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Use of Historic Transportation Structures

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Contents

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Adaptive Use of Historic Metal Truss Bridges

WILLIAM ZUK AND WALLACE T. McKEEL, JR.

In an attempt to preserve a representative number of fast-disappearing old metal truss bridges, a variety of methods of modifying them for contemporary use was explored. Twenty historic metal highway truss bridges located in Virginia were used as case studies. The bridges were investigated as to their potential for sympathetic strengthening and widening to meet current federal standards. In most situations the loading requirement can be met by discreet strengthening, but the geometric requirements can not be met without severe violation of the historic features of the bridges. Also explored were nonvehicular uses of these bridges for controlled architectural conversion into craft centers, museums, restaurants, housing, and the like, at either the present site or a new one. Although the bridges investigated are in Virginia, the findings should have application for those in other states.

In an effort to encourage preservation of a representative number of historic iron and steel bridges, a study was undertaken to explore a variety of methods of modifying them for contemporary use. A wide range of options was investigated by using 20 historic metal truss bridges in Virginia as examples.

The strategy for modification or adaptive use encompasses two basic categories: (a) continued vehicular use and (b) conversion to nonvehicular use. Under (a), there are four subcategories, as follows:

1. Upgrade the bridge at its present site by discreet strengthening;
2. Modify the bridge at its present site by discreet widening;
3. Modify the approach roadway so that the old bridge carries only one-way traffic, and build a new bridge or relocate an old one near the original bridge to carry traffic in the opposite direction; and
4. Move the bridge to a less-demanding traffic location, as in parks or on bicycle trails.

Subcategories under (b), conversion to nonvehicular use, are the following:

1. Restrict use of the bridge at its present site to pedestrians for possible recreational activity;
2. Convert the bridge, by enclosing it at its present site, to architectural use as a museum, craft center, restaurant, or the like;
3. Move the bridge to a new site and convert it to architectural use as in 2;
4. Declare the bridge a historic ruin and place it off limits for anything but viewing;
5. Incorporate portions of the old bridge discreetly into a new bridge, either structurally or decoratively, at the same location; and
6. Disassemble the bridge and store it for some future use.

CASE STUDIES

The 20 bridges selected for case studies were chosen through a systematic procedure described in Newlon (1). Detailed studies of all these bridges are described in Zuk and others (2). In this paper, only a sampling of the studies, along with a summary, is presented. A discussion of methods of strengthening for vehicular use is given first, followed by ways to adapt bridges to nonvehicular use.

Vehicular Use

Structures Evaluated

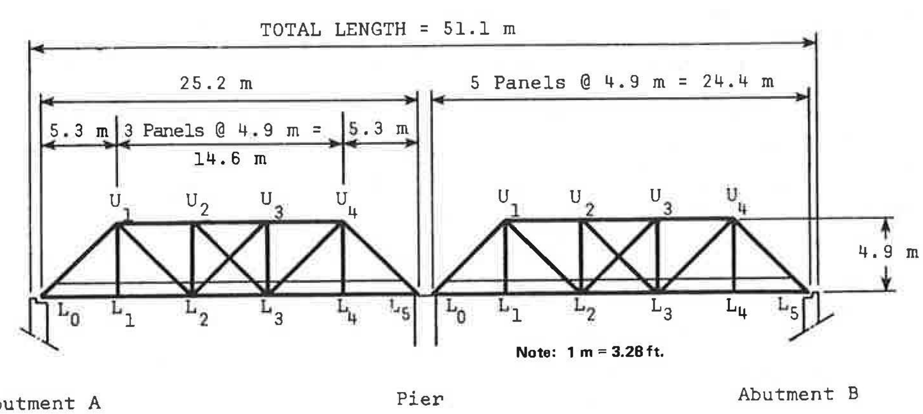
Typical of most of the metal truss bridges in the study is the two-span Pratt truss bridge shown in Figure 1. This structure is located on VA-632 over the South River in Augusta County, Virginia, and was built in 1887. As it is typical, only this one bridge is described. The structure is a one-lane through bridge with a total length of 51.14 m (167.67 ft), a roadway width of 3.28 m (10.75 ft), and an overall truss height of 4.88 m (16 ft). The components consist of rolled steel members, bars, and plates riveted or bolted together. The lower chords are eyebars and the deck is wood plank.

Methods of Strengthening Investigated

The problem of strengthening this bridge to accommodate federal standard AASHTO HS20 loading conditions involves an examination of the floor system, the connections, and the trusses. An engineering analysis has determined that portions of the floor, truss, and connections in this bridge are understrength and require reinforcement. A number of methods can be used to strengthen these elements. However, it is believed that reinforcement of the truss is the most critical aspect from the standpoint of historical preservation.

Seven methods for strengthening the trusses of this bridge were examined by using computer analysis to determine the best technique. As the two spans of the bridge are almost the same length, the span

Figure 1. Elevation and profile of the VA-632 structure.



length of 24.4 m (80 ft) was used for all trusses.

1. Method 1 involves joining the two simple-span trusses to form a single continuous span truss. Continuity is developed by connecting the upper chords by bar U_4U_1 (see Figure 1). To note that this bar is not part of the original truss, it would be painted a color different from that of the truss.

Continuity between the spans did not prove advantageous because heavier loads were transmitted to those members nearest the pier. Although stresses in the counters were reduced, those in the end posts and diagonals nearest the pier were increased. More seriously, compressive stresses were induced in the lower chords L_2L_3 and L_4L_5 and in the diagonal L_2U_1. These light tension members were unable to carry compressive forces of any large magnitude. None of the overstresses in the tension members of the unreinforced truss were reduced below the allowable level by developing continuity between the spans.

2. Method 2 requires adding a pylon and cable stays. A pylon was located at the center pier and assigned a height of 9.8 m (32 ft) (see Figure 2). As in method 1, the added structure of the pylon and cables should be designed in such a way that it would be clearly perceived as being of the twentieth century and not of the nineteenth.

Stress levels in most of the members other than the hangers, counters, and diagonal L_3U_4 were reduced to acceptable levels but, as in the continuous bridge scheme, sizable compressive stresses were induced in some lower chords. It was apparent that unavoidable stress reversals in flexible tension members would render a cable-stayed structure impractical.

3. Method 3 requires the posttensioning of the lower chords of the individual trusses. Reinforcement of trusses through the use of posttensioning rods placed along the lower chords and tightened by turnbuckles has apparently enjoyed some success (3). The rods can be tightened until they share in the dead load stresses or simply be snugged to act under only the live load.

Because of the experience with stress reversal in the lower chords, it was decided to tighten the rods only to a snug fit. Two rod sizes, 322 mm² (0.5 in²) and 645 mm² (1.0 in²), were analyzed, with the latter providing the better results. The scheme relieved the overstress conditions in the lower chords of the unreinforced truss and reduced stresses in the diagonals to less than 6.9 MPa (1 ksi) over the allowable stress. The end posts remained slightly overstressed and the hangers seriously overstressed, as none of these members were affected by the reinforcement. The stresses in the counters remained high, despite some reduction. Certainly, the hangers and counters would require additional reinforcement.

4. Method 4 involves adding a queen post under the individual trusses. It was reasoned that by extending the posttensioning rod and cable below the struts positioned under the hangers, they would provide an upward component to relieve those members as well as the lower chords (see Figure 3). Overstresses in the lower chords were eliminated and those in the hangers were only 4.2 MPa (610 psi) above the allowable value. Unfortunately, stresses in the diagonals were not affected and the counters remained seriously overstressed. However, the principal disadvantage lay in the length of the queen-post struts required. Using an assumed posttensioning force of 89 kN (20 kips), the length of the struts was determined to be 2.4 m (8 ft). Use of an acceptably shorter strut, say around 0.9 m (3 ft), required a much higher force to relieve the hangers and resulted in stress reversals in the lower chords.

The need to extend the queen-post truss 2.4 m below the bridge eliminated method 4 from practical consideration because the truss would be vulnerable to damage at times of high water.

5. Method 5 considers the placing of intermediate supports under the trusses. The construction of intermediate supports occasionally can be advantageous in relieving a weak truss bridge. (It is assumed that the bridge site can accommodate the additional piers.) A trial analysis was performed of the truss span with intermediate piers at panel points L_1 and L_4.

Stresses in the lower chord members were reduced to acceptable levels but those in the diagonals were increased slightly. While stresses in the counters were reduced below those in the unmodified truss, both the counters and diagonals would require additional reinforcement. Hangers L_1U_1 and L_4U_4 over the piers were undesirably placed in compression.

6. Method 6 requires adding longitudinal beams under the trusses. Various configurations of members that act in conjunction with the typical through truss were investigated. Initially, a single rolled steel beam was tried under each of the trusses, but it was found that the optimum beam section did not provide compatibility of deflections with the trusses. The analysis indicated that the truss actually carried the beam in the central portion of the span.

A second approach used a grid composed of six reinforcing beams, one under each line of stringers, which supported the floor beams. Use of the optimum rolled section, W36 x 230, relieved all overstressed members except for a 1.0-MPa (150-psi) overstress in lower chord L_2L_3. However, a great quantity of structural steel, nearly 25 400 kg (28 tons), was required.

7. Method 7 involves adding auxiliary trusses to flank the old trusses. In an effort to reduce the amount of material required, it was decided to evaluate the performance of a supplemental truss on each side of the span (see Figure 4). The use of a Warren truss with a span of 24.4 m (80 ft) and a height of 2.4 m (8 ft), fabricated of steel tubular members, was chosen for evaluation. Its diagonals had the same slope as those of the existing Pratt truss and the lower panel points coincided. For the purpose of analysis it was assumed that the trusses were joined at the upper and lower panel points of the Warren truss, but in practice the auxiliary truss might be separated by a sidewalk or bicycle path. Compatibility of deflections would be required, however.

Several iterations indicated that the most efficient design was a truss composed of 101x101x5-mm (4x4x0.19-in) chord members and 76x76x6-mm (3x3x 0.25-in) web members that weighed slightly more than 1800 kg (2 tons). All stresses in the Pratt truss were reduced below allowable levels. Although the Warren truss was effective and relatively economical, it was visually intrusive. If economy in materials is not a crucial factor, the use of other longitudinal members, such as box beams, is possible.

In this method, it is assumed that the new members would, by their color or form, clearly show that they are not part of the original bridge structure.

Most of the methods evaluated are reasonably independent of the truss configuration, but the length of the existing truss may limit the number of useful reinforcing techniques. A few of the following procedures appear promising:

1. An auxiliary truss, such as the Warren truss

evaluated in the study, might be effective if its visual intrusion were not objectionable. As the length of the existing span becomes greater, the auxiliary truss will, of course, become more prominent.

2. Longitudinal beams or hybrid members under the truss may be effective if the span length is not too great and economy of materials is not a critical factor.

3. The use of posttensioning rods at or just below the lower chords is apparently feasible on short spans. Additional reinforcement of critical truss members may be required.

4. The addition of individual reinforcement to supplement critical members may be sufficient if the proposed capacity is not extremely high.

Nonvehicular Use

Accomplished and Planned Conversions

Use of a bridge for a function other than carrying vehicular traffic is somewhat unorthodox, so a literature study was undertaken to determine what has been done in this regard. The most common conversion found was to pedestrian use, either at the existing site or a new one. New Jersey, Ohio, Maryland, and Virginia each has relocated an old historic metal truss bridge from a highway to a park for use only by pedestrians and bicyclists. The one in Virginia is a bowstring metal arch truss relocated to a rest area on I-81 in Montgomery County.

Figure 2. Elevation and profile of pylon tower with cable stays to truss (method 2).

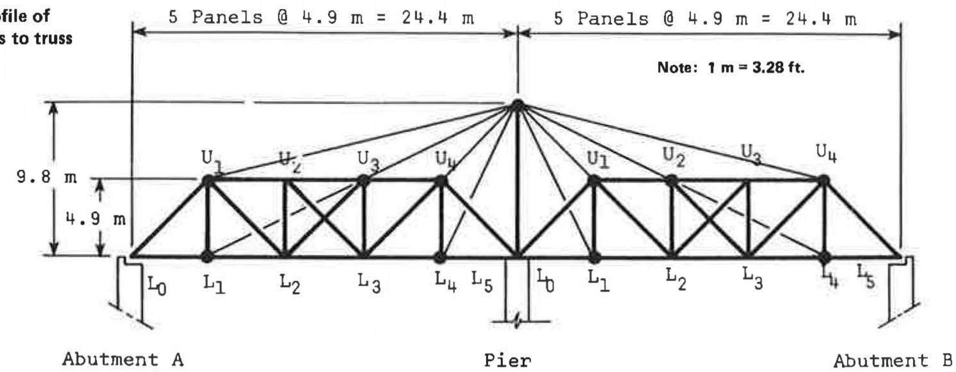


Figure 3. Elevation of queen-post reinforcement (method 4).

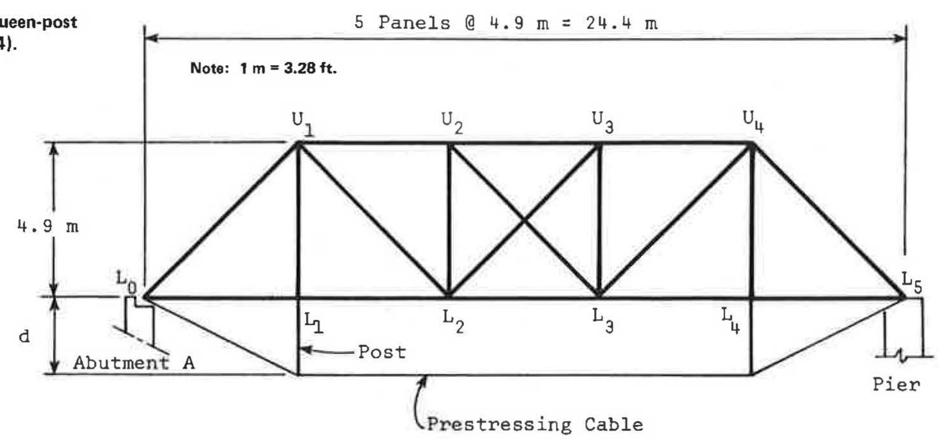
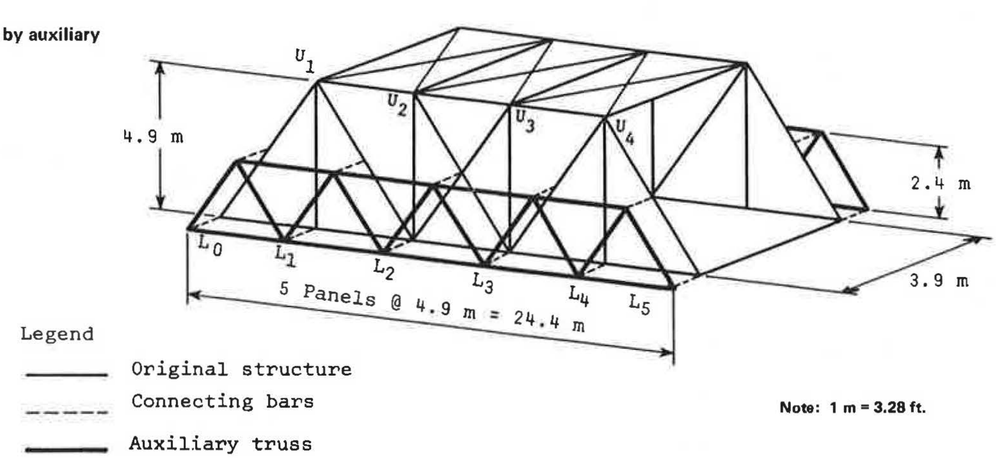


Figure 4. Reinforcement by auxiliary trusses (method 7).



Another structure in Virginia is a partially destroyed wooden truss bridge that formerly carried VA-45 over the James River between Goochland and Cumberland Counties. The end spans remain standing and are used only by pedestrians, primarily as scenic overlooks.

Under consideration is a proposal for converting a nineteenth-century metal truss bridge, complete with Lally columns, to a restaurant-hotel complex. This bridge, whose vehicular traffic is to be rerouted to a new bridge, is on VA-758 across a particularly scenic portion of the Shenandoah River. Adaptive use is to be done by private parties.

Another bridge, this one in Hancock, New York, and also in private hands, has been converted into a restaurant. A portion of the abandoned 152-m (500-ft) long steel deck truss railroad bridge (Orange and Western) has been enclosed below the deck for this facility.

There are two major projects still on the drawing boards. The first will convert the historic Eades Bridge across the Mississippi River at St. Louis, Missouri. The plan is to divert all the vehicular traffic on the little-used Eades Bridge to the new nearby Poplar Street Bridge and to convert the old bridge into offices, restaurants, and the like.

In a second project, the abandoned Big Four railroad bridge in Louisville, Kentucky, a six-span steel through truss bridge across the Ohio River, is being studied for conversion into a large commercial complex. In the complex would be restaurants, hotels, condominiums, apartments, offices, retail shops, exhibition halls, and parking garages, with a marina beneath the bridge.

Adaptive Uses in Case Studies

By using these bridges as precedents, detailed studies were undertaken of each of the 20 bridges chosen for consideration in the study. It was anticipated that an appropriate adaptive use of some of these Virginia bridges would be for architectural structures such as restaurants, museums, craft centers, and housing. To judge the structural feasibility of such use, typical test bridges were analyzed with computers by using floor, roof, wall, and wind loads as required by the building code of Virginia. The existing bridges, with only minor reinforcement or repair at particular joints or members, were found to be structurally satisfactory. In the event that any of the bridges studied are actually converted to an architectural use, additional detailed structural analyses should be carried out.

Aspects of utilities, such as electricity, water, and sewerage, which would be needed for some conversions, were also investigated, since most of the bridges are located in rural areas. The availability of electricity generally proved to be no problem as power lines could be found near all the bridges. It was assumed that water would be available either from wells or by hauling for situations that required small water consumption. Waste could be handled either by conventional septic tanks and drainage fields or by commercially available units that handle solid wastes with little or no water consumption. In special cases, cleanable privies would be used. Heat for the buildings could be supplied by fuel oil, propane gas, electricity, or wood-burning stoves.

In this study, it was assumed that wherever an old bridge was left standing intact, any new replacement bridge would be located so that access to the old bridge would still be possible. It was also anticipated that some of the bridges might require moving to a new location, so estimates of moving costs were determined by interviewing several contractors engaged in bridge work in Virginia. The cost figures for moving a typical metal truss bridge of 24-m (80-ft) span that weighs about 9 Mg (10 tons) were judged to be reasonable. This aspect, therefore, seemed to present no great problem.

Finally, there is the general question of how a highway bridge and related property can be assigned to someone outside the Virginia Department of Highways and Transportation. It is assumed that the department may not wish to destroy a historic bridge and also may not wish to maintain it as a landmark or operate it as a museum or other enterprise. The Code of Virginia (Sections 2.1-503 through 2.1-513) allows for the sale, lease, or transfer of state property when the property is declared surplus, with the final authority for transfer resting with the governor. Agencies such as the department and the Division of Engineering and Buildings are also involved.

Although all 20 bridges were individually studied for possible adaptive nonvehicular use (2), only a few are shown here in Figures 5-12. These uses are presented only as suggestions in that no firm economic analysis was made. However, every attempt was made to match the bridge use with general local conditions.

Summary of Adaption to Nonvehicular Use

As can be seen from the uses shown in Figures 5-12, a wide range of adaptive uses is possible for old metal truss bridges. Some are for public use and some are for private use. Some are converted at the existing site and others are moved to a new site.

The architectural treatments shown are only suggestive of many possible treatments. However, it is felt that whatever the treatment of walls, roofs, fenestration, and materials, the essential nature of the original bridge must show through. In all cases illustrated, the original basic structure is not tampered with and the additions are generally inside the form of the bridge. Where the structure is moved to a new site, the bridge is relocated in an elevated manner and supported at its ends so that it continues to look and function as a bridge.

CHOICE OF MODIFICATION OR ADAPTATION

This study has shown that there are many possible alternatives for modifying historic metal truss bridges so that they can continue to be of use in today's world. The possible use of a given bridge depends on many factors. A list of some such factors includes the condition of the bridge, site considerations, traffic conditions, cost, government regulations, legal liability considerations, commercial conditions, and general interest in preservation.

As this paper is specifically directed toward historic bridges and not just old bridges that may or may not be historic, special attention is paid to methods of modification that keep the historic qualities of the bridge preserved to the extent possible. Although many factors must be considered when deciding on a possible modification for a historic bridge, there is a generally agreed on hierarchy of choices that relate to the historic preservation aspects of possible uses.

1. The first choice is to continue to use the bridge as a bridge in its present location. If repair or strengthening is needed, it should be done discreetly. Widening of the deck to any major degree is undesirable as it significantly alters the appearance of the structure.

2. Should the traffic situation demand widening, such as providing two-way traffic on a one-lane bridge, the historic structure should be left in place and also be upgraded discreetly. A second bridge, as similar in design to the existing one as possible, should be moved to the site of the historic one and erected adjacent to it. Depending on site conditions, which relate to splitting the approach roadway, the distance between the two bridges should be as great as practical so as not to cause undue visual impact on the historic bridge. This pairing arrangement would provide two-way traffic even though each bridge may be only one lane wide.

3. In the event that a historic bridge cannot be left at its original site, it should be moved to

Figure 5. Bridge on VA-746 over Calfpasture River as a greenhouse.

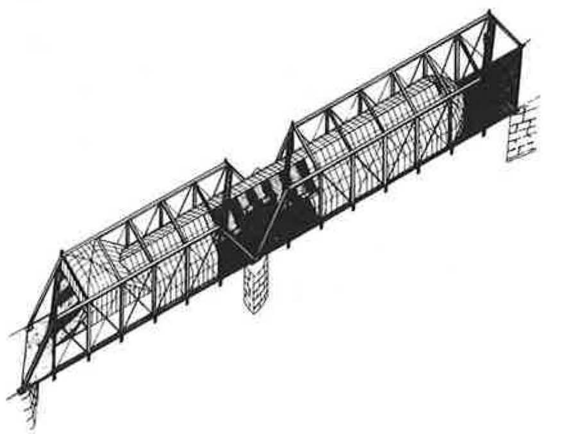


Figure 6. Bridge on VA-715 over Meherrin River converted to an information center at a relocated site.

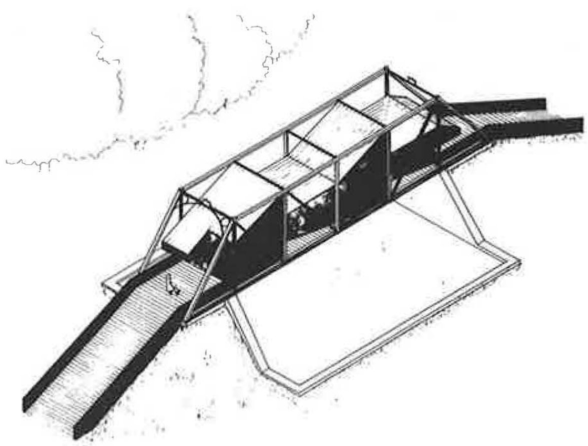


Figure 7. Bridge on VA-673 over Catoctin Creek as a meditation center.

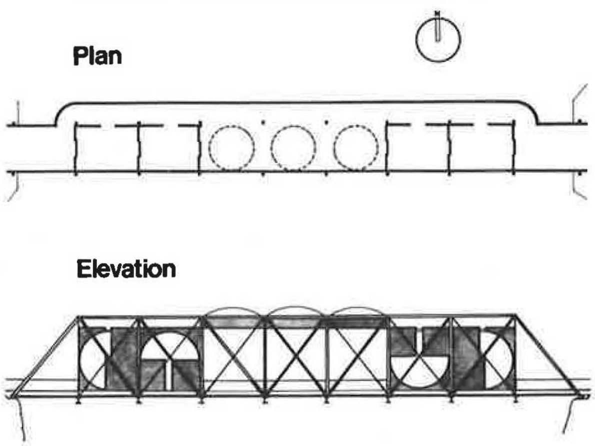


Figure 8. Bridge on VA-620 over Rappahannock River as a picnic shelter.

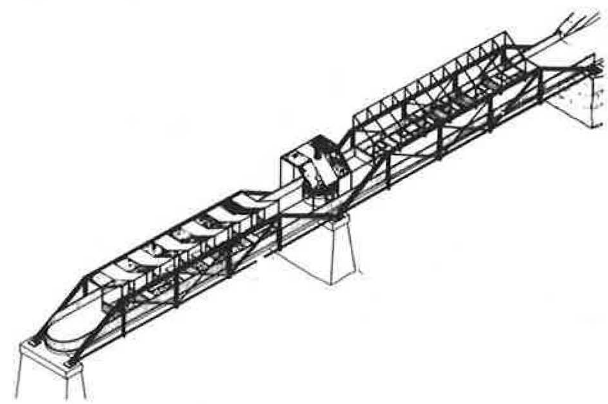


Figure 9. Bridge on VA-640 over Reed Creek as a craft center.

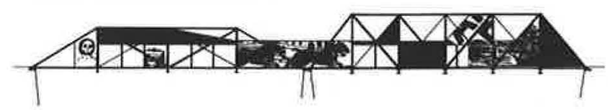


Figure 10. Bridge on VA-657 over railroad converted to a transportation museum.

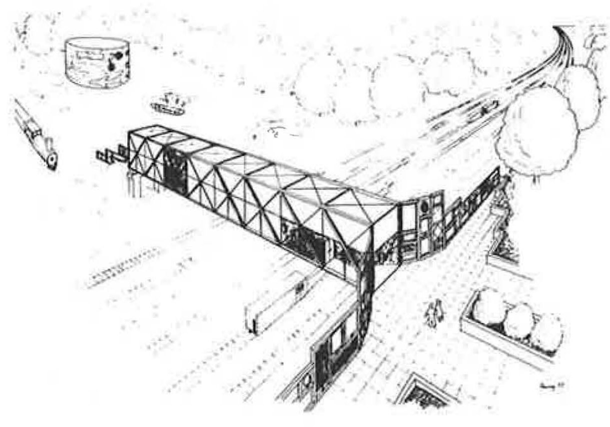


Figure 11. Bridge on VA-632 over South River as a cafe-restaurant.

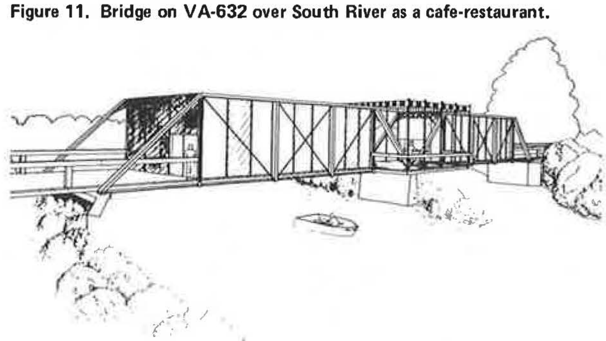
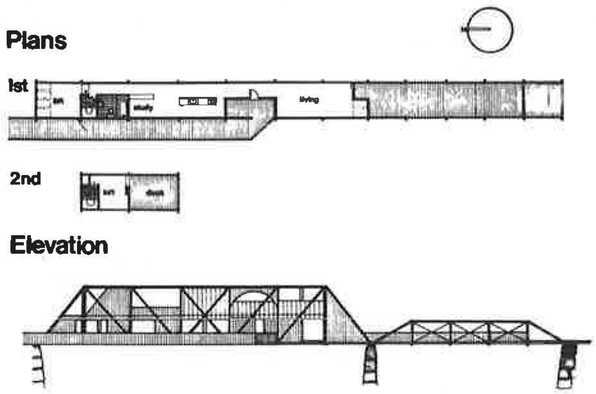


Figure 12. Bridge on VA-615 over Pamunkey River as housing.



another site of a less-demanding nature where it can continue to function as a bridge for light vehicles, bicycles, or pedestrians.

4. If no vehicular use of the historic bridge can be foreseen, it could be converted into some architectural use, such as those described in this paper.

5. In situations where none of the preceding four solutions are possible, the structure should be set off as a historic ruin. Several examples are described in this paper. This arrangement allows the structure to remain standing at a minimal cost.

6. If, of necessity, the structure can no longer be left standing, it should be match-marked, carefully dissembled, and stored in a protected environment with the hope that at some future time and place it could be rebuilt.

7. Further down on the scale of desirability, from a preservation point of view, is to save only selected components of the bridge that would otherwise be totally destroyed. These components could be made into exhibits, as in museums, or even be incorporated as ornamental elements into a new bridge built on the site of the old one.

8. As a minimum, whenever a historic bridge is to be razed, it should be documented with drawings and photographs, and such documents should be preserved in some archive.

Preserving or modifying a historic bridge does mean expending some extra thought or effort, but it does not always mean added expense. Upgrading an old bridge may, in fact, be less costly than building a new one, and converting an old bridge into commercially usable architectural space could even be profitable. Regardless of cost and other factors, ways can always be found to preserve selected historic bridges if there is sufficient commitment to that end.

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An interdisciplinary study of this kind is not possible without the cooperation and assistance of many people. To them, we express our appreciation. In particular, Howard Newlon, long active in historic preservation, was the motivating force behind this study. Reid Reames and George Kirby also greatly assisted in many of the technical aspects of the project.

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Restoration of Meem's Bottom Covered Bridge

KENNETH M. SMITH AND JOHN E. ANDREWS

On October 28, 1976, the Meem's Bottom Covered Bridge in Shenandoah County, Virginia, was set on fire. Listed as a historical landmark on the Virginia Landmarks Register, the structure is the longest covered bridge in the state and is one of two that still carry traffic. At the direction of the Virginia General Assembly, the Virginia Department of Highways and Transportation undertook the task of rebuilding the structure and restoring it to service in such a manner as to maintain its historical significance. The conclusions derived from a structural analysis of the Burr arch-truss design and the novel procedures undertaken by the department to restore the bridge are presented. In completing the task, the department successfully maintained the 80-year-old structure's historical significance and satisfied the mandate of the General Assembly. Although completely destroyed, the load-carrying joints were rebuilt through extensive use of epoxy. Specially treated lumber, fire retardant varnishes, and stainless-steel roofing were used in the restoration to meet the need for fire protection and to minimize maintenance.

Approximately two miles south of the town of Mount Jackson in Shenandoah County, Virginia, the longest remaining covered bridge stretches nearly 61 m (200 ft) in a single span to bridge the North Fork of the Shenandoah River at Meem's Bottom.

The Meem's Bottom Covered Bridge, shown in Figure 1, was built on private property in the mid-1890s. Little concerning its history can be found in public records. Emory Kemp and Charles E. Daniels of the Department of Civil Engineering, West Virginia University, gave some of its history in a report (1) compiled following its near destruction on October 28, 1976.

The bridge apparently was built to provide a direct link between Strathmore Mansion and the Valley Pike (now US-11), which were separated by Meem's Bottom and the North Fork of the Shenandoah River. The Whisler family, who owned the mansion and iron furnaces at Liberty and Columbia, probably engaged master bridge builder John W.V. Woods of Shenandoah County to span the river bottom, thus eliminating several miles from an otherwise circuitous route between their properties.

The Virginia Department of Highways acquired the bridge in 1932 and maintained it in good repair. It carried a 9-t (10-ton) traffic rating until it was set on fire in 1976. In spite of the efforts of a volunteer fire department, the bridge was severely damaged, as can be seen in Figure 2. The roof system, top lateral system, siding, and framing were totally destroyed. The nail laminated oak strip flooring, which had been installed on steel stringers to replace the original timber floor system in 1937, was burned beyond repair but would later serve as a work platform during repairs. Only the main structural members remained and these had lost as much as 3.8 cm (1.5 in) of material from all sides. The heat was so intense that three floor stringers buckled and their weldments to the floor beams were broken.

Figure 1. Meem's Bottom Covered Bridge before the fire.

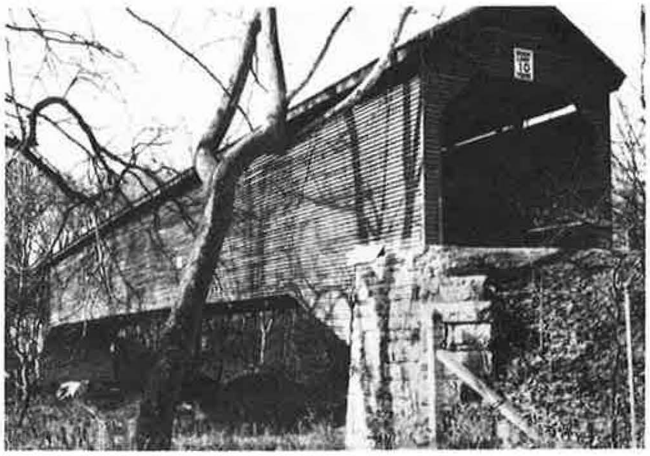
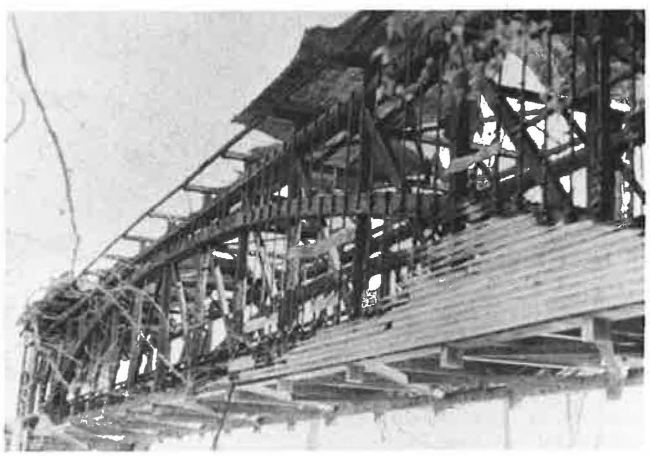


Figure 2. Meem's Bottom Covered Bridge after the fire.



RESTORATION

At the urging of local officials and historic organizations, the Virginia General Assembly directed the Virginia Department of Highways and Transportation to restore and return the bridge to service rather than replace it.

When John Woods built the bridge 80 years earlier, he had no idea of the problems his masterpiece of bridge architecture would present to the bridge engineers of the department. Woods chose to erect a covered timber bridge of the Burr arch-truss system (Figure 3) that incorporated the same skills and craftsmanship in fitting the individual members together as master boatwrights used in building yesteryear's tall sailing ships. Ship lap-splice joints, mortise and tenon joints, and keyed-butt joints fitted together as tightly as joints do in the finest reproduction furniture available today.

STRUCTURAL ANALYSIS

A structural analysis of the bridge was necessary to determine if sufficient strength remained for restoring the bridge to service, assuming that

1. The interlocking joints of the arch and truss, which were completely destroyed by the fire, could be restored;
2. The necessary interaction of the jointed members could be regained and the bearing strength restored; and
3. The arch, which was buckling at its splice points, could be realigned and adequately braced to maintain its proper alignment.

Because of the extreme indeterminate nature of the Burr arch-truss structural system, it was necessary to engage Emory Kemp of West Virginia University as a consulting engineer. Kemp had available the ICES

Figure 3. Schematic of the Burr arch-truss.

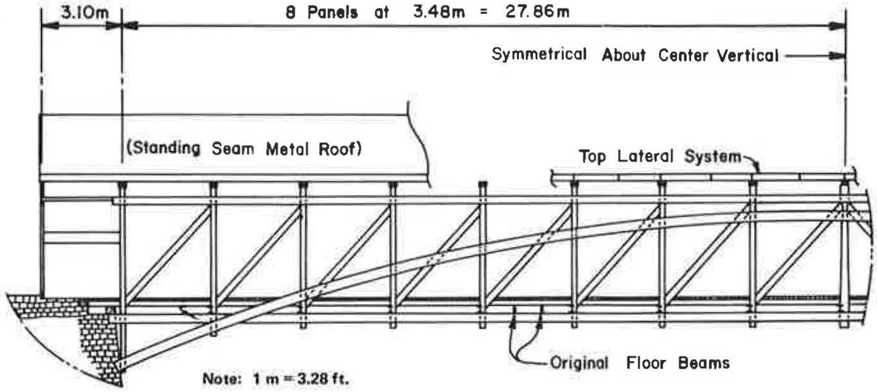


Figure 4. Typical panel details.

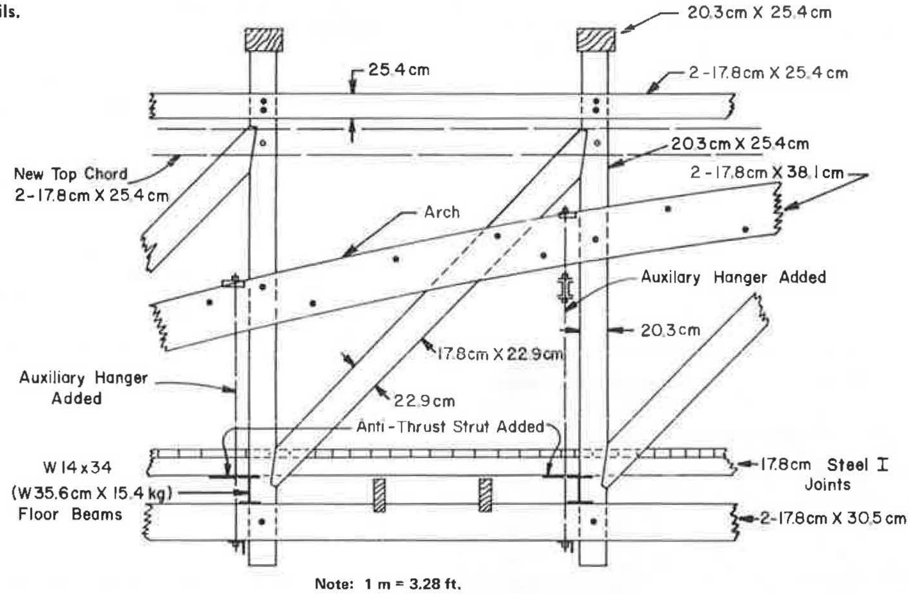


Figure 5. Installation of new top chord.

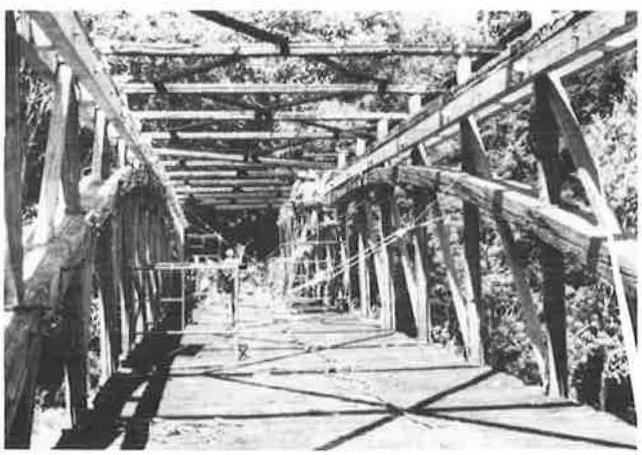
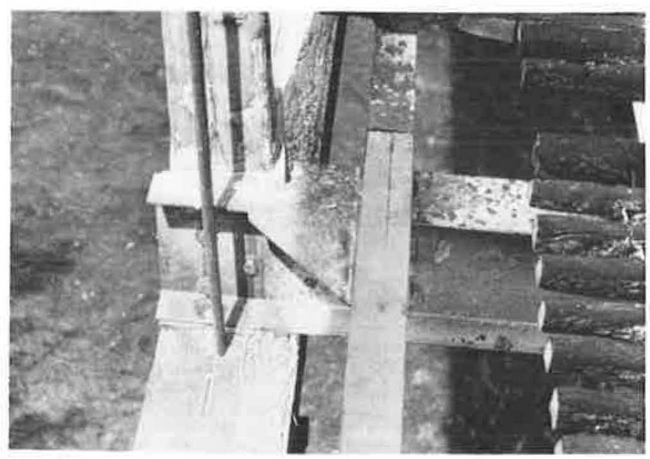


Figure 6. Installation of antithrust strut plate.



STRUDL II computer program that was adaptable to the analysis of this type of bridge.

Remnants of the roof structure and siding framework were removed to eliminate as much dead load from the weakened structure as possible. Char was removed from the members believed to be salvageable and measurements taken.

Kemp's analysis provided insight not only into the potential for restoration but also into the working relation between the arch and truss systems. Many bridge engineers believed that the truss carried the dead load and the arch sustained live loads.

Although Kemp's research did not invalidate this reasoning about the application of various loadings, it did reveal a superior stiffness characteristic of the arch-truss system because of the arch compared with a simple truss. Even in its burnt condition, the structure provided midspan deflections for H15-44 truck loadings well below the 1/800 of the span limitation of the American Association of State Highway and Transportation Officials (AASHTO) specifications (2).

When the results of deflection analysis were compared with the stress calculations for the truss, which neglected the arch, it was found that the arch caused a reduction in stresses in the truss system and significantly reduced the total deflections for the truss that acted independently. The arch curtails deflections attributable to creep and shrinkage of the truss members under sustained loads and loosening of the joint system due to cyclical loadings.

The stress analysis of the truss system revealed that the truss verticals were the critical members. While the axial stresses were within acceptable limits, the analysis indicated the existence of large tension and compression stresses indicative of the presence of undesirable bending moments in the vertical members. Further investigation revealed that these were caused by two significant errors in the design.

The most crucial of these errors was the manner in which the diagonal members were framed into the truss verticals, as illustrated in Figure 4. The eccentricity of the diagonal with respect to intersections of the top and bottom chords and the vertical members created the significant bending moments. The fixed joints at the intersection of the

Figure 7. Burr arch-truss joint details.

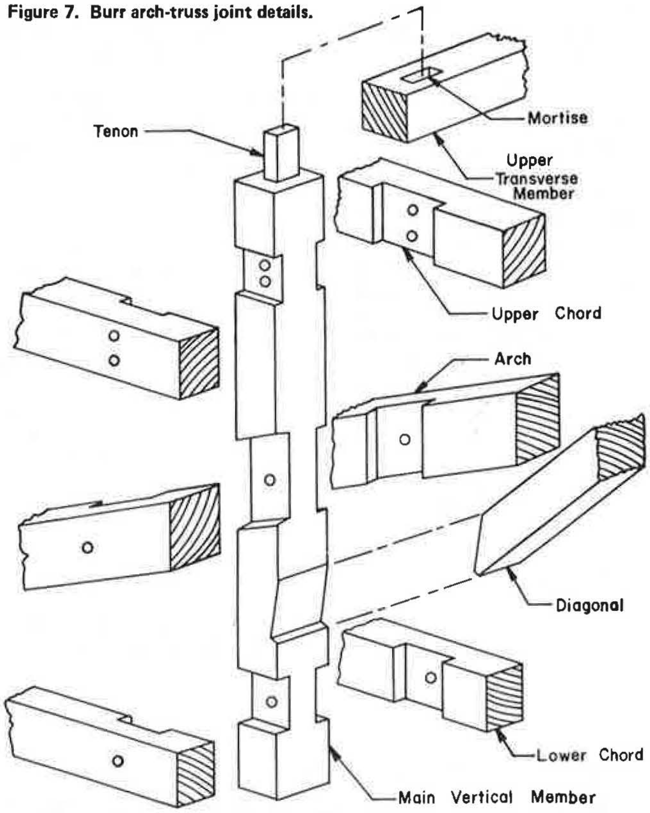


Figure 8. Typical joint destruction.

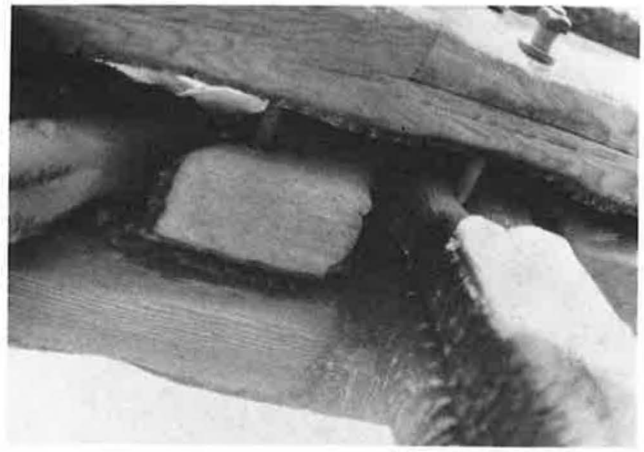


Figure 9. Typical joint restoration.

top chord and verticals contributed further to the bending in the verticals.

The fire damage sustained by the structural system was twofold. First, the overall effectiveness of the truss was reduced, which redistributed the stress in such a manner as to increase the importance of the function of the arch in the arch-truss system. Second, this redistribution of stress occurred without any members other than the already critical vertical members being overstressed. The overstressed verticals were further overstressed; thus, the fire aggravated an already critical problem.

REPAIR PROCEDURES

In planning the restoration, it was clear that the present structural system would be inadequate without taking steps to reduce the stresses to a tolerable level by removing or resisting the eccentric loadings in the vertical members.

The top chord of the truss was severely damaged and was later found to have large sections of rotting material and insect infestation. A new top chord was warranted and could be put immediately below the old one before it was removed so that the eccentric load of the diagonal would be eliminated (Figures 4 and 5).

The point of eccentricity at the bottom chord was at a position where the horizontal thrust of the diagonal could be transferred through the vertical into the floor system by welding a strut plate to the floor beam and the exterior stringer, as shown in Figures 4 and 6. Although all of the bending in the vertical at this point could not be eliminated, this procedure did reduce the undesirable bending to acceptable levels.

With the problem of the bending moment in the vertical truss members resolved and the design of the truss consequently improved, restoring the joints and gaining proper interaction of the joined members remained the big problems to resolve. The realignment of the arch could be determined only by work, and it was felt that the alignment could be held with the new top lateral system of the truss and with properly restored joints.

Originally, the vertical truss member had been shaped to lock into the top chord, arch, and bottom chord and was notched to provide a bearing seat for the diagonal members that passed cleanly through the arch (Figure 7). When a live load was placed on the verticals, the interlocking action of the joints transferred the load to the truss members and into the arch. These joints, which had been cut, shaped, and matched to bear the loads, had been destroyed by the fire, as shown in Figure 8. Large gaps were left where tight bearing surfaces had been. Only the splice joints in the arch escaped fire damage, perhaps because of the tight bearing caused by the dead load. In many places the gap around the vertical through the arch was large enough to pass an arm through the arch all around the vertical. Neat rectangular cross sections no longer existed.

To compound matters, areas in the arch were found to be severely damaged by insect infestation and rot. Exposed to the elements, this deterioration could only accelerate. The restoration of the joints was to become the major task in restoring the structure to service.

The initial repair effort was to bring the arch to as straight an alignment as possible. A combination of cable restraints and compression struts was used to force the warped arch back to its proper alignment. These restraints were left in place for the major part of the repair; the restoration of the joints, installation of the new top lateral system, and framing of the roof were completed before they were released.

Figure 10. Auxiliary hanger system.

Several ideas were considered in engineering the reconstruction of the joints, all of which incorporated the use of epoxy to some degree. Ultimately, a high modulus, low-viscosity epoxy resin system was used that, when mixed with a wood flour, gave the appearance of wood to the rebuilt areas, as can be seen in Figure 9. Several different flours were considered. Walnut shell, maple wood, and pine flours (the last called white tag) were mixed in the laboratory. The specification finally written left the type of flour open and only required that the epoxy and wood-flour mixture should closely resemble the color of the timber being repaired.

The consistency of the epoxy and wood-flour mix could be controlled to meet the demands of its placement in the repair process. Where structural details permitted, the mixture was poured. In other locations it had to be stiff and placed with a trowel.

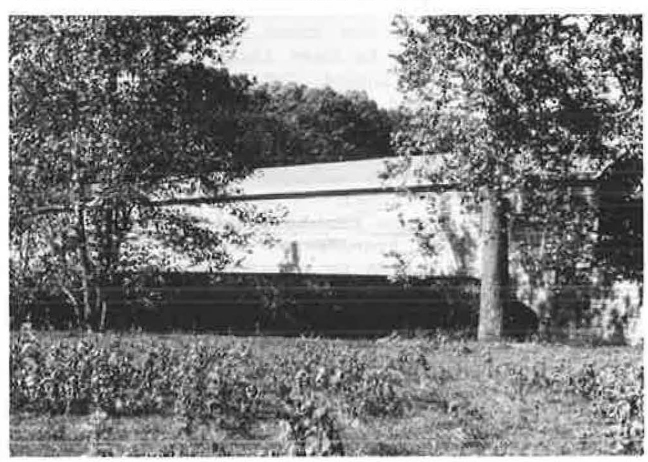
Where it was necessary to remove rot or insect-weakened areas along the arch, the epoxy and wood-flour mixture was used to fill the cavities left by the removal of the deteriorated timber. In exceptionally large cavities, blocks of wood were used for filler, and in one area a salt-treated

Figure 11. Auxiliary hanger system at middle verticals.

Figure 12. Installation of top lateral system.

Figure 13. Interior of bridge after restoration.

Figure 14. Restored Meem's Bottom Covered Bridge.



10.2x10.2-cm (4x4-in) timber was placed and wedged tight in a 2.4-m (8-ft) length of the arch before the mixture was placed.

Wherever truss members jointed with or passed through the arch, the epoxy and wood-flour mixture was used to restore bearing, fill a void, or restore a shape to obtain satisfactory joints of the structural members. With the weakened joints strengthened and restored with the epoxy and wood-flour compound, it was felt that the structure would again carry traffic, provided a method could be devised to safely transfer live loads to the arch. In the original structure this was accomplished at the vertical-to-arch connection by the interlocking joint that provided the transfer through bearing on the arch.

The epoxy-restored joints were considered satisfactory where they were in pure compressive bearing, but there was still doubt about the adequacy of the vertical-to-arch connection. The fire had destroyed these bearing surfaces and the epoxy restoration could not be trusted at this location because its purpose was to fill the void, not to transfer load by shear and tension forces. Consequently, an auxiliary hanger system, shown previously in Figure 4, was devised (see Figure 10). To serve as a stirrup, a structural angle was placed close to the floor beam and under the bottom chord. The stirrup angle was then suspended from the arch by a threaded, high-strength rod that passed through the bottom chord and the arch. Above the arch the rod was attached to a structural steel bearing plate, which was seated in the epoxy and wood-flour compound on a chamfer cut across the arch in such a manner as to ensure that the hanger load was applied uniformly across the arch members.

A slight variation of this device, shown in Figure 11, was necessary at the three middle verticals due to the framing of the diagonal at the top of the arch. At these locations the hanger rod was supported by a bracket composed of two small channels. This bracket was suspended from the arch by two rods that passed through the arch on either side of the diagonal truss member. Individual bearing plates seated on a chamfer and bedded with the epoxy and wood-flour compound on both sides of the diagonal to support the two rods completed this variation of the hanger system.

Now, if either the vertical or its joint with the arch were to fail, the live load and dead load of the floor system carried by each vertical would be transferred through the hanger directly into the arch. The hanger was not tightened enough to preload the rod but was brought up to a snug tightness that would permit the hanger to work along with the vertical as the truss deflected.

The new top lateral system was erected along with the framing for the new roof (see Figure 12). Stringers warped from the intense heat were replaced and the antithrust strut plates (Figure 6), which were to reduce the bending moments in the verticals at the lower diagonal connections, were welded in place.

The arch at this point was still braced and tied off to hold it in its proper alignment. With the epoxy compounds fully cured, all new structural members in place, and the floor system strengthening the lower vertical and diagonal member connections, the restraints to the arch were released. With some minor transverse movement, the arch and truss maintained an acceptably straight alignment.

The charred remnants of the oak-strip deck were removed and a new deck of glued, laminated southern pine deck panels was installed. Framing for the siding and portals was erected and new 2.5x15.2-cm (1x6-in) pine siding was installed.

The metal roof was installed by using the same standing seam method of construction used for the tin roof destroyed by the fire. The roof was of a special terne-coated stainless steel that has weathered to a uniform gray appearance. A stainless-steel roof was chosen to eliminate the hazards associated with having to paint a tin roof 12.2 m (40 ft) above a rocky stream bed. The additional cost was about equal to the initial cost of an original tin roof and one maintenance painting. Additional long-term savings will also be realized.

During construction, insect damage to some of the members at the portals was discovered, as was hidden rot. The areas around the masonry abutments were treated against insect attack, and a covering of the abutment wings was fashioned by using siding and the stainless-steel roofing material to guard against the infiltration of water.

All new timber used in the restoration was given a dual pressurized treatment of a preservative and a fire retardant that would not alter the appearance of the wood. The existing material left in place was given several coats of a clear fire-retardant varnish that slightly darkened the old timbers. Oak plank wearing strips were placed over the deck panels and the bridge was once again ready for service (see Figures 13 and 14).

Three years after the fire the Meem's Bottom Covered Bridge was reopened with a 7.3-t (8-ton) posted capacity at a final restoration cost of $240 000 and carried its first official vehicle, a farm wagon pulled by a team of horses.

ACKNOWLEDGMENT

The contributions of Emory Kemp and Charles E. Daniels of the Department of Civil Engineering, West Virginia University, are gratefully acknowledged. Without the services provided by these consulting engineers and the information in their report (1), much of our report would not have been possible. The assistance of Ray Schutz, formerly with Sika Chemical Corporation, in developing the epoxy and wood-flour compound used in the repair is gratefully acknowledged. The assistance of the Virginia Highway and Transportation Research Council in the preparation of this report is also greatly appreciated.

This restoration project has received the first-place award for the Environmental Preservation and Enhancement category of the U.S. Department of Transportation's Federal Highway Administration biennial awards program for Excellence in the Design of Highway Facilities.

Without the outstanding assistance of the personnel of the Bridge Design Section and the Edinburg Residency of the department's Staunton District, the successful restoration of the Meem's Bottom Covered Bridge would not have been possible. We wish to dedicate this paper to the engineers and their staffs who worked so diligently to bring about the successful completion of a most perplexing and difficult project.

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Commercial Vehicle Trip Generation in Chicago Region

DAVID A. ZAVATTERO AND SIDNEY E. WESEMAN

The results of an analysis of the relation between commercial vehicles and trip generation are presented. The analysis is aggregative and intended to be compatible with conventional urban transportation planning models. Relations between the volume of truck traffic generated (or attracted) to subareas of the Chicago region are estimated based on the land use characteristics of the area. Separate regression models for light-, medium-, and heavy-sized trucks and for six basic land use types are presented. The variation in truck trip generation across these categories is examined and the implications for urban goods movement modeling at the regional level are discussed.

The problem of urban goods movements has only lately begun to receive the attention that it deserves from transportation planners. Several conferences (1,2) have dealt with the problem, and a number of regional transportation studies have attempted data collection and/or modeling of goods or commercial vehicle movements. Significant improvement in the performance of the urban transportation planning process can be expected once goods traffic is successfully modeled. It has also been argued (3-5) that goods movements can be modeled in parallel fashion to the current treatment of person movements. This paper examines the problem of goods trip generation as a step toward such a comprehensive scheme for goods movements.

TRIP GENERATION MODELS FOR URBAN GOODS MOVEMENTS

A fundamental requirement of the transportation planning process is the estimation of the traffic generated by particular land uses. Since our interest is in goods movement generation by particular land uses, three points deserve mention. First, we must distinguish between the generation of shipments (or consignments) and the generation of commercial vehicle trips. Though the factors that influence both are likely to overlap, the magnitude of their effects and the form of the relation may differ. Second, we must consider the level of areal aggregation of the activities whose generation characteristics we wish to describe. Clearly, as we lower the level of aggregation and therefore obtain zones of an increasingly homogeneous nature, it becomes easier to isolate the important factors and possible to examine the effect of activity type on goods generation. To obtain this additional accuracy, however, we must sacrifice some degree of data availability and predictability. Finally, we should note that mode choice is one of the principal issues that complicates generation analysis. The technique of expressing generation properties as a function of land use parameters alone should be reserved for situations in which alternative modes do not exist or where the choice appears in simplified form. The truck being the only mode available for most urban freight movement (especially in the short run), we are able to concentrate attention on land use parameters for estimating goods-generation characteristics.

DATA

The analysis is aggregative in that it deals with zonal subareas of the region rather than with individual establishments. The eight-county northeastern Illinois and northwestern Indiana region, an area of approximately 5000 miles² and more than 8 million population, is subdivided into 64 districts. These districts are arranged in a ring-sector pattern around the Chicago central business district (CBD) and get progressively larger in area and less dense in development as distance from the CBD increases.

Truck travel data are provided by the Chicago Area Transportation Study (CATS) commercial vehicle survey (6). This survey consists of a 1 percent overall sample of all registered commercial vehicles in the Chicago region. Land use and employment data were provided by the Northeastern Illinois Planning Commission and the Northwestern Indiana Regional Planning Commission.

Truck trips to each district are stratified by vehicle size and land use at the destination. Truck types used in the analysis are (a) light for pickup and panel trucks (under 10 000 lb gross vehicle weight), (b) medium for other single-unit vehicles, and (c) heavy for tractor-trailer units (more than 36 000 lb). The following generalized land use categories are used: residential, manufacturing, commercial, public building, public open space, transportation-communications-utilities (TCU), and other developed land. Land area and employment are taken as measures of activity.

Regression analysis is chosen as the appropriate technique to develop the truck-trip-generation models. Districts are chosen as the geographic analysis unit at this stage primarily for the ease with which these data can be obtained and the manageable number of zones that result. The desired accuracy of the specific study should determine the degree of geographic detail. In the next section we examine the relation between truck trip and land use in general terms.

TRUCK TRIP CHARACTERISTICS

As seen in Table 1, there were more than 219 000 commercially registered vehicles in the Chicago region in 1970. The majority of these were classified as light trucks. Commercial vehicles made more than 1.2 million trips on the average day. The highest trip rates per vehicle were generated by the medium-class trucks, which are the vehicles typically used in the majority of urban pickup-and-delivery movements. These trucks also had the shortest average trip length, which indicates many zone-type trips. These trips represent travel within designated pickup or delivery zones with one or more return stem trips to the terminal. In contrast, the larger heavy-class vehicles average trip was nearly three times longer, which implies a somewhat different operation pattern for these trucks. Three-fourths of the registered vehicles are used for at least one round trip on the typical day.

Some basic characteristics of the relation between truck trip generation and land use are discernible in Table 2, which presents truck-trip-generation rates per hundred acres by land use category. An understanding of the functional relations that underlie this truck traffic is obtained by examining the wide variation in generation rates for different types of activities.

Of the nearly one million acres of developed land in the region, more than a third is devoted to residential land uses. However, residential land is a very low generator of commercial vehicle trips. As expected, public open space also generates relatively few truck trips. Public buildings generate commercial vehicle trips at a rate of 40 daily trips/100 acres, which is the approximate average for all types of land.

Table 1. Commercial vehicle survey summary.

Commercial Vehicle Type	No.	Percent	Daily Trips	Avg Use Rate (%)	Avg Daily Trips	Avg Trip Length (miles)
Light	118 653	54.0	479 210	76.0	4.0	5.5
Medium	80 887	36.8	622 507	70.4	7.7	3.9
Heavy	20 152	9.2	129 296	77.6	6.4	11.1
Total	219 692		1 231 473	74.1	5.6	5.3

Table 2. Commercial vehicle trips by land use.

Land Use Type	Commercial Vehicle Trips (%)	Commercial Vehicle Trips per 100 Acres
Residential	34.8	12
Manufacturing	12.2	361
Commercial	37.6	1425
Public building	2.6	40
Public open space	0.4	3
Transportation-communications-utilities	9.0	116
Other	2.2	15
All developed	98.8	130
Undeveloped	1.2	0.7

The heaviest generators are commercial, manufacturing, and TCU activities. These are the types of land uses that require large supplies of goods and ample freight transportation. Altogether, commercial and manufacturing activities attract nearly 50 percent of total commercial vehicle trips. These activities exhibit the highest truck-trip-generation rates with 1425 trips/100 commercial acres and 361 truck trips/100 manufacturing acres. Furthermore, the truck trips to manufacturing destinations are much more likely to be made by heavy vehicles. Overall, the breakdown of truck trips by weight category is 38.9 percent light, 50.6 percent medium, and 10.5 percent heavy. Commercial lands exhibit approximately the same distribution of trips by truck type as the overall category. The distribution of truck types for trips to manufacturing, however, is significantly higher, with 27.8 percent going to heavy vehicles and with light and medium trucks accounting for 25.6 and 46.5 percent, respectively. TCU land also generates a substantial amount of truck traffic and these are again weighted in favor of heavy vehicles. TCU land includes terminal and warehousing activities associated with the urban pickup and delivery aspects of freight distribution.

MODEL CALIBRATION AND RESULTS

We now consider several regression equations that quantify the relation between truck trip generation and land use and are presented in Table 3. The following notations are used for the equations in Table 3:

TTTOT = total truck trips to all land uses,
TOTEMP = total employment,
DEVLU = developed land use,
TTRES = total truck trips to residential areas,
DU = dwelling units,
RESLU = residential land use,
TTMAN = total truck trips to manufacturing areas,
MANLU = manufacturing land use,
MANEMP = manufacturing employment,
TTCOMM = total truck trips to commercial areas,
COMLU = commercial land use,
COMEMP = commercial employment,
TTPB = total truck trips to public buildings,
PBLU = public building land use,
TTTCU = total truck trips to TCU areas,
TCUEMP = TCU employment,
LTTOT = light-truck trips to all land uses,
LTRES = light-truck trips to residential areas,
LTMAN = light-truck trips to manufacturing areas,
LTCOMM = light-truck trips to commercial areas,
LTPB = light-truck trips to public buildings,
LTPOS = light-truck trips to public open spaces,
LTTCU = light-truck trips to TCU areas,
MTTOT = medium-truck trips to all land areas,
MTMAN = medium-truck trips to manufacturing areas,
MTCOMM = medium-truck trips to commercial areas,
MTTCU = medium-truck trips to TCU areas,
HTTOT = heavy-truck trips to all land areas,
HTMAN = heavy-truck trips to manufacturing areas,
HTCOMM = heavy-truck trips to commercial areas, and
HTTCU = heavy-truck trips to TCU areas.

Note that this analysis deals with truck trip destinations within each district. Of course, these destinations are simply the reverse end of the trip origins and this definition balance allows us to concentrate on the analysis of either trip end without substantially affecting the results. Separate regression equations were formulated for each truck type (stratified by weight class) and for total truck trips to the districts. Further, commercial vehicle trips within each truck-type class were subdivided by the type of land use at the destination. In some cases this classification scheme resulted in categories with no (or very few) trips, as in the heavy-truck trips to residential land uses category. Where this happened, it was not possible to run meaningful regression models; thus none were attempted.

In each case but one the estimated regressions were significant at the 0.1 level. In addition, the coefficient of variation is less than 1.00 in all but one case, although some equations display significantly lower variation about the estimated line than others. Of course, the lower the coefficient of variation, the more confident one can be about using the equation for forecasting. Undoubtedly, the fact that these equations are based on district level aggregations, which therefore include wide variations in both the dependent and independent variables, causes the standard error of estimate (and the coefficient of variation) to be higher than it would be with smaller, more homogeneous zones. This suggests that some improvement could be obtained by further analysis at the traffic-zone level.

The most significant total truck models were obtained for trips to all land uses and to manufacturing, commercial, and residential land uses. Total truck trips to all land uses, TTTOT, is best explained when related to total district employment (Equation 1). This model exhibits an R^2 of 0.50, which is significantly higher than the 0.40 displayed in Equation 2. A regression model that relates TTTOT to total district land was estimated but the results were very poor, primarily due to the

Table 3. Truck trip generation equations.

Equation No.	Equation	n	R^2	F	Coefficient of Variation (%)
Total Truck Models					
1	TTTOT = 4573.0 + 33.8 TOTEMP	62	0.50	59.2	51.0
2	TTTOT = 9726.8 + 84.4 DEVLU	63	0.40	40.8	52.0
3	TTRES = 416.7 + 16.0 DU	64	0.37	36.6	-
4	TTRES = 2288.1 + 77.4 RESLU	64	0.37	36.1	-
5	TTRES = 1078.6 + 56.5 RESLU + 11.7 DU	64	0.54	36.0	-
6	TTMAN = 881.8 + 302.8 MANLU	61	0.45	47.4	69.0
7	TTMAN = 730.6 + 9.7 MANEMP	64	0.58	85.4	-
8	TTCOMM = 4885.1 + 168.5 COMLU	61	0.22	16.7	59.0
9	TTCOMM = 2252.7 + 23.7 COMEMP	62	0.50	59.0	45.0
10	TTPB = 112.6 + 73.6 PBLU	64	0.43	47.4	-
11	TTTCU = 1384.1 + 10.3 TCUEMP	64	0.21	16.2	91.0
12	TTTCU = 995.5 + 387.05 ln(TCUEMP)	64	0.30	27.1	85.0
Light-Truck Models					
13	LTTOT = 2427.9 + 11.92 TOTEMP	62	0.32	27.3	67.5
14	LTTOT = 2918.5 + 41.03 DEVLU	63	0.50	60.5	57.5
15	LTRES = 762.7 + 5.43 DU	63	0.21	16.4	94.4
16	LTRES = 631.3 + 40.26 RESLU	63	0.50	60.2	75.5
17	LTRES = -188.8 + 35.38 RESLU + 2.86 DU	63	0.55	36.3	71.9
18	LTMAN = 163.4 + 96.16 MANLU	50	0.48	38.8	73.3
19	LTMAN = 253.8 + 2.10 MANEMP	64	0.25	21.2	98.3
20	LTCOMM = 1112.2 + 9.76 COMEMP	61	0.31	27.0	61.6
21	LTPB = 196.5 + 20.92 PBLU	42	0.17	8.0	61.6
22	LTPOS = 95.5 + 4.39 POSLU	14	0.50	11.9	67.1
23	LTTCU = 279.3 + 7.77 TCUEMP	48	0.65	84.8	61.7
Medium-Truck Models					
24	MTTOT = 2117.6 + 17.65 TOTEMP	62	0.41	41.3	63.4
25	MTTOT = 6232.6 + 29.76 DEVLU	64	0.18	13.5	74.3
26	MTMAN = 933.5 + 31.01 MANLU	61	0.07	4.3	96.3
27	MTMAN = 257.6 + 5.11 MANEMP	61	0.55	69.9	67.5
28	MTCOMM = 2492.1 + 3.60 COMEMP	64	0.34	32.6	61.9
29	MTTCU = 540.6 + 11.51 TCULU	62	0.16	11.7	94.1
Heavy-Truck Models					
30	HTTOT = 835.2 + 3.1 TOTEMP	62	0.20	14.6	84.0
31	HTMAN = 255.8 + 28.2 MANLU	60	0.47	51.9	63.0
32	HTMAN = 271.6 + 2.3 MANEMP	61	0.54	70.6	52.0
33	HTCOMM = 515.7 + 18.9 COMLU	61	0.17	12.2	81.0
34	HTCOMM = 305.7 + 2.2 COMEMP	62	0.18	13.5	81.0
35	HTTCU = 390.4 + 10.5 TCUEMP	59	0.21	15.4	102.0

Note: All equations except 26 significant at the 99 percent level by the F-test.

inclusion of substantial quantities of undeveloped land in the total land area measure.

Stratification of the trips by type of land use improved the results in the residential, manufacturing, and commercial categories over those obtained for the unstratified sample. Previous research has indicated that a homogeneous land use classification scheme was necessary for reliable truck-trip-generation models. It may be possible to improve the results by further disaggregation of these land use classes. Total truck trips to manufacturing activities, TTMAN, are best explained when related to manufacturing employment in the district (Equation 7). Employment at commercial sites also provides the most significant results for trips to commercial activities (Equation 9). In fact, it is only for the public building activities that land area performed better than employment in estimating these truck trip destinations. Interestingly, while TCU employment also provides the best estimates of total truck trips to TCU activities, the form of this relation is nonlinear (Equation 12). That is, there are apparently significant economies of scale in TCU truck trip generation at the aggregate level. This may be due to the fact that zones with large TCU employment include concentrations of commercial vehicle terminals and these transportation businesses are relatively more efficient in the use of their vehicles. For total truck trips to residential land, TTRES--a multiple linear regression that incorporates residential land area and number of dwelling units--provides the best results (Equation 5). Thus, for the more heavily freight-oriented activities, employment is seen to provide reasonable estimates of total truck trip ends while for the residential and public building uses land area measures were more significant.

Models were also specified and estimated for truck trips classified by type of vehicle, and these are also presented in Table 3 for light (Equations 13-23), medium (Equations 24-29), and heavy trucks (Equations 30-35). Examination of these results reveals several interesting points. Total employment continues to yield the best results for all truck-size categories in estimating truck trips to unstratified land use. However, the relation between heavy trucks and total employment (Equation 30) is considerably weaker than this equation is for other truck types. This supports the contention that subdivision of land use types would improve the results, particularly for the heavy-vehicle class. In fact, when heavy trucks to manufacturing activities are related separately to manufacturing employment (Equation 32), the results were much improved over the unstratified model. The relation between light trucks and manufacturing land area was most significant (Equation 18). This was not the case for medium trucks, where manufacturing land area yielded very poor estimates of medium-truck trips to manufacturing (Equation 26). Further research is needed to determine what factors may account for this finding.

There were very few medium- and heavy-truck trips to residential land areas; thus no regression equations could be estimated. Nearly 50 percent of the truck trips to residential land were made by light vehicles. Several equations for light trucks to residential activity were estimated (Equations 15-17). Again, the multiple regression with residential land area and dwelling units proved to be the best model and slightly improved the results obtained for total truck trips to residences.

The subdivision of truck trips by vehicle type did not improve the results in any case for trips to commercial land areas. Commercial employment provided the best-fitting models, although the relation for heavy vehicles was poor. This may indicate that further subdivision of the commercial category is needed in dealing with heavy trucks, since it is obvious that the retail, wholesale, and service activities now included in this aggregate category display substantial differences in the movement of goods that require heavy trucks. For the medium-truck class the best results were obtained when commercial employment was used as the explanatory variable (Equation 28). Finally, the sparse sample of medium and heavy trips to public buildings and public open space land prevented estimation of relations for these categories. Light-truck trips to these land uses, however, were significantly explained by public building and public open space land area, respectively (Equations 21 and 22).

SUMMARY AND CONCLUSIONS

The results obtained even at this rather aggregate level of analysis exhibit sufficient significance to warrant continued effort at a finer level of detail, both spatially and in land use categories. For most models, the statistical tests yielded positive results and support the adoption of this methodological framework for commercial vehicle trip generation analysis. The significant and regular variation in the truck trips per developed land acre and trips per employee ratios as distance from the CBD varies may indicate that adding an access measure to the models would improve their performance. The addition of zonal industrial composition may also improve the results. Such a measure would account for external economies that arise from similar activities being located next to each other and thereby affect their freight-transportation characteristics.

The overriding determinant of truck-trip-generation characteristics, however, remains the type of activity in the zone. We have observed substantial improvement over the unstratified results when trips were subdivided by type of activity. This was particularly evident in the total truck models but also appeared to a lesser degree in the models for individual truck types. In general, the weight-classification scheme for vehicle type did not seem to yield improved results. Except for the heavy-truck trips to manufacturing activities, better results were obtained with the total truck models. This preliminary finding, however, does not justify elimination of this truck-type factor from further consideration in the generation analysis. Because heavy and medium trucks tend to concentrate service to freight-oriented industries, future work will be devoted to analyze these heavy-freight generators. Finally, this analysis has proved encouraging and should be continued with effort devoted to resolving some of the problems that remain.

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Service and Supply Trips at Federal Institutions in Washington, D.C., Area

FRANK SPIELBERG AND STEVEN A. SMITH

Knowledge of the number and time distribution of goods and service trips is essential for the proper planning of dock and parking facilities at large employment sites. Federal office buildings in Washington, D.C., are typical of many large office complexes, particularly those of state governments. Federal warehouse operations have characteristics similar to those of large distribution centers. The results of a survey of goods and service vehicle trips to federal facilities in the Washington metropolitan area are presented and suggest specific guidelines for the planning and operation of similar facilities. Data were collected on vehicle trips that involved a service or supply function at 10 federal facilities in the Washington area. By using a combination of on-site observation and driver interviews, data on arrival and departure times, vehicle characteristics, trip purpose, origin of trip, and nature and size of load were obtained, analyzed, and used to develop planning guidelines.

Although the charge to analyze goods movements has been with urban transportation planning agencies since 1962, it was only in the 1970s that substantial attention was devoted to the issue. This period saw not only the undertaking of significant studies by several local planning groups but also

Table 1. Sites selected for service and supply trip surveys.

Site	Location	Type of Operation
Cameron Station	Northern Virginia	Military warehousing and supplies
Department of Commerce	Washington CBD	Government offices
GPO	Washington CBD	Printing
GPO, Eisenhower warehouse	Northern Virginia	Bulk document distribution
GPO, Franconia warehouse	Northern Virginia	Paper supply
NBS	Maryland	Offices, research
National Park Service	Washington	Maintenance depot
NRL	Washington, outskirts	Offices, research
Pentagon	Northern Virginia	Military offices
VA hospital	Washington, outskirts	Hospital

new research at the federal level. These federal studies included Urban Mass Transportation Administration (UMTA) research on problems and opportunities in urban goods movement and the preparation for the Federal Highway Administration (FHWA) of a handbook on planning for urban goods movement.

As a result of these efforts a body of knowledge has begun to develop on the size of the urban goods problem. Data on delivery and service-trip-generation rates have been assembled and a start has been made toward the development of planning standards.

In the Washington, D.C., metropolitan area, planning for the largest employer--the federal government--is overseen by the National Capital Planning Commission (NCPC). To improve the planning for federal installations NCPC commissioned a study of service and supply trips. The data from this study, presented here, provide guidance on goods movement requirements at similar sites.

STUDY METHODOLOGY

NCPC has, over the last several years, been conducting the federal transportation study. Phase 4 of the study consists of an assessment of trips to federal government installations by tourists, visitors, and service and supply vehicles. The purpose of the study is to determine current and future requirements at government facilities for serving such trips.

The study reported on here concerns the service and supply trip element of the NCPC study. For purposes of this study, service and supply trips were defined as trips in which a service was performed (e.g., repairing office equipment, work utilities, etc.) or in which some type of commodity was either picked up or delivered. Thus, the study considered trips that may have been made in vehicles other than trucks.

Site Selection

Sites were selected by using general site selection criteria, which include the following:

1. Geographic location,
2. Type of operation,
3. Size of operation, and
4. Feasibility of conducting the surveys.

The application of the above criteria resulted in the 10 selected sites shown in Table 1.

Data Collection

Data were collected on service and supply trips during the summer 1979. Interviewers were stationed at each location at a particular building where service and supply trips were expected. The observers were responsible for identifying those vehicles that arrived at a building that were performing a service or supply function. There were very few instances where this could not be easily done. However, the vehicle had to be marked with a company name or other identifier to be included. The observers recorded information on vehicle type, whether it was government owned, arrival and departure time, and parking location, and questioned the driver in regard to origin of trip, trip purpose, and specific commodities carried or service to be performed. In many cases, some of the driver interview questions could be observed directly.

Obtaining sufficient origin information proved to be a fairly difficult task. First, drivers were often reluctant to give any information whatsoever, and when information was given, it was very general. Most often, it was given in the form of a large geographic area (e.g., Largo, Maryland).

OVERVIEW OF FINDINGS

As would be expected in a small sample of this type, there was significant variation among the sites in the nature of goods movement activity, the types of vehicles used, number of goods-related trips, and the duration of stay. For each site surveyed an individual data sheet was prepared. These showed the percentage distribution of

1. Vehicle type,
2. Government owned versus private,
3. Time of arrival,
4. Duration of stay,
5. Purpose of visit,
6. Type of commodity, and
7. Weight of commodity.

At warehouse-distribution facilities, semitrailers tend to predominate. At all other facilities the majority of deliveries are by van or single-unit truck. However, all facilities surveyed received at least a portion of deliveries by semitrailer, which indicates a need to provide for such vehicles in site design. Privately owned vehicles accounted for most of the goods movement activity at all sites, and much of the government-owned vehicle activity was related to mail.

All sites, whether city, suburban, office, or warehousing, show peak arrival activity between 8:30 and 9:30 a.m. Arrivals are high throughout the morning hours but decline sharply about noon. At all sites a secondary peak occurs just after lunch. Arrivals after 4:00 p.m. are rare.

The duration of stay is a function of the type of activity performed and the facilities visited. For warehouse-distribution sites, trucks tended to remain for extended periods that averaged almost 1.5 h. The duration of stay at office sites showed considerable variation, which ranged from 18 to 51 min. For the typical office site the mean duration was 30-35 min.

Except for the Government Printing Office (GPO) on North Capitol Street, which is a distribution site, more than one-half the trips at all locations

Table 2. Summary of service and supply trip generation rates.

Site	Daily Trips	Employees No.	Employees Trip Rate[a]	Occupiable Space Square Feet (000s)	Occupiable Space Trip Rate[b]	Loading Docks No.	Loading Docks Trip Rate[c]
Cameron Station	128	3 330	0.038	835	0.153	-	-
Department of Commerce	91	4 790	0.019	1019	0.089	8[d]	11
GPO, North Capitol	265	5 350	0.050	952	0.278	18[d]	15
GPO, Franconia	21	17	1.235	148	0.142	3	7
GPO, Eisenhower	19	178	0.107	102	0.186	4	5
Hoffman Building	34	4 800	0.007	776	0.044	4	9
NBS	65	3 160	0.021	1319	0.049	10[d]	7
National Park Service	104	117	0.889	-	-	-	-
NRL	63	4 350	0.014	1550	0.041	-[e]	-[e]
Pentagon	219	23 200	0.009	3784	0.058	≥15	15
VA hospital	26	1 650	0.015	387	0.067	4	7

[a]Trips per employee.
[b]Trips per 1000 ft².
[c]Trips per loading dock.
[d]Approximate.
[e]Unknown.

Table 3. Summary of truck trip generation rates.

Site	No. of Trips	No. of Trucks	No. of Employees	Square Feet (000s)	Trip Generation Rate: Truck Trips per Employee	Truck Trips per 1000 ft	Total Trips per 1000 ft
Cameron Station	128	125	3 330	835	0.037	0.149	0.153
Department of Commerce	91	66	4 790	1019	0.014	0.065	0.089
GPO, North Capitol	265	175	5 350	952	0.033	0.184	0.278
GPO, Franconia	21	17	17	148	1.0	0.115	0.142
GPO, Eisenhower	19	14	178	102	0.078	0.137	0.186
Hoffman Building	34	32	4 800	776	0.007	0.041	0.044
NBS	65	54	3 160	-	0.017	-	-
NRL	63	56	4 350	1550	0.013	0.036	0.041
Pentagon	219	175	23 200	3784	0.008	0.046	0.058
VA hospital	26	11	1 650	387	0.007	0.028	0.067

Table 4. Representative time distributions of arrivals.

Time	Percentage of Arrivals: GPO, North Capitol	NBS	NRL	Pentagon	Cameron Station
7:00-8:00 a.m.	3	4	6	10	9
8:00-9:00 a.m.	10	4	8	12	14
9:00-10:00 a.m.	20	15	20	18	17
10:00-11:00 a.m.	23	22	18	18	12
11:00 a.m.-noon	15	9	17	12	13
Noon-1:00 p.m.	5	0	7	4	8
1:00-2:00 p.m.	9	12	9	6	10
2:00-3:00 p.m.	8	16	10	10	8
3:00-4:00 p.m.	7	15	5	5	9
4:00-5:00 p.m.	0	3	0	2	0

involved deliveries. On average, about 10 percent of the truck trips to office activities involved service calls.

SPECIFIC RESULTS OF SERVICE AND SUPPLY SURVEY

Classification of Sites

Sites surveyed are of three basic types. The following sites have characteristics that are primarily office: Department of Commerce, Hoffman Building, National Bureau of Standards (NBS), Naval Research Laboratory (NRL), Pentagon, and Veterans Administration (VA) hospital.

Characteristics of terminal-warehouse facilities are found at Cameron Station (also includes substantial office functions); GPO warehouse, Franconia; and GPO warehouse (Eisenhower, although slightly different due to the high proportion of deliveries).

GPO on North Capital Street has characteristics of both office and warehouse facilities. The VA hospital also has unique characteristics but is included in the office category.

The National Park Service Maintenance Depot is a garage facility. It is unlike any of the other sites as its primary function is the storage of vehicles.

For planning purposes, the items of interest in the analysis of plans for federal installations are

1. Number of truck trips,
2. Time-of-day distribution of trips,
3. Size of loads,
4. Vehicle type, and
5. Duration of stay.

Items 1 through 4 are required for site impact analysis. Items 1 through 5 are required for design of loading facilities. In the following discussion we present summaries of the data together with some suggested planning guidelines.

Trip Generation Rates

As would be expected in a small sample of this type, there was considerable variation among the sites in the nature of the goods movement activity. Table 2 summarizes service and supply trip generation rates for the sites surveyed. The survey data indicate substantial variation in the rate of service and supply trips per employee or gross (occupiable) square feet. However, as shown in Table 3, when surveyed trips by vehicles other than trucks are deducted, a pattern does emerge.

For office-type facilities the number of truck trips seems best related to the number of employees, as shown in the table below:

Location	Truck Trips per Employee
Commerce Department	0.014
NBS	0.017
NRL	0.013
Pentagon	0.008
Hoffman Building	0.007
VA hospital	0.007

The range is from 0.007 to 0.017 truck trips/day per employee, with a suggested tendency for the rate to drop with a larger facility (e.g., Pentagon). The Hoffman Building may have special characteristics that lead to the observed low rate.

The range is considerably lower than the rate for office space of 0.05/employee (based on 2.0/10 000 ft^2), which is suggested in the report on urban goods movement prepared by FHWA. This may be a result of the special nature of government work. Government installations, because of their size, tend to make the consolidation of service and supply functions much easier than in the private sector. This was observed in the course of the surveys as a single Government Services Administration (GSA) truck would often deliver days or weeks worth of certain types of supplies for a large number of employees. A value of 0.013/employee would seem appropriate for planning purposes.

For warehouse-type facilities the truck trip rate seems best related to square footage, as shown in the table below:

Location	Truck Trips per 1000 ft^2
Cameron Station	0.149
GPO, North Capital	0.184
GPO, Franconia	0.115
GPO, Eisenhower	0.137

The range is from 0.115 to 0.184. A value of 0.15 truck trips/day per 1000 ft^2 would be appropriate for planning.

Time of Day

The time-of-day distribution of truck arrivals shows a consistent pattern for the sites surveyed. There is little activity prior to 8:00 a.m. Most loading facilities maintain regular 8-h/day working hours. During the morning, arrivals per hour are roughly constant. A distinct drop is observed from 11:30 a.m. to 1:30 p.m. Afternoon arrivals are at a lower rate than morning arrivals, falling rapidly after 4:00 p.m.

The time distributions of arrivals shown in Table 4 are those observed at several sites of varied character and location. The distributions are representative, rather than typical, of the surveyed installations.

The single peak hour occurs in the morning--roughly between 9:30 and 10:30 a.m. Approximately 20 percent of all arrivals occur in this interval. A planning parameter of 25 percent will ensure that adequate loading space is provided.

Size of Load

The typical load size varies with the character of the installation. The table below presents the proportion of commodities greater than and less than 100 lb:

Site	Percentage of Commodities <100 lb	>100 lb
Department of Commerce	60	40
Hoffman Building	43	57
NBS	61	39
NRL	37	63
Pentagon	44	56
VA hospital	65	35
GPO, North Capital	74	26
Cameron Station	32	68
GPO, Franconia	19	81
GPO, Eisenhower	27	73

This weight is used as a breakpoint because it represents the division between hand carried and other types of loads.

No clear pattern can be discerned in these data as to the load size to be expected. What can be said is that at all sites the proportion of loads exceeding 100 lb is sufficiently great that provision must be made to accommodate such loads.

Type of Vehicle

The type of vehicle used to make deliveries affects not only the design of loading space but also the impact of truck trips on surrounding streets. Table 5 presents the observed distribution by vehicle type. Perhaps the only inference that can be drawn from these data is that shippers do not use semitrailers for deliveries to downtown locations. The lowest proportion of semitrailer trips was observed at the downtown facilities (Department of Commerce and GPO, North Capitol). The low proportion observed at the Pentagon may be a function of either the type of delivery or the loading-dock facilities. As it is generally more efficient for shippers to use larger vehicles, this suggests the need for NCPC to assure that loading areas and approaches to loading areas provide adequate space for semitrailers.

Duration of Stay

The duration of stay of vehicles is a critical measure in the design of loading facilities. Sufficient space must be provided to accommodate the maximum accumulation of vehicles. Observed duration at the survey is a function of the number of trips, existing loading facilities, type of commodity, initial operation of the installation, and management practices. A central-receiving function that obviates the need for drivers to deliver to individual locations within buildings will substantially reduce time at the loading dock and promote more-efficient use of dock space.

For the facilities surveyed the mean duration of stay ranged from a low of 18 min at NBS to a high of 86 min at the GPO, Franconia, as shown in the table below:

Location	Mean Duration of Stay (min)	Percentage of Load More Than 100 lb
NBS	18	39
Hoffman Building	26	57
GPO, North Capitol	27	26
Department of Commerce	29	40
NRL	39	63
VA hospital	39	35
Pentagon	51	66
GPO, Eisenhower	28	73
Cameron Station	79	68
GPO, Franconia	86	81

For office-type facilities, the range is from 18 to 51 min with some slight indication that the variation is related, in part, to the preparation of deliveries that exceed 100 lb. An average of about 30 min should be useful for planning purposes. The larger value at certain locations suggests that the goods receiving and dispatching functions may not be organized or that loads have special characteristics.

For warehouse facilities that have both pick-up and delivery functions a duration of about 80 min was observed. The relatively short duration (28 min) at GPO, Eisenhower, appears to be a result of the fact that 84 percent of the truck arrivals were for delivery only. It is not clear if this pattern represents a typical day. The table above also lists the percentage of trips for which size of loads were more than 100 lb. The duration of stay could be logically related to size of load, but the data suggest only a moderate degree of correlation.

Table 5. Distribution of trips by vehicle type.

	Percentage of Service-Supply Trips by		
Location	Automobile, Pickup, and Van	Single-Unit Truck	Semi-trailer
Department of Commerce	74	22	4
Hoffman Building	28	35	37
NBS	41	45	14
NRL	33	46	21
Pentagon	59	36	5
VA hospital	58	42	0
GPO, North Capitol	63	28	9
Cameron Station	21	56	23
GPO, Franconia	18	15	67
GPO, Eisenhower	27	26	47

Table 6. Percentage of service and supply trips by purpose.

Location	Pick-Up	Delivery	Pick-Up and Delivery	Service Call	Service Call and Pick-Up and Delivery
Cameron Station	9	72	9	7	3
Department of Commerce	25	62	8	6	0
GPO, Eisenhower	5	84	11	0	0
GPO, Franconia	37	57	5	0	0
GPO, North Capitol	48	44	6	2	0
Hoffman Building	15	64	6	12	3
NBS	18	63	15	3	0
NRL	3	70	4	14	9
Pentagon	10	60	16	13	1
VA hospital	13	46	33	4	4

Vehicle Ownership

The table below lists the percentage of arriving vehicles that are government owned.

Location	Percentage of Government-Owned Vehicles
Cameron Station	8
Department of Commerce	44
GPO, Eisenhower	16
GPO, Franconia	14
GPO, North Capitol	42
Hoffman Building	32
NBS	34
NRL	6
Pentagon	35
VA hospital	8

The largest percentage of government vehicles was 44 percent at the Department of Commerce. The warehousing-type facilities tend to have the smaller percentage of government vehicles. From the data and from discussions with dock superintendents, it appears that much of the heavier goods movement operations are contracted out.

Purpose of Visit

Table 6 summarizes the purposes of service and supply trips to government facilities. In most cases, the data can be related to the type of operation. For example, the functions of the GPO, North Capitol, with the highest percentage of pick-up trips, is to print and deliver government documents. The incoming materials tend to come in bulk loads while the outgoing products are picked up in smaller quantities to be disseminated to diverse locations. Most of the other installations tend to be users rather than producers of goods and services and thus have high delivery percentages.

Types of Commodities and Services

Table 7 indicates the type of commodities and services that are primarily being dealt with at government installations. These percentages can also be related to type of operation involved. For example, GPO operations deal largely with paper products, which is reflected in the percentages. The types of commodities and services are reflected in the types of vehicles used, as discussed in a previous section.

Planning Guidelines

The observations of the service and supply survey suggest the following planning guidelines for federal office facilities:

1. 0.013 truck trips/day per employee,
2. 25 percent peak-hour factor (mid-morning), and

Table 7. Types of commodities and services.

	Commodities					Services			
Location	Mail and Trash	Food and Beverage	Hard Goods	Paper	Other	Utilities	Office Equipment	Vending Machine	Other
Cameron Station	5	30	38	2	12	5	1	4	3
Department of Commerce	16	7	38	30	4	1	0	0	2
GPO, Eisenhower	10	0	10	80	0	0	0	0	0
GPO, Franconia	14	5	0	81	0	0	0	0	0
GPO, North Capitol	14	4	6	59	12	1	2	0	2
Hoffman Building	20	33	0	9	6	0	20	0	12
NBS	11	15	63	2	5	2	0	0	0
NRL	11	7	43	6	3	7	16	3	3
Pentagon	11	9	36	26	2	5	1	1	9
VA hospital	12	20	56	4	0	4	0	4	0

3. 30-min mean duration.

Minimum space requirements may be estimated based on the above data. However, it is important to recognize that each site may have significantly different requirements due to particular functions contained, size of facility, and other factors.

For planning purposes it should be assumed that at least one-third of the vehicles will be semi-trailers. A minimum of one dock space should be provided for such vehicles, with 1 of 3 dock spaces designed for semitrailers in larger facilities.

The survey also suggests the following planning guidelines for federal warehouse facilities:

1. 0.15 truck trips/day per 1000 ft^2,
2. 25 percent peak-hour factor, and
3. 80-min duration.

The same qualifications in regard to the application of these data to facility planning as were mentioned for office facilities should be recognized. At least one-half of the dock spaces should be designed for semitrailers.

The guidelines above relate to design of the facility. Impact of truck traffic on adjacent streets is a function of the number of trips that occur during the peak hour of on-street traffic. As noted, truck activity prior to 8:00 a.m. is quite low. However, for certain locations pick-up and delivery activity between 8:00 and 9:00 a.m. may conflict with adjacent street traffic. The guidelines for these analyses are 12.5 percent for 8:00-9:00 a.m. deliveries and 0.8 vehicles/1000 employees for office and 0.025 vehicles/1000 ft^2 for warehouse-type facilities.

CONCLUSIONS

The data obtained in the survey and presented in this paper relate to a specific type of facility--federal employment sites in the Washington, D.C., area. The findings, therefore, are most applicable to these operations. However, federal government facilities in Washington have characteristics similar to those found in many large office centers, particularly those of state government. To this extent the findings will provide assistance to those involved in planning similar facilities.

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Direct and Indirect Energy Consumption by Chicago's Urban Trucking Industry

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A procedure for establishing a set of urban truck movement energy accounts is described. Direct energy consumption, in the form of truck fuel consumption, and indirect energy consumption on terminal, vehicle, roadway and fuel operation, maintenance, and construction are discussed. Another form of indirect energy consumption is the passenger vehicle fuel consumed due to truck-induced traffic congestion. The procedures are applied to an empirical study of the urban trucking industry in Chicago. Estimates are provided for the total direct and indirect energy consumed on an annual basis. By using a marginal approach to indirect energy accounting, both direct and indirect energy can be specified on a vehicle-kilometer or ton-freight kilometer of travel basis. Direct fuel energy consumption rates are compared across truck sizes, fuel, carrier and commodity types, time of day, and by base terminal district. Emphasis is given to the effects of truck route circuity on fuel consumption.

To date, very little work has been done to quantify the energy consumed by urban goods movement systems, despite the findings of the few studies available that indicate the potential for considerable energy savings in the urban trucking industry. In this paper we present an accounting framework for estimating such energy consumption and present the results from an application of the accounting procedure to the urban trucking industry in Chicago. The results are taken from a study by Southworth and others (1) for the Illinois Institute of Natural Resources, in cooperation with the Chicago Area Transportation Study (CATS). Since trucks move some 90 percent of all urban freight within our cities, we concentrated our analysis on this single mode.

Figure 1 shows the major data inputs required by our energy accounting procedures. The accounts pay particular attention to the distinction between "direct" fuel consumption energy and the "indirect" energy requested for system construction, operation, and maintenance. The indirect energy analysis is itself divided into three sections:

1. Infrastructure energy consumption (the energy required to operate, maintain, and renew vehicles, terminal facilities, and roads),
2. Fuel production energy consumption (the energy used in producing gasoline and diesel fuel for urban trucking), and
3. Congestion energy consumption (the additional fuel energy used by personal travel vehicles due to interaction with trucks in the same traffic stream).

On the transportation supply side we are concerned with the available terminal, roadway, vehicle, and fuel resources. On the demand side we are dealing with the interindustry demand for urban freight pickups, deliveries, and services. The manner in which carriers respond to this demand through investment in, and use of, their resources will determine the resulting pattern of truck movements at any given time. This pattern of pickups, deliveries, and service calls in turn determines the energy consumed by urban truck freight movements.

DIRECT ENERGY ACCOUNTS

Truck Travel Data

The data base used was the CATS internal commodities and commercial vehicles survey (2). This survey sampled some 5000 trucks that operate local and Interstate Commerce Commission (ICC) regulated contract and common carriage within the 800-km² Chicago standard consolidated statistical area (SCSA). The data constitute a 1.8 percent sample of trucks less than 8181-kg unloaded weight, rising to a 7.1 percent sample of heavy-truck trailers more than 16 363 kg. The complete survey provided 25 831 separate truck trip records, each factored for aggregate predictions by expansion factors based on the number of registered vehicles in the Chicago SCSA. The travel time and resulting average operating speed were identified for each trip in turn and the appropriate energy coefficient (in megajoules per kilometer) multiplied by the kilometers traveled between stops. This result was then stored for subsequent aggregation by the truck weight and fuel category, by commodity type, and by truck base terminal district.

In addition to this mobile vehicle direct energy consumption, a probably conservative 2-min idling energy cost was assigned to each trip. Truck trip distances were based on a set of x, y coordinates that point locate each terminal and pickup, delivery, and service location. These straight-line distances were factored by 1.2 to approximate over-the-road distances. Truck trip travel speeds were based on truck driver estimates of the time taken to travel between stops.

Direct Energy Consumption Coefficients

The second data input is a set of direct energy coefficients cross-classified by truck operating speeds, loaded truck weight, and fuel type used (gasoline or diesel). A review of the recent literature (3-9) indicates that distance traveled is the major determinant of direct fuel energy consumed, and the factors that affect the rate of energy consumption are as follows: (a) operating speed, (b) loaded vehicle weight, (c) fuel type (gasoline or diesel), (d) idling time, (e) truck body type (panel, pickup, semitrailer), (f) roadway conditions (lane number and width, grade, surface, curves), (g) traffic conditions (notably number of stops and starts due to congestion), (h) truck age, and (i) ambient air temperature. The approach adopted for computation of the direct energy consumption coefficients is based on the explicit interaction of factors a to c, plus factor d as an additional component, based on information in Winfrey (8, pp.

Figure 1. Urban freight energy accounts.

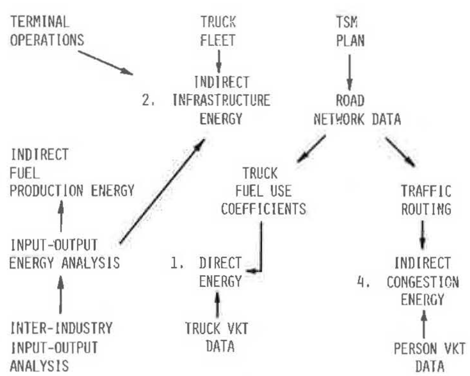


Figure 2. Direct energy consumption rates by speed and truck weight and fuel type.

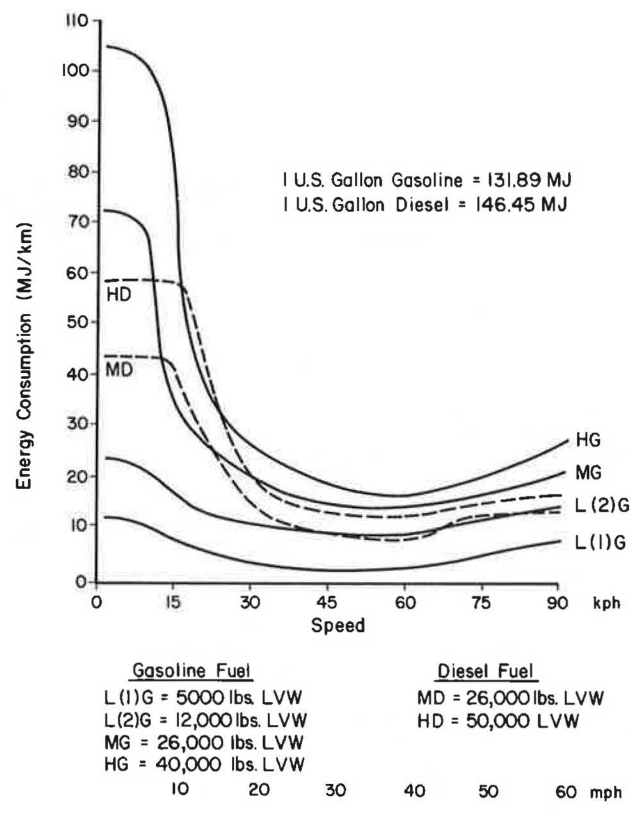
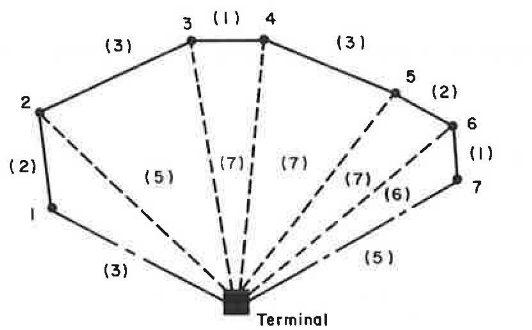


Table 1. Daily weekday direct energy consumption statistics by commodity class.

Commodity Class	Megajoules (000s)	Megajoules per VKT	Megajoules per Ton Kilometer of Travel	Avg Trip Distance (between stops)	Truck Route Circuity Factor	Route Stem/ Total VKT Ratio	VKT Peak Hours (%)
Empty	40 259	13.32	-	-	-	-	-
Farm, tobacco, fresh fish, and marine products	3 319	10.07	2.72	12.53	0.63	0.63	9.4
Food and kindred products	8 778	12.47	3.73	5.86	0.48	0.54	11.8
Metallic ores and ordinance	3 301	12.71	3.04	13.22	0.63	0.43	12.6
Nonmetallic minerals	12 717	15.28	1.07	18.28	0.63	0.48	10.7
Energy products	4 255	17.84	1.30	12.96	0.62	0.50	8.0
Forest products	2 887	12.68	4.54	13.38	0.13	0.68	16.5
Fabricated metals	11 937	9.92	4.20	10.05	0.09	0.57	16.0
Primary metals	7 047	17.66	2.05	8.97	0.40	0.44	10.4
Mixed shipments	4 473	13.63	4.10	8.89	0.40	0.52	20.8
Retail and wholesale products	7 661	10.62	6.21	8.12	0.12	0.49	12.2
Total	106 634[a]	12.90	3.6	9.3	0.36	0.59	13.6

[a]Round figure.

Figure 3. Example of truck route circuity factor.



Notes: ——— = actual route
- - - - - = hypothetical all-stem distance
— — — = coincidence of actual and hypothetical stem distance
4 = a truck pickup, delivery, or service stop
(3) = a trip distance (i.e. between consecutive stops)
Actual route distance = (3) + (2) + (3) + (1) + (3) + (2) + (1) + (5) = 20 km.
All-stem basis = [(3) + (5) + (7) + (7) + (7) + (6) + (5)] x 2 = 80 km.
TRC factor = 20/80 = 0.25.

705-723) and the road tests reported by Claffey (9). (No more recent, and equally comprehensive, set of figures on truck energy consumption could be obtained.)

Categorization of Direct Energy Accounts

Our direct energy consumption accounts are built around the important planning variables relevant to urban goods movement. These variables were identified as (a) truck type, (b) fuel type, (c) commodity type, (e) base of terminal operations, (f) truck route, (g) carrier type, and (h) time of day of operation. Noting that it is through the combined effects of these variables that the total direct energy account of the region is determined, we will now consider briefly the main energy consumption impacts of each variable in turn.

The effects of both truck loaded vehicle weight (LVW) and fuel type are shown in Figure 2. The breakdown of all truck categories by LVW and fuel type is as follows: light (1) gasoline [L(1)G] = 2272 kg, light (2) gasoline [L(2)G] = 5454 kg, medium gasoline (MG) = 11 818 kg, heavy gasoline (HG) = 18 181 kg, medium diesel (MD) = 11 181 kg, and heavy diesel (HD) = 22 727 kg. For subsequent accounting, trucks were assigned to the following LVW and fuel categories by using the appropriate curves shown in Figure 2: (a) 3636-kg gasoline, (b) 3636- to 7272-kg gasoline, (c) 7272- to 16 363-kg gasoline, and (d) 16 363-kg diesel.

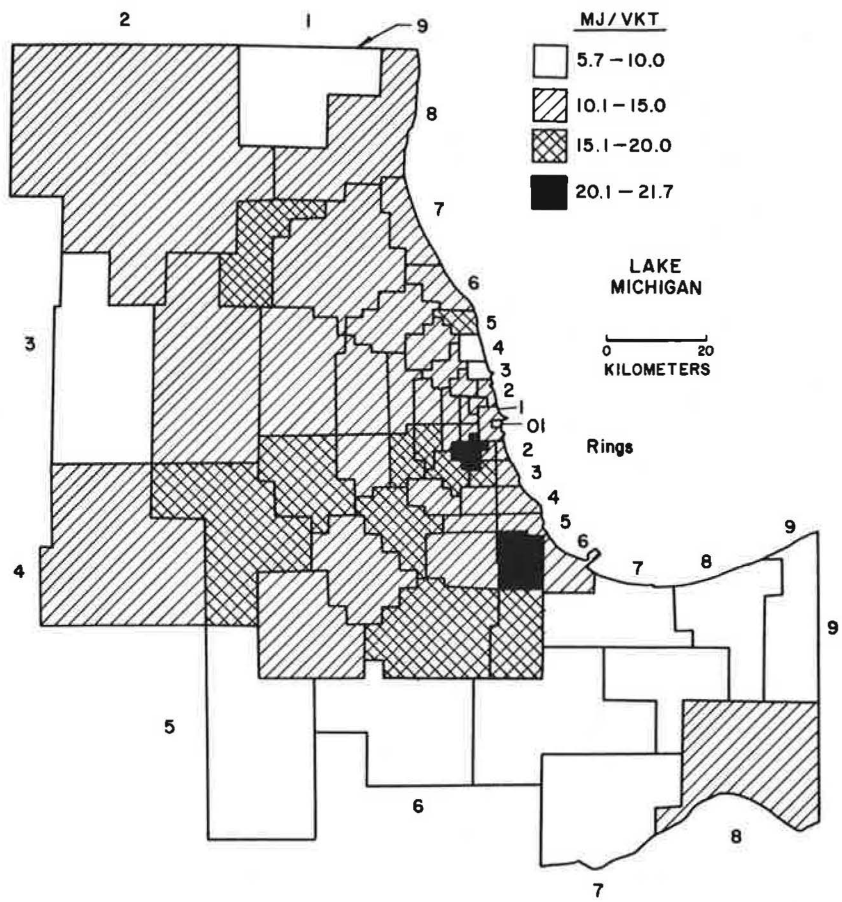
The type of commodity being moved affects energy consumption through both its physical attributes (notably volume-to-weight ratio and perishability) and the type of delivery schedule it requires. In our present study the sampling allowed only the relatively crude 11 commodity-type breakdown shown in Table 1. This table lists, by commodity type, the megajoules, average megajoules per vehicle kilometer of travel (VKT), and average megajoules per ton kilometer of travel, based on all truck movements in the Chicago SCSA. The megajoules per VKT figure of 12.90, averaged over all 11 commodity groups, implies an average fuel consumption of 2.7 VKT/L. These regionwide figures also indicate that 37.7 percent of all direct energy is consumed daily by empty truck trips. Although much of this empty truck travel may be avoidable (particularly in the high stem percentage routes), it is likely that many empty VKTs could be saved by better carrier routing procedures (10).

Not only do different commodities require different sizes of vehicles for their movements, they may also require quite different truck routing procedures. Unlike the single daily assignments performed by intercity trucks, most urban (intracity) trucks make a large number of pickups, deliveries, and/or service calls during a single working day. Typically, the unit of work that a truck and its driver are assigned is a day's activity referred to as a route. Each truck route is composed of the following activities, irrespective of the specific service provided:

1. Terminal activities, which include loading and unloading;
2. Stem driving, defined as driving from the truck's base terminal to the first pickup, delivery, or service point (the stem-out) and from the last pickup, delivery, or service point back to the terminal (the stem-in);
3. Zone driving, defined as driving between the first and last pickup, delivery, and service points in the journey; and
4. Stop or dwell time activities for pickup, delivery, and service functions.

The resulting physical distribution characteristics of such routes, based on time schedules and/or stop parameters, vary considerably by commodity type

Figure 4. Megajoules/VKT by truck base terminal district.



and carrier type involved. A relatively simple but quite effective way to gauge the impacts of different truck routing practices on commodity types is to define a truck route circuity (TRC) factor in conjunction with the average ratio of stem and total (zone plus stem) driving distance per commodity type. Figure 3 gives an example of the TRC factor calculation for a hypothetical daily truck route. The TRC factor is a ratio of the actual route distance traveled to the hypothetical all-stem route distance that would result if the truck made a round-trip journey from its terminal base to each pickup and delivery point on its schedule. (The maximum value of such TRC factors ought to be 1.0 in most cases.) For a large number of trucks (T), operating routes out of terminals in district i, we calculate the average TRC factor F by district i, commodity type g, and truck size (weight) ℓ as follows:

$$F_{ig\ell} = \sum_{t\epsilon T(ig\ell)} [({}_r t_{ig\ell})/(\sum_j Sij\ell + Sji\ell)]/T \qquad (1)$$

where $r^t ig\ell$ is the actual route distance by truck t, and $Sij\ell$, $Sji\ell$ are the stem-out and stem-in distances, respectively, to shipper demand point j by the least-expensive route for trucks of size ℓ. The summation $t\epsilon T(ig\ell)$ refers here to all trucks t in the relevant terminal district, commodity, and truck loaded weight categories. Such commodity-specific TRC factors, averaged over all i terminal districts in the Chicago SCSA, are given in Table 1.

These TRC factors, when considered in conjunction with a ratio of the commodity's average stem and total VKT, offer useful insight into the differences in truck routing across commodity types. (The factors here measure the average ratio of real and all-stem VKT per commodity class, which includes the empty as well as loaded truck VKT associated with a commodity movement.) For example, note that both fabricated metals and forest products, two of the three commodity classes that display very low TRC factors, also display two of the three highest ratios of stem and total VKT, which reflects the relatively long stem journeys by these trucks, at the end of which are a number of relatively short, closely grouped pickup and delivery stops.

Terminal locations can have significant impacts on fuel energy consumed through (a) the number of stem kilometers required to serve the daily scheduled shipper demand points and (b) the energy lost through traffic congestion at or near the terminal. Since most urban trucks return to their base of terminal operations at least once each day, we have chosen the location of such terminals as the major spatial component of our energy accounts. The Chicago region's terminal location pattern is heavily concentrated around the central area as a result of shipper demand locations and the constricting influence of the Chicago motor vehicle commercial zone (11). Figure 4 shows the district-specific megajoules per VKT statistics, aggregated over all vehicle sizes, carrier, time of day, and cargo types. The patterns that result are due to the combined effects of each of these planning factors on each district's operating characteristics.

Time of day can have a significant effect on fuel consumption rate for vehicles that move within the Chicago SCSA. The lower average speeds, increased number of stops and starts, and the longer idling times experienced in morning and evening traffic peaks account for significant increases in the transportation energy consumption in the SCSA. Some 27 percent of all trips (passenger and freight) begin between either 7:00-9:00 a.m. or between 4:00-6:00 p.m. each weekday. Trucks that operate during these peak traffic periods are much less energy efficient than trucks that operate during the rest of the day. The 13.6 percent of trucks that start trips during morning or evening peaks account for 22.9 percent of all direct urban trucking energy consumed in the SCSA. Peak consumption rates were found to be particularly high for trucks based in terminals along the Stevenson Expressway, just to the southwest of the Chicago central business district (CBD). This sectional trend occurs in conjunction with a radial trend toward higher consumption rates associated with proximity to the CBD (where total traffic congestion is at its worst). Table 1 also shows that some significant differences exist across commodity classes with respect to the time of day of travel. Over one-fifth of all mixed-commodity shipments in the region are on the road during either the morning or evening peak starting times. In contrast, farm and marine, food, nonmetallic minerals, energy, and retail and wholesale goods movements are concentrated more in the midday and to some extent early morning and mid-evening hours.

As a final variable in our direct energy accounts we included carrier type. Table 2 gives the megajoules consumed per carrier type and truck weight and fuel type categories. The results indicate very similar megajoules per VKT averages across carrier types within any single loaded truck weight and fuel category, with the highest consumption rates by heavy (>7272-kg) gasoline trucks. If we look at megajoules per truck, however, the common carriers show considerably higher figures across all truck weights due to the much higher mileages covered per day by these for-hire vehicles. Both the common and contract carriers surveyed used more heavy-diesel trucks than any other type of vehicle. In contrast, the region's many private carriers used only a very small percentage of trucks more than 3636-kg LWV. Finally, Table 2 also shows the significant difference between private and for-hire carriers with respect to time of trip departures; for-hire trucks tend to operate more in the peak traffic periods than do private carriers.

INDIRECT ENERGY ACCOUNTS

Methodology

In this section we describe the empirical derivation of a set of indirect energy accounts for Chicago's urban trucking industry for both 1970 and 1980. This is a potentially very large, complex task, and our objective was not to seek decimal-point accuracy but to yield estimates that have the proper orders of magnitude.

Although direct energy is used in the form of fuel to operate VKT, indirect energy is consumed by all the preceding stages of production that make this vehicle operation possible (12). The indirect energy required to keep trucks on the road is composed of the following:

1. Truck construction and maintenance energy;
2. Terminal construction, operation, and maintenance energy;
3. Roadway construction, operation, and maintenance energy;
4. Fuel production energy; and
5. The effects of truck traffic on the direct energy consumption of passenger vehicles on the same transportation system.

A marginal approach to estimating indirect energy requirements was used. This means that we estimated the energy required to maintain and operate the existing system and to construct and maintain whatever infrastructure is required for future system development. The estimation procedure used is due to Bullard and others (12). By using our marginal approach, the resulting indirect energy consumption estimates may be divided by the annual truck VKT of the region to give indirect energy in megajoules per VKT for comparison with the direct energy results derived in the preceding section.

All of the industrial sectors that make significant inputs to urban freight transportation have had their primary energy intensities derived by Bullard and others (12). These energy intensities are based on the estimation of the average energy embodied in a dollar of input from one or more of the primary energy sectors of the coal, crude petroleum and gas, and hydro and nuclear electricity production industries into the sectors listed. This transfer of energy takes place in some instances through a series of intermediate industrial sectors, with the principle of "conversation" of energy that ensures that we can trace all energy consumed back to one of the primary energy sectors. The flow of materials between 357 industrial sectors in the U.S. national economy was provided, on a dollar basis, by a 1967 input-output (I-O) analysis (12). By using the indirect energy coefficients provided, data on the dollar costs of trucking infrastructure are then necessary to obtain the total indirect energy consumed per year.

Indirect Infrastructure Energy Components

Table 3 contains a summary of our estimates of the construction energy per vehicle, maintenance, and operation energy per vehicle kilometer, and the construction and maintenance and operation energies per trucking terminal and per highway kilometer, respectively. For detailed breakdowns and all data sources, the reader should see Southworth and others (1).

Item A in Table 3 gives the total manufacturing energy costs for light, medium, and heavy trucks. The 1970 and 1980 truck prices were obtained through truck dealers in Illinois, which include Dodge, Ford, and International trucks. The 1967 cost figures are derived via I-O sector-specific price indices that discount 1970 and 1980 dollars to their respective 1967 equivalents. The last two columns in this table are our estimates of megajoules consumed per unit of infrastructure. Based on an estimated annual vehicle fleet renewal rate of 6 percent of the light-duty truck fleet and 4 percent renewal of medium- and heavy-truck fleets for both 1970 and 1980 (13), we estimate a marginal truck fleet renewal energy cost of 4.59 and 9.76 million MJ per year in 1970 and 1980, respectively.

Item B gives the annual maintenance and operation energy consumption per truck for the four truck size categories. Multiplying these results by the Chicago SCSA truck fleets yields annual energy consumption estimates of 1443 million MJ and 3736 million MJ for 1970 and 1980, respectively.

In item C we present the construction and maintenance energy per terminal, based on the average leasing costs and size of terminals in operation in 1970 and 1980, respectively. A terminal door refers to a loading-unloading bay that is used by one truck at a time. In 1980 a smaller 35-door satellite terminal is considered to be the most appropriate level of operation and as such was the only sort of terminal to be constructed in the Chicago SCSA in the late 1970s. Such terminals are, in part, a

Table 2. Direct energy consumption statistics by carrier, truck weight, and fuel types.

Truck LVW and Fuel Type	Private			For-Hire Common			For-Hire Contract		
	Megajoules (000s)	Megajoules per VKT	Megajoules per Truck	Megajoules (000s)	Megajoules per VKT	Megajoules per Truck	Megajoules (000s)	Megajoules per VKT	Megajoules per Truck
L(1)G	18 877	7.9	456	720	9.1	832	661	7.9	580
L(2)G	13 890	15.0	918	1 606	15.0	1134	1258	15.6	1554
MG	23 907	25.0	2068	6 766	26.1	2482	2842	29.8	1962
HG	26 382	35.5	3690	10 848	37.2	3692	5280	36.5	3902
MD	1 830	21.2	2679	2 324	18.0	3218	941	23.5	2923
HD	2 297	28.1	3880	16 936	26.5	4233	7231	28.4	4180

Note: Percentage of VKT in peak hours = 10.2, private; 17.2, common; and 16.1 contract.

Table 3. Summary of infrastructure energy consumption.

Item	Category	1970	1980
A	Vehicle construction energy (MJ 000s)		
	Light and medium trucks	569	662
	Heavy trucks	1738	1880
B	Vehicle maintenance and operation energy (MJ/vehicle-km)		
	2 272 kg, panel	1.29	1.78
	5 454 kg, single unit	1.90	2.45
	18 181 kg	2.27	2.88
	22 727 kg, 2-52 trailer	2.64	3.56
C	Terminal construction and maintenance and operation energy per typical terminal (MJ 000s)		
	Construction	26 653	15 624
	Maintenance and operation	4198	3163
	Administration	3597	2104
	Insurance	1484	939
D	Highway construction and maintenance energy per lane-kilometer (MJ 000s/km)		
	Expressway construction	66 006	99 440
	Expressway maintenance	280.0	227.8
	Arterial construction	22 428	9353
	Arterial maintenance	81.0	62.3

response to the industry's recognition that diseconomies of scale may manifest themselves with increased terminal size.

A cost breakdown for a typical local trucking industry is estimated in Wilson (14). This breakdown gives the terminal maintenance cost (rent plus upkeep costs) as 5.5 percent of the total cost, while administration costs and insurance costs of freight and equipment are 7.5 percent and 4 percent of the total budget, respectively. Combining these figures with the $84 000 maintenance cost assigned to sector 73.01 (miscellaneous business services) and $61 090 as the annual insurance cost (sector 70.06), for 1980 these administrative and insurance costs are calculated to be $148 910 and $79 418, respectively. By multiplying our findings by the 297 terminals in the Chicago SCSA in 1970, we get an annual 1970 terminal maintenance and operation energy cost of nearly 2776 million MJ. For 1980, with an estimated 272 terminals, our annual estimate is 1685 million MJ. New constructions do not enter our marginal accounts.

If we wish to calculate the energy required to construct and maintain highways for urban trucks, we must face the same conceptual problem as the transport economist who faces an equitable road pricing policy decision. That is, we need to know how much is the additional expense of allowing trucks to use highways that were built essentially to serve the private automobile. This additional expense (and its resulting energy costs) results from the potentially excessive pavement damage that a heavy truck may cause. Without the heavier truck traffic, our highways would last longer and need less repair. Recognizing the essential nature of urban goods movements by trucks, the problem is then one of determining how much this freight traffic adds to pavement wear.

The typical approach to highway traffic pricing (15, pp. 461-473) is to calculate the cost of constructing and maintaining an automobile-only road for an assumed known level of traffic, and to set a rate for operating such vehicles (through the road-fund tax on fuel, for example). The additional expense of upgrading the road to take a certain volume of heavier (truck and bus) traffic may then be calculated--for the same assumed road life and level of maintenance as the automobile-only road. By applying the same rationale to energy consumption, we obtained figures for the construction and maintenance of a typical lane-kilometer of urban highway in Chicago from the Illinois Department of Transportation, Highways Division. The results in Table 3, item D, used these 1970 and 1980 prices as discounted to their 1967 equivalents (16,17). Only urban expressways and primary and secondary arterial roads are included in the analysis. Local road construction and maintenance energy are assumed to be attributable entirely to Chicago's passenger transportation modes.

Boyce and others (18), in a study of passenger transportation energy consumption within the Chicago SCSA, estimate that trucks and buses account for 50 percent of the region's annual roadway (expressways plus arterials) maintenance costs and 38.4 percent of new roadway construction costs. The rest is attributable to automobile traffic. Reducing the megajoules per lane-kilometer figures in item D by one-half and multiplying by the number of lane-kilometers in the SCSA give the annual roadway mainte-

Table 4. Energy consumption due to urban trucking in Chicago SCSA (major components).

Item	1970 Equivalent U.S. Gallons of Gasoline (000 000s)	1970 MJ (000 000s)	1970 Total (%)	1980 Equivalent U.S. Gallons of Gasoline (000 000s)	1980 MJ (000 000s)	1980 Total (%)
Direct energy	231.0	30 485.1	62.3	437.2	57 709.2[a]	64.2
Indirect energy						
Infrastructure	66.4	8 771.3	17.9	105.4	13 910.7	15.5
Fuel production	61.0	8 048.1	16.5	115.4	15 235.2	16.9
Congestion	12.3	1 629.9	3.3	23.3	3 071.1	3.4
Subtotal	139.7	18 444.3	37.7	244.0	32 217.0	35.8
Total	370.7	48 929.4		681.2	89 926.2	

[a]Based on estimated increases in truck VKT derived from Knorr and Millar (21).

nance figures shown (in megajoules). Combining expressway and arterial results gives an annual roadway maintenance energy consumption total of 928.75 million MJ for 1970, which is attributable to truck traffic. Prorating this maintenance cost on a truck kilometer basis and recalling that 77 percent of all SCSA truck VKT in 1970 was due to urban trucking give us an urban trucking energy consumption estimate of 715.13 million MJ. Assuming the same ratio of urban and interurban truck VKT, the 1980 figure is estimated to be lower, at 565.24 million MJ (77 percent of 734.07 million MJ for all 1980 truck movements in the SCSA).

Construction costs for highway lane-kilometers are not included in our marginal accounts, although forecasts of energy consumption per planned lane-kilometer can easily be derived by using the information in item D and remembering to multiply by the appropriate automobile and regional truck percentages.

Indirect Fuel Production Energy for Chicago SCSA

The operation of a truck consumes gasoline that contains 131.89 MJ of combustible energy per U.S. gallon. This is direct energy consumption. However, the industry that produces refined petroleum products itself consumes, on average, an additional 0.227 MJ for each megajoule of gasoline used in direct energy consumption (12). This equals 29.94 MJ of indirect energy consumption per U.S. gallon of gasoline fuel, if we assume that gasoline represents an average product of the oil-refining industry. In addition, energy is required to transport gasoline and diesel from refineries to highway filling stations. Thus, energy consumed by wholesale and retail transactions equals approximately 4.87 MJ/U.S. gal. Recognizing that most of this last figure is consumed on intercity transportation (plus use of pumping machinery), we include it here to be added to our accounts.

Congestion Analysis

For estimation of the energy cost due to truck-induced traffic congestion, we used the approach developed by A.T. Kearney, Inc., (4, Appendix D), but instead used Chicago-specific VKT figures. Briefly, the analysis consists of the following steps:

1. Calculate automobile-equivalent daily VKT by (a) peak, midday, and night; (b) central area and noncentral area; (c) expressway and arterial cross-classifications (a truck was set equal to 2.0 automobiles and a bus to 1.6 automobiles based on American Association of State Highway and Transportation Officials passenger car equivalents).
2. By using information provided by the then Highway Research Board (19) and the Urban Mass Transportation Administration (20) on the relation between vehicle speeds and roadway volume/capacity (V/C) ratios, calculate an average speed for each time-of-day, area, and roadway classification for all traffic.
3. Based on the percentage reduction in V/C ratios caused by removing the daily automobile-equivalent (x2) truck VKT from each area, roadway, and time-of-day category, calculate the new average traffic speeds.
4. Multiply the total nontruck VKT by the appropriately determined average speed and automobile direct energy consumption coefficients (9) to obtain the additional fuel energy lost because of truck-induced traffic congestion by time-of-day, area, and roadway category.
5. Sum all categories and multiply by 312 to obtain the annual congestion energy losses due to trucks (for an assumed 6-day week).

The results of this analysis for the Chicago SCSA in 1970 suggest an additional automobile fuel consumption of 1630 million MJ/year. This represents 12.3 percent of the total annual indirect energy consumption of the region.

SUMMARY AND CONCLUSIONS

Table 4 contains a summary of the estimated total annual regional energy consumption for 1970 and 1980. The 83.8 percent increase over the decade is attributable to an estimated 89.3 percent increase in truck VKT, based on national projections (21-23).

The results of our direct energy analysis suggest that more research should look into the combined effects of truck size and fuel type, its base of terminal operations, and the type of firm (private and for-hire) operating it. Such investigations must be commodity-specific (with far more detailed breakdowns than our 11 commodity groups). A potentially fruitful line of research would be to seek to incorporate such truck-routing statistics as average trip lengths, TRC, and ratios of stem to total driving distance within terminal- and commodity-specific equations of average fuel consumption rates. This means extending the sort of speed and vehicle fuel and weight equations derivable from Winfrey (8) and Claffey (9) to incorporate such spatial factors. We also note here that extensive work is needed into the effects of truck age and ambient air temperature on the fuel consumption rates of different size trucks [in addition to the limited evidence in Morral and others (24) and the Tri-State Transportation Commission (25), for example].

Finally, scrutiny of our individual truck trip records suggests that further research should investigate the impacts of carrier type on average fuel consumption rates, paying particular attention to the frequency of mismatches between truck and cargo size and to the opportunities for savings through more mixed commodity carriage. Certainly, where sample size precludes extensive and detailed commodity-type breakdowns, average energy consumption rates by carrier type provide a useful surrogate measure (as in Table 2).

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