel time for $\alpha = 0.5$.

blocked one through lane. By comparing travel times when the lane was blocked by one or more vehicles with the travel time without blockage, an estimate of the effect of the restriction was obtained. Clearly, having one vehicle illegally parked was not the same as having the lane full; however, it only took one blockage to substantially reduce the utility of the lane. Importantly, collecting data during the time of day that the restrictions were in effect controlled for the effect of pedestrian and vehicle flows directly.

In addition to the presence of the illegally parked vehicles, their location was also recorded. Vehicles parked farthest upstream on a block were recorded as in the last third of the block, vehicles in the next third as in the middle of the block. Vehicles closest to the traffic signal controlling traffic on the block under study were recorded as in the first third of the block. The hypothesis was that vehicles parked in the first third of the block had the largest effect on travel time because they directly affected queue discharges and turns. This was an important comparison because it helped to determine how close to the intersection to allow loading and unloading if the restriction was modified.

Two separate comparisons were conducted. The first compared travel times with and without illegal standing on each blockface of 49th and 50th streets. The second attempted to determine the effect of having a vehicle in the first third of the block compared with one or more parked in the other two-thirds. Due to a limited sample size, the latter comparison could not be made for each blockface. Instead, data were aggregated from all blocks and, to correct for the effect of distance, speed rather than travel time was used.

Comparisons for Each Block

Figures 9 and 10 show the travel time comparisons for 49th and 50th streets, respectively. Although the travel times on 49th Street were generally higher when standing was observed, none of the differences was statistically significant. Travel times on the west end of 49th Street were nearly the same, irrespective of the presence of illegal curb use.

The results for 50th Street were similar to those for 49th Street: none of the blocks had significantly different travel times because of illegal curb use. Interestingly, on two blocks (Lexington and Madison), travel times were slightly higher,

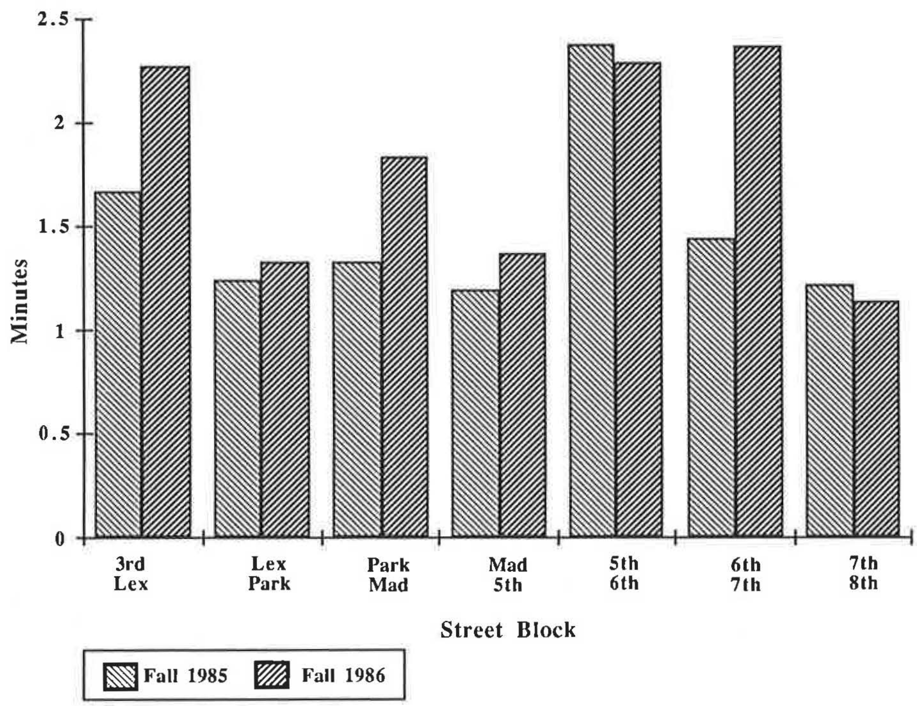

FIGURE 8 Block travel time: 8:00 a.m. to 6:00 p.m. on 51st Street.

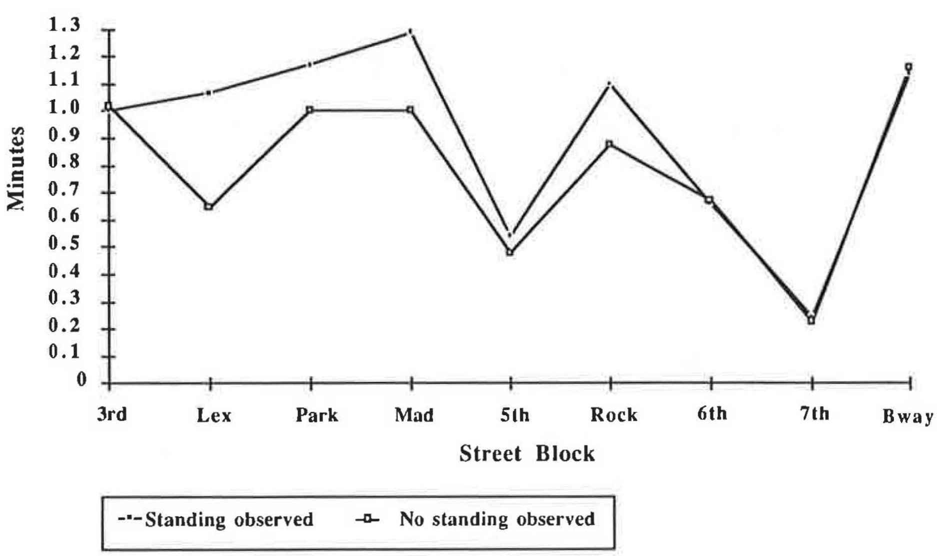

FIGURE 9 Impact of "No Standing" on travel time: 49th Street.

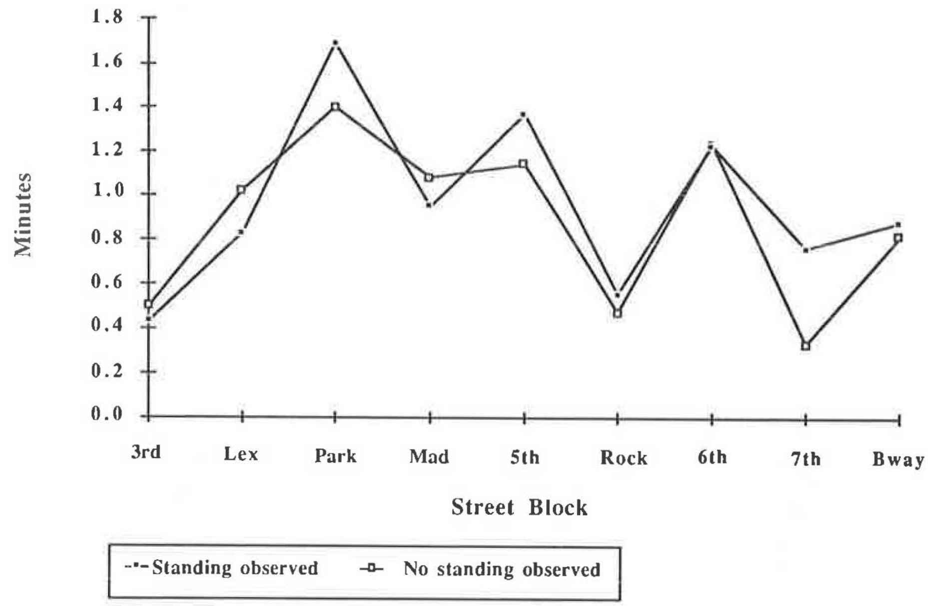

FIGURE 10 Impact of "No Standing" on travel time: 50th Street.

with no curb use. Again, none of these differences was statistically significant.

Effect of Location of Illegal Curb Use

The second set of analyses compared travel times for two conditions:

1. When vehicles were illegally parked in the first third of the block, and
2. When vehicles were illegally parked in the end, middle, or both remaining thirds of the block.

The average speed was 8.3 mph for the first case and 8.9 mph for the second case. Statistical tests found no difference between them. There appeared to be no measurable effect of allowing loading and unloading far upstream of the exit intersection. Thus, given the nature of the experiment and the importance of allowing for queueing and turns, it appeared reasonable to allow loading and unloading in the two-thirds of the block farthest from the controlling traffic signal.

Discussion of Results

These detailed comparisons largely support the conclusion of the previous section: The restrictions that had the greatest effect on travel time were the priority lane and mandatory turns. In comparison, the effect of the loading and unloading restrictions was extremely small.

It could be argued that these analyses were not valid because the effect of one truck at the curb is very different from that of a full curb. Although in principle this is true, from the perspective of the number of available approach lanes it is not. Vehicles would have to merge to pass the illegal vehicle; the merging action would slow them down enough to result in some travel time difference. However, in these data, no significant effect was evident. The volumes appeared to be low enough that the merging and weaving around illegally parked vehicles could be executed with limited delay.

Thus, for this package of restrictions, the loading and unloading regulations make little sense and should be eliminated. To allow easy access for turns, curb use prohibitions should remain for the first third of each block. Travel time data should be collected to monitor this change in the restrictions. After several months of study testing and evaluation in the field, a more definitive judgment could be made on effects of loading and unloading restrictions. Because flow data are not systematically available in the corridor, it is difficult to offer more precise guidelines to other potential users of these types of restrictions. Flows with the bus and taxiway were clearly heavy but not oversaturated. The restrictions on loading and unloading were implemented during midday, when peak commuter traffic was much less of a problem. From a traffic management perspective, the restrictions on loading and unloading appear to have had limited effect because of their midday imposition; it is this timing, however, that makes them particularly onerous to delivery and service vehicles attempting to meet customer needs in the area. For these reasons, the study concluded with recommendations for a set of field experiments that selectively remove portions of the restrictions. These recommended studies are discussed in the following section.

SUMMARY AND CONCLUSIONS

Extensive data analyses were conducted to assess the travel time impact of the 49th and 50th Street bus and taxiway in Manhattan. A before-and-after comparison was conducted using data provided by NYCDOT (to characterize conditions before the restrictions) and data collected by Northwestern University Transportation Center (to characterize conditions afterward). Data were compared between fall 1985 and fall 1986 to control for seasonal traffic fluctuations and allow time for corridor users to respond to the restrictions.

The travel time studies yielded remarkably different results for the two streets on which the restrictions were implemented. There were significant travel time reductions on the west side of 49th Street throughout the day. Although there were scattered time savings approaching other mid-Manhattan and east-side streets, the savings were not sustained throughout the day and were balanced somewhat by increases in travel time approaching Lexington and Park avenues.

On 50th Street, traffic patterns were more complex; some blocks had time savings, whereas others experienced travel time increases. The conclusion is that crosstown travel times did not change significantly for the entire day or for specific time periods during the day, including the time when the curb use restrictions were in effect.

Attempts to isolate the effect of the loading and unloading restrictions revealed that the travel time savings, when they occurred, were overwhelmingly due to the priority lane and mandatory turns, not the curb use restrictions.

There were significant travel time increases along 51st Street, apparently because of the restrictions on 49th and 50th streets. The increases were particularly large approaching Lexington, Madison, and 7th avenues.

The analyses identified several locations that experienced no change in travel time with the bus and taxiway. Experiments with removal of the mandatory turn restrictions should be performed. These proposed changes in the turn requirements recognize the cost paid by nonpriority vehicles due to the eight-block circuitous routing. A series of experiments should be conducted in which the turn restrictions are changed to ease traffic circulation. The effect of these changes on corridor travel time can be closely monitored during the experiment so that taxi and bus travel time savings are not eroded.

This fine tuning of the taxiway system should retain savings for buses and loaded taxis while allowing some cost relief for other corridor users. Air quality is also likely to benefit from concurrent vehicle mileage reductions.

It is recommended that the restrictions on loading and unloading be removed on 49th and 50th streets except for the third of each block that is closest to the controlling traffic signal. Although it appears from the analysis that the restrictions on loading and unloading could be eliminated completely, preserving a third of the block for moving vehicles may be advisable.

Despite a rather extensive data collection effort after imposition of the bus and taxiway, it was extremely difficult to attribute delays to particular causes and even more difficult to offer specific advice about likely effects should these policies be attempted elsewhere. The process of experimental removal and monitoring of the traffic regulations along 49th and 50th streets is recommended so that the government's ability to provide priority service for selected road users can be determined by the costs imposed on nonpriority vehicles. Although other analysis techniques, such as simulation, may be attempted to estimate travel time effects, the complexity of the regulations argues for an experimental approach.

The basic question that is left unanswered is, which street, 49th or 50th, has given results that are more typical or expected? The short answer is one of uncertainty; however, the focus of travel time changes primarily along one block of 49th Street and the more varied and dispersed changes along the remainder of 49th and all of 50th Street argue for a cautious approach to implementation of this mix of tactics in other locations. If the more incremental experimental approach is adopted in Manhattan and elsewhere, more can be learned about how these regulations interact.

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REFERENCES

1. K. Bashar, J. L. Schofer, and P. P. Jovanis. *Urban Goods Movement Literature Review.* Transportation Center, Northwestern University, Evanston, Ill., 1986.
2. *49th/50th Street Bus and Taxiway.* Final Report. New York City Department of Transportation, Feb. 1987.
3. *Speed Book.* New York City Department of Transportation, Spring 1985.
4. *Speed Book.* New York City Department of Transportation, Fall 1985.
5. Institute of Traffic Engineers. *Transportation and Traffic Engineering Handbook.* Prentice-Hall, Englewood Cliffs, N.J., 1976.
6. P. P. Jovanis, K. Bashar, and J. L. Schofer. *The Effect of the Manhattan 49th and 50th Street Bus and Taxiway on Vehicular Travel Times.* Transportation Center, Northwestern University, Evanston, Ill., Feb. 1988.

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Effects of Truck Restrictions on Regional Transportation Demand Estimates

JOHN P. REILLY AND JEFFERY J. HOCHMUTH

The effects of currently imposed truck restrictions on transportation demand estimates, the mix of trucks in congested traffic, and truck travel times and trip length are examined. During the past 3 years, the Chicago Area Transportation Study (CATS) has been developing the Transportation System Development Plan for 2010. The travel demand process incorporates the results of a 1986 commercial vehicle survey, 1980 and 2010 socioeconomic variables, and network characteristics in the traditional four-step demand modeling process. The CATS practice of combining truck trips with automobile trips in the form of automobile vehicle equivalences before path assignment does not accurately reflect demand on a number of major Chicago area roadways where truck restrictions exist. The assignment procedure has been adjusted to prevent trucks from being loaded to restricted roadways. The resulting traffic assignment shows the significant effects of the restrictions on the vehicle mix of congested roads. A comparison of restricted versus unrestricted demand estimates shows that truck restrictions affect truck travel times and trip lengths. It was determined that these restrictions significantly affect the transportation industry and do not appear to be effective in reducing overall congestion in selected locations.

The effects of currently imposed truck restrictions on traffic congestion, travel times, and route length of truck trips on Chicago area roadways are examined. In addition, some questions regarding truck restrictions are explored.

The Chicago Area Transportation Study (CATS) has adopted a long-range program known as the 2010 Transportation System Development (TSD) Plan (*1*). In creating the plan, travel demand estimates were developed for commercial vehicles as separate trip types. Many transportation planning agencies model truck travel by increasing automobile person trips by 5 to 15 percent, but CATS has traditionally used separate demand estimate models to account for truck travel. For the 2010 TSD plan, truck trip characteristics were developed for four distinct types of commercial vehicles according to the results of the CATS 1986 commercial vehicle survey (*2*). These truck trips were then combined with automobile trips to estimate travel demand on alternative highway networks.

The current practice of combining automobile and truck trips, before trip assignment, on the simulated networks assigns vehicles to roadways without regard to truck access limitations. This practice assumes that all vehicles have equal access to all streets and does not accurately reflect the actual circuitous routes that trucks are forced to take because of restrictions on numerous streets in the region. CATS staff have explored a new method to analyze the assignment of commercial vehicles in the regional demand modeling process, the results of which are reported here. CATS is currently developing other methods (e.g., parallel path assignments) that may improve the modeling process further.

Truck restrictions are in place for a number of reasons:

- To improve or maintain the residential quality of neighborhoods,
- To remove trucks from roads such as parkways and boulevards,
- To reduce damage to roadways and bridges,
- To minimize noise levels,
- To restrict the movement of hazardous materials,
- To minimize pedestrian conflicts, and
- To increase the roadway capacity available to automobile drivers.

Many large trucks are also effectively restricted from access to some major streets because of low clearances under older railroad viaducts, most of which are in the city of Chicago. In addition, truck restrictions interact with many strategic decisions and operational characteristics of private-sector transportation companies, such as the location of and access to manufacturing plants and industrial complexes.

The following discussion covers the effect of truck restrictions on the local nonrestricted roadways (increasing the percentage of trucks on nonrestricted streets), the added costs to the transportation function for many businesses (from the increase in travel and delivery times), and the possible environmental implications (from longer and more circuitous truck trips).

DEFINITIONS

In 1986, CATS embarked on a major study of commercial vehicle behavior. As presented in Table 1, the majority of commercial vehicles are divided by the Illinois Secretary of State into two separate groups for licensing purposes: (a) the Weight Plates Group (WPG), which includes local cartage companies such as United Parcel Service and Waste Management, and (b) the International Registration Program (IRP), which includes over-the-road operators such as Yellow Freight. Also included in the survey were United States Postal Service (USPS) vehicles. The USPS operates 1 percent of the total commercial vehicles in the region. As seen in Table 1, 360,000 commercial vehicles were registered in the six-county Chicago area in 1986.

The four vehicle class definitions [i.e., B truck (Illinois license plates that end with B or have B TRUCK written on

Chicago Area Transportation Study, 300 West Adams Street, Chicago, Ill. 60606.

the side), light, medium, and heavy] presented in Table 1 were necessary to model their distinct trip characteristics more accurately in the regional modeling process. Table 2 presents the average (mean and median) daily trip frequency and trip length for the four classes of commercial vehicles. The survey demonstrated that the length and type of trips made by step-vans and pickup trucks were different from the length and type of trips made by the large tractor-semitrailers.

Because the regional highway assignment allocated trips and calculated capacity in a base unit of passenger automobiles, truck trips were converted to automobile vehicle equivalents (VEQ) in the modeling process. The presence of a heavy commercial vehicle on a section of road is obviously much different from that of a passenger car. Given the various types of operational considerations (e.g., size, weight, acceleration, speed, and maneuverability) of the distinct truck classes and the various types of roadway characteristics (e.g., speed limit, level of access control, parking, intersection capacity, and lane width) throughout the region, the VEQ for each class represents an average equivalent number of passenger automobiles that a truck from that class represents on the road. For example, in the regional model, one heavy truck added to a section of road would have the assumed equivalent effect on capacity and traffic congestion of three automobiles. The VEQs applied in the development of the 2010 plan and for this exercise are 1 VEQ for B and light trucks, 2 VEQs for medium trucks, and 3 VEQs for heavy trucks.

With the goal of adequately measuring the impact of restrictions on larger commercial vehicles, a number of resources were reviewed to determine what type of commercial vehicle classes should be defined as large trucks. These trucks would be prohibited from using the restricted streets on the regional network. It was determined that the medium and heavy groups defined in the survey would be aggregated as large trucks. This group consisted of those vehicles with a gross weight range of 28,001 to 80,000 lb, corresponding closely to the 26,000-lb threshold established for Class 7 and 8 vehicles as defined by the Motor Vehicle Manufacturers' Association (*3*). Examples of this large truck group include beverage trucks, concrete mixers, charter buses, dump trucks, fuel trucks, tractor-semitrailers, and multitrailer vehicles. The total number of trips for the base year of 1980 and the forecast year of 2010 are presented in Table 3.

RESTRICTED ROADWAYS

The CATS internal study area consists of six northeastern Illinois counties. In addition, CATS has divided the region into 1,542 internal zones and 101 external zones. In general,

TABLE 1 COMMERCIAL VEHICLE REGISTRATIONS IN NORTHEASTERN ILLINOIS

Vehicle Class	Weight Plates Group: License Plate	Gross Vehicle Weight[a] (lb)	No. of Vehicles Registered	Group Totals: WPG	IRP	USPS	Total No. of Vehicles	Examples
B truck	B	Up to 8,000	237,400	237,400	0	3,200	240,600	Pickup trucks, small vans, and some articulated trucks
Light	D	8,001 to 12,000	20,133	47,232	650	300	48,182	Step vans, cargo vans, panel trucks, armored cars, and school buses
	F	12,001 to 16,000	7,233					
	H	16,001 to 24,000	13,949					
	J	24,001 to 28,000	5,917					
Medium	K	28,001 to 32,000	2,217	13,850	7,950	0	21,800	Beverage trucks, concrete mixers, garbage trucks, and charter buses
	N	32,001 to 40,000	1,417					
	P	40,001 to 45,000	1,967					
	R	45,001 to 50,000	4,566					
	S	50,001 to 59,500	2,583					
	T	59,501 to 64,000	1,100					
Heavy	V	64,001 to 73,280	5,317	6,701	41,800	300	48,801	Semitrailers and twin trailers
	X	73,281 to 77,000	417					
	Z	77,001 to 80,000	967					
Total medium and heavy			20,551	20,551	49,750	300	70,601	
Total			305,183	305,183	50,400	3,800	359,383	

NOTE: Data are from 1986 commercial vehicle survey (*4*).

TABLE 2 TRIP FREQUENCY AND TRIP LENGTH OF COMMERCIAL VEHICLES

Vehicle Class	VEQ[a]	Total Registrations	Working Vehicles[b]	Daily Trip Frequency[c]: Mean	Median	Average Trip Length[d]: Mean	Median
B truck	1	240,600	129,398	6.9	5.0	11.1	7.4
Light	1	48,182	28,277	7.9	6.0	9.6	7.3
Medium	2	21,800	12,240	9.3	8.5	10.4	8.4
Heavy	3	48,801	12,854	5.9	4.8	24.9	22.4

[a]VEQ is automobile vehicle equivalent.
[b]Working vehicles is the average number of vehicles operating in commercial activity on an average day.
[c]Trip frequency is the number of trips per day.
[d]Trip length is average miles per trip.

TABLE 3 CHICAGO AREA TRUCK TRIPS

	No. of Trips by Type of Vehicle	
Year	All Commercial Vehicles	Medium and Heavy Trucks > 28,000 lb
Internal[a]		
1980	1,348,155	180,915
2010	1,713,488	156,805
External[b]		
1980	115,644	67,493
2010	131,551	77,087
Total Trips		
1980	1,463,799	248,408
2010	1,845,039	233,892

[a]Trips made within the region.
[b]Trips into, out of, or through the region.

the size of the zone is determined by the population, household, and employment density. The internal zonal system is shown in Figure 1.

The CATS highway network file contains over 18,000 links (a section of roadway that connects two intersections) that represent over 11,000 bidirectional mi of roadway. Speed, distance, capacity, impedance, and other variables are coded as network characteristics for each link. A list of restricted links was compiled and applied to the highway network file. The impedance variable on this file allows the analyst to effectively eliminate the link as a possible path for choice components.

Given that (a) not all roads and streets are coded into the highway network (especially residential streets), (b) not all types of truck restrictions apply exclusively or completely to

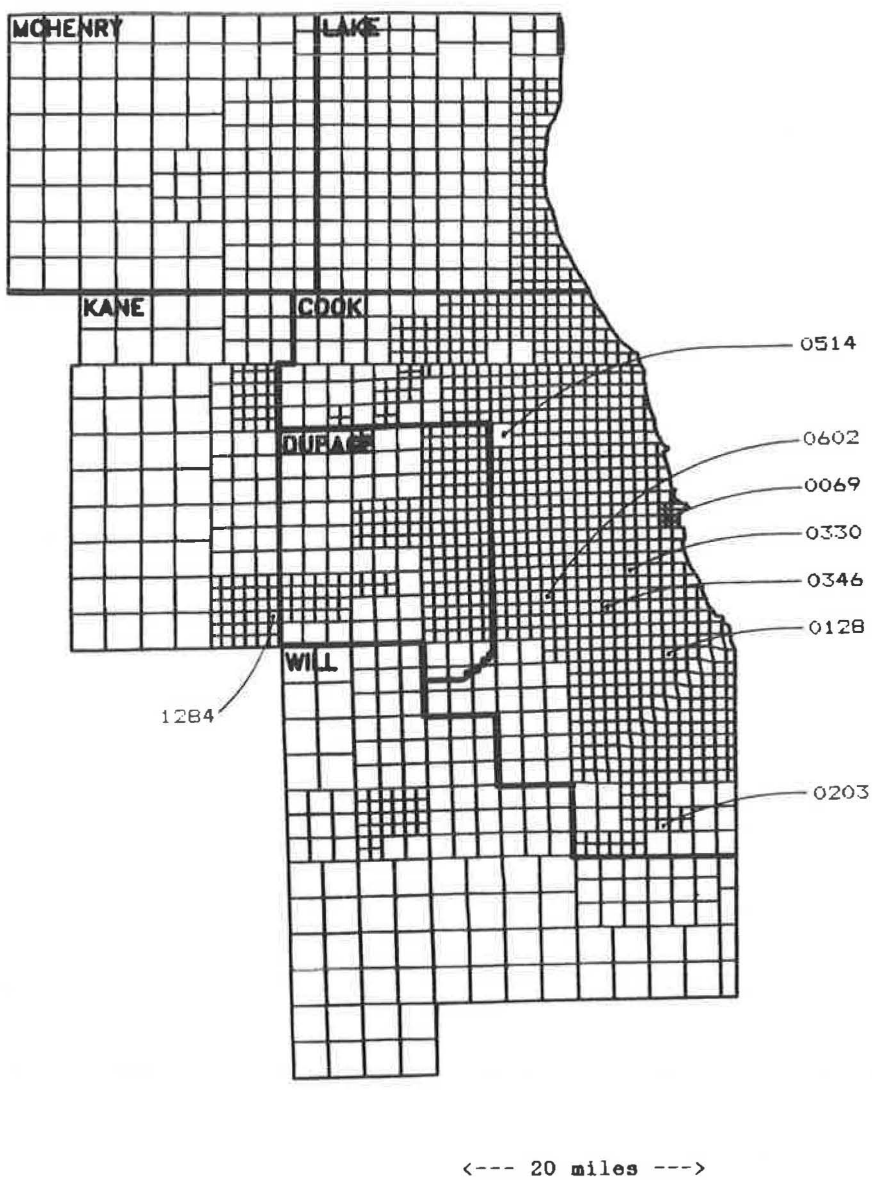

FIGURE 1 Traffic assignment zone system (revised 1984).

the large truck group as defined, (c) not all truck operators comply with the restrictions as posted, and (d) staff-hour and computer-time constraints exist, it was determined that only one network with all of these restricted links would be necessary for this exercise. If the results were determined to be significant (measurable), then further research would be warranted.

Examples of restricted links in this study include the express lanes of I-90/94 (Kennedy and Dan Ryan expressways), Lake Shore Drive (US-41), the boulevard system in the city of Chicago, and locations where height restrictions (viaduct clearances less than 13 ft) prohibit tractor-semitrailer activity. In fact, many truck drivers avoid clearances in the 13 ft 0 in. to 13 ft 6 in. range because of variances between the posted sign and the actual clearance. These restricted roads and the limits of the restricted links are presented in Tables 4 and 5, respectively. Only a few of these roads are not on the CATS highway network.

In total, 568 links representing 377 directional mi were effectively removed from the network as restricted roads. Table 6 presents the 2010 base network file's directional miles and number of links. The last two columns indicate the number of links and miles that were removed. Most of these links are in the city of Chicago, and a significant percentage is in the older industrial section of the south and southeast portions of the city.

TRAVEL DEMAND ANALYSIS

Future travel demand estimates are generated from forecast socioeconomic data and proposed network improvements using the four-step transportation demand modeling process. Internal truck trip productions and attractions were generated for each zone from rates developed in the 1986 commercial vehicle survey and applied to household and employment levels (*4*). Trip distributions were then developed from the productions and attractions using a doubly constrained intervening opportunities model (IOM), in which trip destinations are a function of production and attraction values for each zone matched against the distribution of trips from all zones. To properly measure the total activity level of commercial vehicles, CATS applied the results of a 1984 external survey (*5*). This survey determined the number of truck trips into, out of, and through the region. Commercial vehicle trips in the external analysis were divided into comparable classes of commercial vehicles and then combined with the results of the 1986 survey. Total commercial vehicle and large-truck trips are presented in Table 3.

In trip or vehicle assignment, truck trips are traditionally combined with automobile trips in the network as VEQs and then an equilibrium assignment process is used. Paths are chosen on the basis of minimum times and loaded using a series of all-or-nothing (AON) assignments. Link impedances are computed after each AON assignment and used to calculate a new set of paths, which are then reloaded. Five iterations of this process are combined to compute the equilibrium volumes. The five sets of paths from the assignment on the restricted network are saved.

The large-truck trips were reloaded onto these paths and combined using the equilibrium weights from the initial assignment to get the final large-truck link loads (*6*). This process was run using both an unrestricted and a restricted network. The loads on unrestricted streets in a restricted network were then compared with the unrestricted large-truck link loads from the original assignment. The analysis of this procedure generates some ideas concerning the effect restrictions have on the mix of vehicles on congested unrestricted streets.

TABLE 4 TRUCK-RESTRICTED ROUTES DUE TO BOULEVARD DESIGNATION, LOAD LIMIT, OR LENGTH LIMIT

Route Name	From	To
100th Boulevard	Escanaba Blvd.	Avenue "L" Blvd.
103rd Street	Western Ave.	Vincennes Ave.
107th Street	Western Ave.	M.L. King Dr.
112th Boulevard	Avenue "L" Blvd.	Indiana state line
115th Street	Western Ave.	Vincennes Ave.
24th Boulevard	Marshall Blvd.	California Ave.
26th Street	Kostner Ave.	Kedzie Ave.
31st Boulevard	California Blvd.	Western Ave.
31st Street	Ogden Ave.	IL 50 (Cicero Ave.)
33rd Boulevard	Michigan Ave.	South Pkwy.
43rd Street	Archer Ave.	Western Blvd.
51st Street	Cottage Grove Ave.	Lake Park Ave.
57th Boulevard	IC Railroad	Stony Island Ave.
59th Street	IL 50 (Cicero Ave.)	California Ave.
71st Street	Ashland Ave.	I-94 (Dan Ryan)
71st Street	Pulaski Rd.	Western Ave.
83rd Street	Kedzie Ave.	Halsted Ave.
92nd Boulevard	Jeffery Ave.	Anthony Blvd.
Adams Boulevard	Central Ave.	Austin Blvd.
Anthony Boulevard	92nd Blvd.	Escanaba Blvd.
Ashland Avenue	Irving Park Rd.	Clark St.
Ashland Boulevard	Pratt Blvd.	Fargo Ave.
Ashland Boulevard	Roosevelt Rd.	Lake St.
Augusta Boulevard	Elston Ave.	Austin Blvd.
Austin Boulevard	Cermak Rd.	North Ave.
Avenue "L"	100th Blvd.	112th Blvd.

TABLE 4 (*continued on next page*)

TABLE 4 (*continued*)

Route Name	From	To
California Avenue	51st St.	67th St.
California Avenue	Archer Ave.	47th St.
California Boulevard	24th Blvd.	31st Blvd.
California Boulevard	Roosevelt Rd.	18th St.
Campbell Park Boulevard	Oakley Blvd.	Leavitt St.
Central Avenue	State Rd.	103rd St.
Central Avenue	31st St.	Pershing Rd.
Central Avenue	Cermak Rd.	26th St.
Central Park Boulevard	Jackson Blvd.	5th Ave.
Central Park Boulevard	Madison St.	Jackson Blvd.
Central Park Boulevard	West Service Dr.	Garfield Sq.
Chicago Avenue	Thatcher Ave.	Austin Blvd.
Damen Avenue	47th St.	87th St.
Dearborn Parkway	Burton Place	North Blvd.
Diversey Parkway	Cannon Dr.	Oakley Blvd.
Division Street	Thather Ave.	Austin Blvd.
Douglas Boulevard	Independance Sq.	Douglas Park
Drexel Square	Drexel Blvd.	Cottage Grove Ave.
Escanaba Boulevard	Anthony Blvd.	100th Blvd.
Franklin Boulevard	Sacramento Sq.	Central Park Blvd.
Fullerton Parkway	Lincoln Park West	Orchard St.
Fulton Boulevard	Sacramento Blvd.	Central Park Blvd.
Garfield Boulevard	M.L. King Dr.	Western Avenue
Garfield Square Boulevard	Monticello Ave.	Central Park Ave.
Hamlin Boulevard	Lake St.	5th Ave.
Humboldt Boulevard	Palmer Square	North Ave.
Hyde Park Boulevard	Drexel Blvd.	56th St.
Independance Boulevard	Garfield Park	Independance Sq.
Independance Square	Independance Blvd.	Independance Sq.
I-90/94	Express lanes of the	Kennedy Expressway
I-90/94	Express lanes of the	Dan Ryan Expressway
Jackson Boulevard	Austin Blvd.	S Lake Shore Dr.
Jeffery Avenue	Jackson Park	92nd Blvd.
Kedzie Boulevard	Logan Sq.	Madison St.
King Drive	I-94 (Calumet)	115th St.
King Drive	I-90 (Skyway)	US 12/20 (95th St.)
King Drive	26th St.	63rd St.
Lake Shore Drive	Hollywood	Hayes Dr.
Laramie Avenue	Lake St.	I-290
Lincoln Park West	Clark St.	Fullerton Pkwy.
Logan Boulevard	Diversey Pkwy.	Logan Square
Logan Square	Troy St.	Kedzie Blvd.
Loomis Boulevard	47th St.	87th St.
Marine Drive	Sheridan Rd.	Foster Dr.
Marquette Road	IL 50 (Cicero Ave.)	Stony Island Ave.
Marshall Boulevard	Douglas Park	24th Blvd.
Michigan Avenue	Oak St.	Garfield Blvd.
Midway Plaisance	Stony Island Ave.	Cottage Grove Ave.
Normal Boulevard	Garfield Blvd.	72nd St.
North Avenue	Clark St.	East End Turnabout
Oak Park Avenue	North Ave.	Cermak Rd.
Oakley Boulevard	Roosevelt Rd.	North Ave.
Oakwood Boulevard	M.L. King Dr.	Drexel Blvd.
Ogden Boulevard	Oakwood Blvd.	Albany Ave.
Palmer Boulevard	Kedzie Blvd.	Humboldt Blvd.
Pershing Avenue	Kedzie Ave.	Archer Ave.
Pratt Boulevard	Lake Michigan	CNW RR
Randolph Drive	Lake Shore Dr.	Michigan Ave.
Ridge Boulevard	Devon Ave.	Howard St.
Ridgeland Avenue	North Ave.	Roosevelt Rd.
Roosevelt Road	Ashland Blvd.	Ogden Ave.
Sacramento Boulevard	Augusta Blvd.	Douglas Park
Sacramento Square	Sacramento Blvd.	Sacramento Blvd.
Sheridan Road	Melrose St.	Diversey Pkwy.
Sheridan Road	Chicago city limits	Lake Shore Dr. feeder
South Shore Drive	Jackson Park	83rd Pl.
State Parkway	Schiller St.	North Blvd.
Warren Boulevard	Ogden Ave.	Garfield Park
Washington Boulevard	Harlem Ave.	1st Ave.
Washington Boulevard	Canal St.	Austin Blvd.
Western Boulevard	Garfield Blvd.	31st Blvd.
Yates Boulevard	71st St.	87th St.

TABLE 5 TRUCK-RESTRICTED ROUTES DUE TO LOW CLEARANCE (CLEARANCE < 13 ft 0 in.)

Route Name	Overhead Facility	[------- Link closed From	--------] To
16th Street	BRC	IL 50	Kostner
18th Street	ATSF	Wentworth	Clark
18th Street	ATSF	Canal	Wentworth
26th Street	CR	Ryan Feeder	State
43rd Street	CR	Ryan	State
47th Street	IHB	Halsted	Racine
63rd Street	Metra	Ryan	State
67th Street	Metra	Normal	Vincenes
67th Street	CR	State	M.L. King
67th Street	CWI	Halsted	State
71st Street	IC/Metra	Cottage Grove	Stoney Island
71st Street	CWI	Halsted	Normal
71st Street	Metra	Normal	Wentworth
83rd Street	Metra	Halsted	Vincenes
Armitage Avenue	CNW	IL 50	Kostner
Belmont Avenue	Metra	Kostner	Pulaski
Broadway Street	Metra	Western	Francisco
Canal Street	ATSF	Cermak	Archer
Central Avenue	CNW/CTA	Lake EB	Lake WB
Chicago Avenue	CNW	Kedzie	Sacramento
Clyborn Avenue	CNW	Fullerton	Diversey
Colfax Avenue	BRC	95th	93rd
Diversey Avenue	CTA	Lincoln	Halsted
Diversey Avenue	CNW	Damen	Ashland
Elston Avenue	CNW	North	Courtland
Foster Avenue	CNW	Damen	Ashland
Foster Avenue	CTA	Broadway	Sheridan
Fullerton Avenue	Metra	Kostner	Pulaski
Halsted Street	ATSF	Archer	Cermak
Halsted Street	CR	Pershing	43rd
Halsted Street	BN/CNW	16th	Roosevelt
Homan Avenue	CSX	Roosevelt	Eisen
Howard Street	CNW	Clark	Ridge
Howard Street	CTA	Clark	Rogers
Indiana Avenue	IC/Metra	130th	138th
Jeffery Avenue	BRC	95th	93rd
Kedzie Avenue	WC	North Ave.	Armitage
Kedzie Avenue	CNW	Chicago	Augusta
Kimball Avenue	CNW	Addison	Kennedy
Kostner Avenue	BN	Ogden	26th
Lake Street	CTA	IL 50	Kostner
Laramie Avenue	CNW	Lake	Chicago
Lawrence Avenue	CTA	Broadway	Sheridan
Madison Avenue	CNW	California	Western
North Avenue	CNW	Elston	Kennedy
Ogden Avenue	CTA	Cermak	Central Park
Racine Avenue	BN/CNW	16th	Blue Island
Ridge Boulevard	CNW	Peterson	Devon
State Street	CR	63rd	Skyway
Touhy Avenue	CNW	Clark	Ridge

Key to Overhead Facilities:

ATSF	Atchison, Topeka and Santa Fe Railway Company
BN	Burlington Northern Railroad Company
BRC	Belt Railway Company of Chicago
CNW	Chicago and North Western Transportation Company
CR	Consolidated Rail Corporation
CSX	CSX Transportation, Inc.
CTA	Chicago Transit Authority
CWI	Chicago and Western Indiana Railroad Company
IC	Illinois Central Railroad Company
IHB	Indiana Harbour Belt Railroad
Metra	Metropolitan Rail (commuter railroad)
WC	Wisconsin Central

TABLE 6 2010 BASE NETWORK MILES AND NUMBERS OF LINKS ON TOTAL AND RESTRICTED NETWORKS

	[---- Total	----]	[-- Restricted	--]
	Directional Miles	Number of Links	Directional Miles	Number of Links
Total	22,450.29	18,036	376.79	568
Facility Type				
Arterial	16,526.12	13,756	329.39	501
Expressway	819.51	768	47.04	65
Ramps	267.52	835	0.00	0
Other	4,837.14	2,677	0.36	2
Functional Class				
Freeway	726.34	634	14.92	10
Major Highway	975.79	833	0.00	0
Area Service	1,388.30	1,190	12.94	19
Principal Arterial	451.63	518	42.54	70
Minor Arterial	3,325.18	3,335	73.73	121
Urban Collector	2,703.49	3,292	209.66	317
Rural Local Road	4,828.83	2,967	22.64	29
Rural Collector	2,943.37	1,758	0.00	0
Other	5,107.37	3,509	0.36	2

TABLE 7 TRAVEL AND CONGESTION FORECAST

	VEQ Miles of Travel			Bidirectional Miles of Roadway		
Year	Total Automobile and Truck	Excess	Congested	Total	Congested	Percent
1980	108,229,548	8,180,174	43,543,539	9,437	1,377	14.59
2010	143,846,969	16,372,952	75,343,521	9,579	2,275	23.75

NOTE: Congestion is defined as exceeding level-of-service D.

TABLE 8 SUM OF TRAVEL TIMES AND DISTANCES BETWEEN ALL 1,542 INTERNAL ZONES

	Travel Times (min)			Distances (mi)		
Year	Unrestricted	Restricted	Percent Increase	Unrestricted	Restricted	Percent Increase
1980	5,397,756.36	5,989,457.71	10.96	3,009,173.30	3,046,229.65	1.23
2010	5,896,105.15	6,503,624.99	10.30	3,237,160.37	3,281,369.49	1.37

TABLE 9 VMT, EXCESS TRAVEL, AND COST DUE TO RESTRICTED NETWORK

	1980	2010
VMT (VEQ mi of travel)		
Unrestricted	7,093,414	7,047,696
Restricted	11,268,955	11,294,243
Percent increase	58.87	60.25
Avg daily excess hours of travel	52,631.73	53,526.75
Avg daily cost to trucking industry ($)	1,003,844.26	1,016,374.46
Annual cost[a] ($)	250,961,065.50	254,093,614.88

NOTE: For March 1988 there were 46,319 trucking company employees in the Chicago area. Their average salary was $14.70/hr. Fuel cost is estimated at $1.00/gal.

[a]At 250 trading days per year.

The results of the 2010 TSD plan modeling process indicate that congestion is a problem in the Chicago area. From the 1980 simulations, it was estimated that 15 percent of the road mileage was congested, defined by exceeding level of service E. The congested mileage will increase to 24 percent in 2010. As presented in Table 7, 40 percent of the total vehicle miles of travel (VMT) is on congested roads; this will increase to 52 percent in 2010. One of the basic assumptions made in this analysis was that, as trucks (in VEQs) are removed from the restricted routes, they will be replaced by an equivalent number of automobiles (in VEQs). Similarly, where the truck link volumes increase, an equivalent number of automobiles is removed. Therefore, the total congestion on both the restricted and nonrestricted roads is assumed to remain constant. This assumption appears to be reasonable for this analysis because the modeled unrestricted traffic volumes (which included trucks as VEQs) on truck-restricted routes are close to the actual automobile counts.

RESULTS

The sum of travel times and the sum of the miles required to travel between each of the 1,542 internal zonal pairs increased from the unrestricted networks to the restricted networks. As presented in Table 8, increases were seen for both 1980 and 2010. The sum of restricted 2010 travel times increased 10.3 percent, and the sum of the miles required to travel increased 1.4 percent. These network characteristics are in minutes and miles. They are not weighted by the number of trips between each zone and converted to vehicle minutes and vehicle miles. For example, a single truck making a trip between a zonal pair will travel an average of 1.4 percent longer distance on a restricted network and will take an average of 10.3 percent more time.

In the original unrestricted network simulations, average trip distances for the four truck classes were calibrated to match the results of the 1986 commercial vehicle survey. However, most of the restricted links, along with many manufacturing facilities, truck terminals, and intermodal yards, are in the city of Chicago and therefore a significant portion of the large truck travel is in the older portions of the city.

As shown in Table 9, the actual increase in total VMT for the large-truck group, as measured in VEQ, was 60 percent on the restricted network. The economic effects of restrictions and the concentration of truck activity can be seen when the data are broken down to examine the actual average daily excess hours of travel required (53,527 hr for 2010) on a restricted network, the additional truck fuel consumption (250,000 gal), and the average daily cost to the trucking industry ($1,016,000) from restrictions and circuitous routes.

Tables 10 through 13 present travel times and distances for selected zones in the region for 1980 and 2010 for unrestricted and restricted assignments. Travel times between zones increased more than the miles required to travel, and the effect on trips made from zones in the older, industrial regions of the city (e.g., CATS zone 0330) was larger than the effect on zones in other areas. If the previous routes were based on minimum times in a larger, less restricted network, it is obvious that minimum time paths on a smaller, more restricted network would be less direct and therefore more time-consuming. This rerouting forces trucks off the unrestricted minimum time paths onto slower, more congested parallel or alternative streets.

Table 14 shows that trucks, as a percentage of the total loadings, increased dramatically on the unrestricted links. As

TABLE 10 TRAVEL TIMES BETWEEN SELECTED ZONES: 1980

		Time (min) from:							
Zone	To:	Loop	Roseland	Chicago Heights	Brighton Park	West Lawn	O'Hare	McCook	Aurora
0069	Loop								
	Unrestricted	0.00	27.67	54.74	17.79	26.52	32.56	28.09	64.20
	Restricted	0.00	43.43	70.68	28.70	28.82	34.13	29.77	64.26
0128	Roseland[a]								
	Unrestricted	24.39	0.00	29.85	22.32	19.90	51.27	36.93	73.14
	Restricted	37.62	0.00	30.28	35.60	25.26	62.83	40.71	75.62
0203	Chicago Heights								
	Unrestricted	51.35	29.64	0.00	50.48	42.97	65.81	46.95	77.51
	Restricted	65.42	29.72	0.00	63.75	48.88	69.77	50.14	77.45
0330	Brighton Park–4300 S. Archer								
	Unrestricted	15.94	22.95	51.29	0.00	10.64	40.33	18.09	57.96
	Restricted	28.03	35.61	63.91	0.00	22.64	51.22	28.16	67.42
0346	West Lawn–6700 S. Cicero								
	Unrestricted	24.66	20.48	44.81	10.47	0.00	48.58	19.06	60.21
	Restricted	28.22	27.75	49.96	21.65	0.00	49.88	20.52	60.40
0514	O'Hare								
	Unrestricted	33.50	55.18	69.82	42.17	50.55	0.00	33.91	53.34
	Restricted	38.04	66.28	75.73	55.75	53.41	0.00	34.76	53.70
0602	McCook–Summit								
	Unrestricted	26.60	39.12	49.43	18.72	19.40	32.71	0.00	47.00
	Restricted	28.67	41.09	53.73	27.83	19.49	33.34	0.00	46.45
1284	Aurora								
	Unrestricted	63.06	75.78	78.08	59.94	61.59	52.37	47.95	0.00
	Restricted	63.82	77.08	78.09	69.82	62.59	52.88	47.91	0.00
Total									
Unrestricted		73,444.34	86,415.35	103,225.98	76,260.06	80,464.06	66,074.88	67,830.42	86,987.00
Restricted		89,174.69	101,735.68	115,729.07	103,179.49	92,408.82	76,661.09	77,427.23	96,663.10
Mean									
Unrestricted		47.63	56.04	66.94	49.46	52.18	42.85	43.99	56.41
Restricted		54.28	61.92	70.44	62.80	56.24	46.66	47.13	58.83
Percent increase		13.95	10.49	5.22	26.98	7.79	8.89	7.13	4.29

NOTE: Total equals total travel time between Zone *i* and all other zones (1,542) in the six-county region. Mean equals the average travel time between Zone *i* and all other zones.
[a]Junction of I-57 and I-94.

TABLE 11 TRAVEL DISTANCES BETWEEN SELECTED ZONES: 1980

		Distance (mi) from:							
Zone	To:	Loop	Roseland	Chicago Heights	Brighton Park	West Lawn	O'Hare	McCook	Aurora
0069	Loop								
	Unrestricted	0.00	13.38	32.24	7.32	11.61	17.84	15.17	40.93
	Restricted	0.00	14.93	33.43	8.64	13.03	17.87	15.58	41.09
0128	Roseland[a]								
	Unrestricted	12.83	0.00	14.30	10.25	9.21	29.83	22.69	43.49
	Restricted	13.40	0.00	14.30	10.21	10.31	34.90	17.05	43.82
0203	Chicago Heights								
	Unrestricted	32.05	14.30	0.00	23.88	22.41	44.38	27.50	51.59
	Restricted	34.40	14.30	0.00	31.21	23.41	44.38	29.58	52.09
0330	Brighton Park–4300 S. Archer								
	Unrestricted	7.01	10.30	23.69	0.00	4.34	21.25	10.31	40.65
	Restricted	6.97	10.26	25.20	0.00	5.27	21.54	10.31	40.98
0346	West Lawn–6700 S. Cicero								
	Unrestricted	11.62	9.26	22.92	4.34	0.00	30.99	7.50	39.19
	Restricted	13.05	10.24	23.92	4.44	0.00	32.29	7.50	40.82
0514	O'Hare								
	Unrestricted	18.60	30.83	46.45	21.71	31.84	0.00	21.29	36.93
	Restricted	18.24	36.08	46.45	22.00	24.01	0.00	21.29	36.93
0602	McCook–Summit								
	Unrestricted	14.92	17.05	30.17	10.35	7.50	20.46	0.00	30.47
	Restricted	15.39	17.19	30.41	10.35	7.50	20.51	0.00	30.80
1284	Aurora								
	Unrestricted	41.35	45.97	48.16	41.37	39.67	36.36	31.14	0.00
	Restricted	41.57	45.88	48.33	42.33	40.63	36.58	32.10	0.00
Total									
Unrestricted		45,798.63	51,899.95	66,424.45	45,617.40	47,807.88	43,702.73	42,024.86	56,621.53
Restricted		50,668.00	57,248.28	69,820.66	50,549.09	51,169.93	49,712.62	47,295.22	62,733.58
Mean									
Unrestricted		29.70	33.66	43.08	29.58	31.00	28.34	27.25	36.72
Restricted		30.84	34.84	42.50	30.77	31.14	30.26	28.79	38.18
Percent increase		3.83	3.52	−1.35	4.00	0.46	6.76	5.62	3.98

NOTE: Total equals total distance between Zone *i* and all other zones (1,542) in the six-county region. Mean equals the average distance between Zone *i* and all other zones.
[a]Junction of I-57 and I-94.

TABLE 12 TRAVEL TIMES BETWEEN SELECTED ZONES: 2010

		Time (min) from:							
Zone	To:	Loop	Roseland	Chicago Heights	Brighton Park	West Lawn	O'Hare	McCook	Aurora
0069	Loop								
	Unrestricted	0.00	31.34	57.32	19.86	28.87	42.12	30.95	71.68
	Restricted	0.00	46.58	72.43	34.66	38.08	51.84	37.00	77.31
0128	Roseland[a]								
	Unrestricted	29.14	0.00	29.39	22.64	20.42	62.52	38.34	80.19
	Restricted	46.72	0.00	29.10	37.92	27.28	71.15	40.38	80.09
0203	Chicago Heights								
	Unrestricted	55.82	29.09	0.00	49.77	42.97	72.35	47.87	81.37
	Restricted	72.66	28.94	0.00	64.70	50.47	78.42	51.02	79.39
0330	Brighton Park–4300 S. Archer								
	Unrestricted	18.58	22.91	50.76	0.00	10.57	48.73	18.58	66.10
	Restricted	30.00	37.71	65.48	0.00	22.13	64.06	28.87	77.41
0346	West Lawn–6700 S. Cicero								
	Unrestricted	27.08	20.44	44.23	10.35	0.00	54.50	18.83	67.51
	Restricted	32.57	25.60	51.41	21.70	0.00	57.53	19.37	69.20
0514	O'Hare								
	Unrestricted	37.99	58.22	76.00	46.23	54.35	0.00	38.85	60.50
	Restricted	47.22	77.22	82.00	62.86	58.04	0.00	40.56	61.56
0602	McCook–Summit								
	Unrestricted	28.17	37.55	49.79	17.52	18.19	38.11	0.00	52.94
	Restricted	30.79	39.81	53.67	26.86	18.90	39.87	0.00	53.26
1284	Aurora								
	Unrestricted	67.12	79.43	81.25	63.30	64.87	59.47	51.37	0.00
	Restricted	66.74	78.98	80.21	72.59	65.54	57.28	51.33	0.00
Total									
Unrestricted		78,842.90	88,608.92	106,066.94	77,747.99	81,019.99	73,998.49	69,961.80	93,886.73
Restricted		96,441.44	103,377.58	117,627.35	104,773.42	93,739.93	85,758.38	78,868.34	103,943.60
Mean									
Unrestricted		51.13	57.46	68.79	50.42	52.54	47.99	45.37	60.89
Restricted		58.70	62.92	71.59	63.77	57.05	52.20	48.00	63.26
Percent increase		14.80	9.50	4.08	26.48	8.59	8.77	5.80	3.91

NOTE: Total equals total travel time between Zone *i* and all other zones (1,542) in the six-county region. Mean equals the average travel time between Zone *i* and all other zones.
[a]Junction of I-57 and I-94.

TABLE 13 TRAVEL DISTANCES BETWEEN SELECTED ZONES: 2010

		Distance (mi) from:							
Zone	To:	Loop	Roseland	Chicago Heights	Brighton Park	West Lawn	O'Hare	McCook	Aurora
0069	Loop								
	Unrestricted	0.00	15.00	32.28	7.70	11.99	17.77	15.55	41.09
	Restricted	0.00	13.96	32.82	7.58	12.88	18.71	15.43	40.97
0128	Roseland[a]								
	Unrestricted	13.02	0.00	14.30	10.24	9.25	29.83	17.22	43.28
	Restricted	15.21	0.00	14.30	10.21	10.32	34.90	17.08	45.69
0203	Chicago Heights								
	Unrestricted	32.24	14.30	0.00	22.98	22.41	44.38	27.50	47.88
	Restricted	34.68	14.30	0.00	25.82	23.41	44.38	27.50	52.80
0330	Brighton Park–4300 S. Archer								
	Unrestricted	7.20	10.25	25.78	0.00	4.34	20.98	10.31	44.73
	Restricted	7.69	10.21	25.89	0.00	4.34	23.38	10.31	41.92
0346	West Lawn–6700 S. Cicero								
	Unrestricted	11.64	9.21	21.50	4.34	0.00	30.99	7.50	43.27
	Restricted	13.26	10.27	24.31	4.38	0.00	30.99	7.50	40.46
0514	O'Hare								
	Unrestricted	17.19	29.78	45.03	23.05	23.74	0.00	16.12	34.70
	Restricted	19.04	40.50	46.45	21.26	22.55	0.00	20.63	34.70
0602	McCook–Summit								
	Unrestricted	15.11	17.03	28.75	10.35	7.50	20.46	0.00	28.32
	Restricted	15.60	17.08	30.17	10.35	7.50	20.46	0.00	28.32
1284	Aurora								
	Unrestricted	41.35	45.97	48.06	41.41	39.71	35.72	31.18	0.00
	Restricted	41.36	45.68	52.38	41.05	39.35	35.72	29.26	0.00
Total									
Unrestricted		45,768.43	51,775.31	64,947.16	46,554.89	46,040.26	41,446.66	41,506.43	56,805.55
Restricted		52,392.58	60,912.32	70,429.54	51,195.16	51,372.12	47,521.60	45,654.51	62,694.45
Mean									
Unrestricted		29.68	33.58	42.12	30.19	29.86	26.88	26.92	36.84
Restricted		31.89	37.07	42.87	31.16	31.27	28.92	27.79	38.32
Percent increase		7.44	10.41	1.78	3.21	4.72	7.61	3.23	4.03

NOTE: Total equals total distance between Zone *i* and all other zones (1,542) in the six-county region. Mean equals the average distance between Zone *i* and all other zones.
[a]Junction of I-57 and I-94.

large-truck trips were removed from the restricted roads, the trips were forced onto unrestricted roads. As presented in Table 14, the level of truck activity on unrestricted roads showed a significant increase when this shift occurred. For example, in 1980 the average percentage of large trucks (in VEQ) over the total assignment load was 7 percent (on the unrestricted expressway sections). After the trucks were removed from the restricted links and forced onto unrestricted roads, this value increased to 28 percent. In the case of express lanes, most trucks were shifted to the local, unrestricted lanes. In the case of arterial restrictions, trucks were forced onto parallel arterial sections.

RECOMMENDATIONS

Truck restrictions significantly affect the vehicle mix on unrestricted roadways and increase the travel times of total (and individual) truck movements. Therefore, proposed restrictions or removal of restrictions should not be viewed in isolation. Methods of accounting for truck travel and truck restrictions throughout the planning process must be explored. The processes that define commercial vehicles by size and weight, account for restrictions in network coding and simulation, and determine the VEQ factors should be evaluated so that restrictions that do not adversely affect traffic can be chosen or removed.

Restrictions increase the costs of transportation. These increases inflate the cost of goods to manufacturers and eventually to end users. The excess fuel consumption (and corresponding increase in pollution) caused by these inefficiencies could also be a significant factor. However, these negative consequences must be balanced against the many social, political, and economic pressures that support the benefits of truck restrictions, such as residential quality of life, pedestrian and automobile safety, and the cost of removing restrictions (e.g., viaduct rehabilitation or reconstruction and a possible increase in automobile-truck accidents).

Truck restrictions can be seen as a proactive measure, such as designating specified truck routes, or as a reactive measure, such as restricting truck traffic to allow commuters and automobiles to have access to larger levels of roadway capacity. In many cases, the restrictions are part of the historical nature of the road system and do not change with employment and housing patterns. Planners and highway agencies do not have to reevaluate the truck impact and the automobile-truck conflicts every few years to validate the original reasons for specific truck restrictions. However, agencies should be prepared to respond to questions concerning specific restrictions.

Two choices planners have in directing commodity flow (e.g., hazardous materials and steel coils) are to implement a designated or preferred truck route network or to restrict one set of roads while improving access on alternative or preferred routes. The process of implementing such plans on

TABLE 14 AVERAGE PERCENTAGE OF LARGE TRUCKS (IN VEQ) (FOR UNRESTRICTED 1980 NETWORK LINKS ONLY)

Facility Type	Unrestricted	Restricted	# of Obs.
Arterial	0.72 %	5.01 %	13,332
Expressway	6.79 %	28.10 %	732
Ramps	2.03 %	12.58 %	762

Functional Class	Unrestricted	Restricted	# of Obs.
Freeway	6.98 %	29.57 %	653
Major Highway	1.90 %	6.88 %	841
Area Service	1.04 %	5.28 %	1,177
Principal Arterial	0.97 %	5.04 %	454
Minor Arterial	0.67 %	5.32 %	3,242
Urban Collector	0.63 %	6.34 %	2,997
Rural Local Road	0.45 %	3.45 %	2,942
Major Collector	0.80 %	4.37 %	1,257
Minor Collector	0.57 %	3.50 %	508

(for the Unrestricted 2010 Network Links only)

Facility Type	Unrestricted	Restricted	# of Obs.
Arterial	0.58 %	4.20 %	13,247
Expressway	6.02 %	24.85 %	701
Ramps	1.60 %	8.75 %	754

Functional Class	Unrestricted	Restricted	# of Obs.
Freeway	6.20 %	26.36 %	625
Major Highway	1.70 %	6.22 %	833
Area Service	0.93 %	4.58 %	1,171
Principal Arterial	0.69 %	4.38 %	448
Minor Arterial	0.57 %	4.63 %	3,214
Urban Collector	0.46 %	5.00 %	2,975
Rural Local Road	0.37 %	2.98 %	2,930
Major Collector	0.57 %	3.30 %	1,251
Minor Collector	0.46 %	2.90 %	507

a large scale in mixed-use neighborhoods requires a significant level of coordination and continual interplay among representatives of the community, industry, land use planners, and transportation agencies.

As part of the 2010 TSD plan, CATS has developed a network of strategic regional arterials. This 1,300-mi network will be studied over the next 5 years. One of the key elements in the plan of study for these arterials will be an evaluation of the long-haul truck traffic options.

Other truck restriction programs, such as restrictions that are based on the hour of day or number of trucks, may require an exorbitant level of personnel to administer. Although the elimination of some current restrictions (e.g., increased viaduct clearances) is generally supported for economic and safety reasons, such activities will change traffic patterns and should be evaluated.

It has been shown that truck restrictions can be reasonably incorporated into the traditional travel demand modeling process. The effect of truck restrictions on model outputs is significant on the regional level. To provide more effective regional transportation system plans, analysts must consider the effect of restrictions and the ways they affect unrestricted, alternative roads and other transportation-related activities.

REFERENCES

1. *2010 Transportation System Development Plan.* Chicago Area Transportation Study, Ill., April 12, 1989.
2. *Research News*, Vol. 26, No. 1, Feb. 1987.
3. *The Truck and Bus Manufacturing Industry: Building the Tools That Move America.* Motor Vehicle Manufacturers' Association, Nov. 1983.
4. *2010 Transportation System Development Plan: Technical Process Report.* Chicago Area Transportation Study, Ill., Jan. 1989.
5. *1984 Cordon Line Survey.* CATS Working Paper 86-9. Chicago Area Transportation Study, Ill., April 1986.
6. *An Alternative Approach to Performing Selected Link Analysis.* CATS Working Paper 86-1. Chicago Area Transportation Study, Ill., Dec. 1985.

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Abridgment

Effects of Truck Strategies on Traffic Flow and Safety on Multilane Highways

NICHOLAS J. GARBER AND RAVI GADIRAJU

Recent legislation has encouraged the increased operation of trucks (defined here as vehicles having six or more wheels in contact with the road and a gross vehicle weight greater than 10,000 lb) on Interstate and primary highways. This has affected safety and the quality of traffic flow on multilane highways. Imposing certain restrictions on truck operations on these highways has been identified as a way to reduce this effect. However, the overall impact of these restrictions on safety and traffic flow has not been fully studied. For example, restricting trucks to specific lanes or lowering their speed limit could have varied effects on traffic. The primary objective of the research described in this paper was to provide information on the nature and extent of the effects of such truck control strategies on traffic flows, speeds, headways, and accident patterns. Simulation was used to study these effects on multilane highways. The results did not indicate any safety benefits from the imposition of these strategies but suggested that the potential for an increase in accident rates would be created, particularly if the strategies were imposed on highways with high volumes and a high percentage of trucks.

Numerous factors have been cited as criteria for judging the operating efficiency of the highway transportation system. The most important parameters named, however, are the speed of travel, congestion, delay, and safety (*1*). The increased operation of trucks with larger dimensions and different handling properties on the nation's highways may affect the interaction between these vehicles and other vehicle types, which may in turn affect the operating criteria. For example, maneuvers such as passing, merging, and lane changing can be impeded by the presence of large trucks, resulting in serious degradation of flow quality.

Therefore, the concept of imposing certain restrictions on truck operations on multilane highways has been identified as a way to reduce the interaction between trucks and other vehicles and compensate for the different operational characteristics of trucks. The two most common restraints are (a) limiting truck traffic to specific lanes of the highway, and (b) imposing a lower speed limit for trucks. Little is known about the effects of these strategies on accident rates and the speed-flow characteristics on different traffic lanes. This study therefore investigated the effects of these truck strategies (when used alone or in combination) on traffic performance and accident patterns.

PURPOSE AND SCOPE

The scope of this study was limited to Virginia highways, but sites were selected to reflect different percentages of trucks in the traffic stream. The specific strategies investigated are presented in Table 1.

The objectives of the study were

- To determine the speed-flow relationships for different traffic lanes at different locations,
- To investigate the relationship between congestion (*V/C* ratio) and accident rates on multilane highways,
- To determine the effect of each strategy on speed and flow distributions on different lanes at different locations, and
- To investigate the effects of lane-use restrictions on accident rates and time headways of vehicles on different lanes.

DATA COLLECTION

Selection of Study Sites

Test sites for the simulation were chosen from sections of Interstate and arterial highways that carry a significant portion of truck traffic. A list of candidate sites was first identified to cover a wide range of truck percentages (from about 5 to 40 percent), and a final set of nine locations was then selected for simulation. The criteria used were (a) ease of collecting traffic data, (b) truck percentages within the range being considered, and (c) availability of accident data. The data on traffic composition were obtained from annual average daily traffic statistics compiled by the Virginia Department of Transportation (VDOT).

Traffic Data

Traffic data collected at the test sites included individual vehicle spot speeds and volume counts. The Streeter Amet recorder was used to collect the data, which were further analyzed by TRAFCOMP computer software to obtain statistics such as speed distributions and volume counts by hour. The data on speed and volume distributions were obtained during 24 continuous hours of monitoring on weekdays.

Accident Data

Data on accident characteristics were obtained from computerized files prepared by VDOT and the Virginia Department of Motor Vehicles (VDMV) for 1985 through 1987. Each study site was identified by its route number, the city or county in which it is located, and its section number. A summary of the accident data is presented in Table 2.

School of Engineering and Applied Science, Department of Civil Engineering, University of Virginia, Thornton Hall, Charlottesville, Va. 22903-2442.

TABLE 1 STRATEGIES USED IN SIMULATION

Strategy	Differential Speed Limit	Truck Right Lane Restriction
1	55/65	Yes
2	55/65	No
3	60/65	Yes
4	60/65	No
5	50/60	Yes
6	50/60	No
7	55/55	Yes
8*	55/55	No
9	65/65	Yes
10#	65/65	No

\# Base strategy for Rural Interstate highways.

* Base strategy for Urban Interstate and Primary highways.

TABLE 2 SUMMARY OF TRAFFIC AND ACCIDENT DATA AT STUDY SITES

SITE	ROUTE	AADT	LANE NO.	MEAN SPEED	NUMBER OF ACCCIDENTS* FATAL	INJURY	PDO	TOTAL
1	95	68728	1	54.09	2	8	17	27
			2	64.71				
			3	73.15				
2	195	75342	1	59.67	0	6	10	16
			2	60.19				
			3	61.88				
3	95	90205	1	55.15	0	50	62	112
			2	61.25				
			3	62.90				
4	581	75657	1	60.81	1	45	74	120
			2	63.06				
			3	66.49				
5	95	149273	1	64.73	0	24	70	94
			2	65.38				
			3	65.67				
			4	66.14				
6	360	10348	1	52.03	0	9	14	23
			2	55.18				
7	29	22110	1	55.56	2	64	91	157
			2	56.58				
8	58	9050	1	55.34	2	38	50	90
			2	58.24				
9	81	23257	1	64.75	0	18	30	48
			2	66.49				
FOR ALL NINE SITES					7	262	418	687

* Total Number of Accidents at Study Sites (1985 thru 1987).

ANALYSIS OF FIELD DATA

Analysis of Traffic Characteristics

The volume and speed data collected at each site were analyzed to identify temporal and locational variations. For highways with two lanes in one direction, traffic volume was higher in the right lane and lower in the left lane. On the average, the right lane carried about 76 percent of the traffic and the left lane about 24 percent. For highways with three lanes in one direction, the right lane carried about 25 percent of the traffic, the center lane about 46 percent, and the leftmost lane about 29 percent. For highways carrying heavy volumes, however, significant differences were not observed among the left lanes. The results of an analysis of variance (ANOVA) suggested that at sites with high volumes, the middle and left lanes were operating with similar traffic characteristics, and the right lane was operating at near capacity. At sites with relatively low volumes, significant differences were observed among the different lanes at a 5 percent significance level.

Development of Traffic Flow Models

The traffic data observed at each site were fitted to the Greenshields traffic flow models (*2*). Separate models were fitted for the individual lanes of each site to observe differences in the traffic stream characteristics among lanes traveling in the same direction. The R^2-values obtained showed that the Greenshields models adequately describe the traffic flow characteristics in each lane. The computed capacity (Q_m) values were then used to determine congestion parameters, as discussed in the next section.

Accident Data Analysis

Accidents in 1985 through 1987 that could be attributed to vehicle and highway interactions were considered in the analysis. Accident involvement rates in terms of 100 million vehicle miles of travel (VMT) were then computed for all vehicles as well as for trucks. These were used to develop models relating accident rates and congestion, as presented in Table 3. These models were used to evaluate the effect of the different truck strategies on highway safety.

Truck Involvement in Accidents

To investigate the effect of each strategy on the accident involvement rate of trucks, it was necessary to develop a simple relationship that would not only describe the truck involvement rate adequately but also contain independent variables that were sensitive to each strategy. It was found that the truck involvement rate (TRINV) was strongly associated with truck volume (TRVOL). Regression analysis was then used to develop the following relationship:

$$TRINV = 8.27 + 0.00278 * TRVOL$$

The effects of implementing truck strategies can result in the redistribution of truck volumes among the lanes, and hence may affect the truck accident patterns in each lane. This model was therefore used to investigate the effect of each strategy on truck-involved accident rates.

SIMULATION OF TRUCK STRATEGIES

The vehicle behavior in each lane at each site was modeled using SIMAN, a simulation software package (*3*). The effects of the different strategies on traffic volumes, speeds, headways, and accident rates at the various study sites were then determined. The basic vehicle movement and operating conditions were modeled before simulating the different restrictions or truck strategies. The vehicles in each lane were represented as entities in a queue. They were generated according to the input volume distributions obtained from the field data, then coded in the experiment frame of SIMAN. As each vehicle was generated, its characteristics (attributes), which included the vehicle type, speed, length, and lane, were assigned.

A highway section approximately 3 mi long was simulated. To simulate vehicle dynamic behavior, a detection mecha-

TABLE 3 ACCIDENTS AS A FUNCTION OF CONGESTION

NO.	ROUTE	CITY/COUNTY	RELATIONSHIP	R^2
1	95	HENRICO	ACCRT = 0.85 + 2.52(V/C)	0.681
2	195	RICHMOND	ACCRT = 1.75 + 8.52(V/C)	0.720
3	95	Pr.WILLIAM	ACCRT = 1.48 + 3.05(V/C)	0.692
4	581	ROANOKE	ACCRT = 1.60 + 2.73(V/C)	0.834
5	95	FAIRFAX	ACCRT = 0.95 + 6.23(V/C)	0.720
6	360	AMELIA	ACCRT = 3.71 + 6.82(V/C)	0.602
7	29	CAMPBELL	ACCRT = 3.37 +11.73(V/C)	0.764
8	58	PITTSYLVANIA	ACCRT = 0.96 + 6.99(V/C)	0.889
9	81	ROCKBRIDGE	ACCRT = 1.16 + 8.08(V/C)	0.627

nism, which scanned the vehicles in each lane every 20 sec, was modeled. The scan shuffled the vehicles into different lanes, subject to prevailing lane-changing and car-following conditions. The vehicle in each lane was processed according to the dynamic conditions modeled for that lane. The model determined if the following car's speed was greater than the lead car and if the time headway was less than 2 sec. If a gap greater than the vehicle length plus a fixed clearance was found in an adjacent lane, the vehicle would move to that lane and its lane code would be changed. (The fixed clearance varied according to the vehicle type.) Trucks were treated differently when truck lane restrictions were being simulated. They were identified by the vehicle type attribute and were restricted to a specific lane (or lanes) using the scan mechanism.

In modeling driver response to posted speed differentials, the change in operating speeds was accomplished by specifying compliance with speed limits. This information was obtained from analyzing the existing speed distributions. Once in each scan the vehicle's distance attribute was updated to reflect distance traveled. The model also determined if the distance was greater than 3 mi, in which case the vehicle was eliminated.

A data collection mechanism triggered at the end of each hour recorded hourly vehicle counts and mean speeds in each lane. Using the output analysis module of SIMAN, the speed distributions were examined and ANOVA tests were performed.

The model logic and the operations simulated at the exit section were verified by comparing the hourly volumes input to the model obtained from the field data with the hourly vehicle counts made by the model. The results indicated that both sets of volumes were approximately equal, suggesting that the logic was acceptable.

SIMULATION RESULTS

Impacts on Traffic Volumes

In analyzing the simulation results regarding the percentage of vehicles that changed lanes (a justifiable parameter for interaction), the imposition of no differential speed limit (DSL) minimized interference among cars and trucks. From less to greater interference, the DSLs, with lane restriction, can be ordered as 65/65, 55/55, 60/65, 55/65, and 50/60. However, results of imposing DSLs with no lane restriction did not produce adequate evidence to ascertain which restrictions are better than no restriction.

The operation of trucks was affected by the imposition of DSLs. Under lane restriction, all trucks are in the right lane; however, under DSLs with no lane restriction, the distribution of trucks among lanes was influenced by the amount of speed differential and number of lanes.

Effects of Truck Strategies on Time Headways

Imposing truck speed and lane restrictions on given volumes may affect vehicle headways. The imposition of speed strategies alone did not cause any significant impact (at 5 percent significance level) on the headways of vehicles in different lanes. However, the restriction of trucks to the right lane resulted in significant decreases in time headways of vehicles in the right lane at some of the study sites (see Table 4).

The results also indicated that the time headways of vehicles in the right lane decreased significantly at sites with high average annual daily traffic (AADT) and a high proportion of trucks. A significant reduction in headways in the right

TABLE 4 EFFECTS OF LANE RESTRICTION ON TIME HEADWAYS ON RIGHT LANE

Site	No. of Lanes	Truck %	AADT	Headways(sec) Before	Headways(sec) After	Percent Decrease	Significant Decrease ?
1	3	15.76	68728	6.48	5.47	15.6	Yes
2	3	3.59	75342	9.61	8.67	9.8	No
3	3	13.13	90205	7.54	5.54	26.5	Yes
4	3	8.42	75657	15.90	9.68	39.0	Yes
5	4	11.58	149273	6.64	4.43	33.2	Yes
6	2	21.99	10348	21.91	20.92	4.5	No
7	2	12.17	22110	11.55	10.91	5.5	No
8	2	17.45	9050	34.49	34.18	0.9	No
9	2	32.71	23257	60.88	23.86	60.8	Yes

NOTE : AADT values given are projections for 1989.

lane implies a reduction in the number of acceptable gaps available for drivers wanting to merge from entrance ramps. This creates the "barrier" effect, making it difficult to merge, which results in a hazardous situation at and near each entrance ramp. These results suggest that, for highways with three and four lanes in one direction, the imposition of a right-lane restriction for trucks may create an unsafe condition at entrance ramps when the truck proportion is higher than 3.6 percent and the AADT is greater than 75,000.

Effects on Vehicle Speeds

Figure 1 shows typical results of the speed distributions in the right lane, before and after simulating a 55/65 DSL with lane restriction. Figure 2 shows the speed distributions in the right lane due to the imposition of the 55/65 DSL and lane restriction at three different study sites, carrying 4, 16, and 33 percent truck volumes. Figure 1 shows that the speed distribution tends to be symmetrical with no restriction but skewed with restriction. Figure 2 also shows that the skewness increases with the percentage of trucks in the traffic stream. It is well known that the potential for accidents in a traffic stream increases with increases in skewness of its speed distribution. Therefore, the results suggest that the potential for accidents increases in the right lane with the imposition of the DSL and lane restriction. Also, this effect increases further with increases in truck percentage. The speed distributions in other lanes did not change significantly, although the mean speeds varied slightly.

Effect on Accident Rates

Using the appropriate relationship between the congestion and accident rates mentioned earlier in this paper, the expected changes in accident rates were determined using the hourly counts and truck volumes from the simulation results.

The results of ANOVA tests indicated that the accident rates did not change appreciably in any of the lanes, except in the cases of lane restriction, where the all-vehicle accidents as well as the truck-related accidents in the right lane increased slightly. However, none of the effects were significant at a 95 percent confidence level. Table 5 presents the average statistics computed from the results obtained for the right lane, due to different truck lane restrictions.

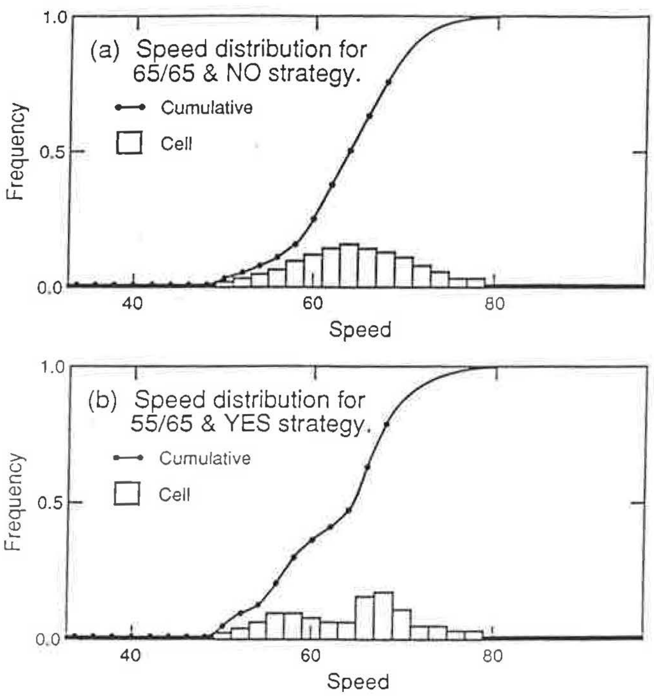

FIGURE 1 Effect of lane restriction on speed distributions on the right lane of Site 9.

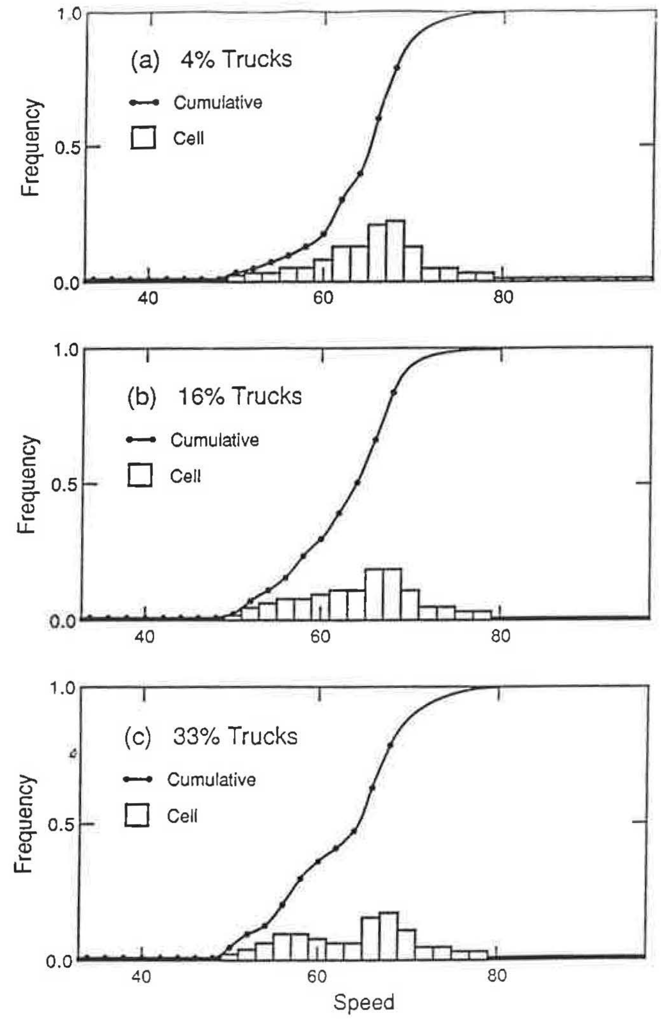

FIGURE 2 Speed distributions on the right lane at sites carrying different truck percentages.

CONCLUSIONS

Conclusions from this research are as follows:

- The imposition of a DSL alone did not result in significant changes in the volume distribution of trucks and nontrucks among the different lanes of multilane highways.
- The imposition of a DSL in addition to lane restriction increased the interaction between cars and trucks and therefore the potential for accidents. With regard to reducing this interaction, the best speed strategy was 65/65, with the following ranking:

TABLE 5 EFFECTS ON ACCIDENT RATES FOR THE RIGHT LANE

Site	All vehicle Accidents		Truck Related Accidents	
	% Increase	Confidence level	% Increase	Confidence level
1	3.65	Low	3.93	64%
2	0.94	Low	1.72	Low
3	4.21	Low	2.89	Low
4	1.67	Low	2.12	Low
5	8.23	33%	6.23	49%
6	4.14	25%	4.79	Low
7	0.73	Low	2.14	38%
8	1.29	Low	3.01	51%
9	6.89	56%	15.72	77%

1. 65/65,
2. 55/55,
3. 60/65,
4. 55/65, and
5. 50/60.

• Restricting trucks to the right lane resulted in a decrease in vehicular headways in that lane. This decrease was significant on three-lane (one-direction) highways carrying AADT greater than 75,000 and a truck proportion greater than 3.6 percent and on two-lane (one-direction) highways having AADT greater than 23,000 and a truck proportion greater than 32 percent.

• The restriction of trucks to the right lane and imposition of a DSL skewed the speed distribution in the right lane. The degree of skewness increased with the magnitude of the speed differential and the percentage of trucks in the traffic stream.

• The imposition of DSLs and lane restrictions did not change the accident rates in the left lanes but slightly increased the accident rates in the right lane for both truck-related and all vehicle accidents, although these increases were not significant at the 5 percent significance level.

• No safety benefits were observed by implementing any of the truck strategies tested. However, the potential for increased accident rates was observed with the implementation of each strategy, particularly on highways with high AADT and a high percentage of trucks.

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REFERENCES

1. *Special Report 211: Twin Trailer Trucks.* TRB, National Research Council, Washington, D.C., 1986.
2. B. D. Greenshields. A Study of Highway Capacity. *HRB Proc.*, Vol. 14, 1934.
3. D. C. Pegden. *Introduction to SIMAN.* Systems Modeling Corporation, Nov. 1987.

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