Sponsored by

Mid-America
Transportation Center

Hosted by

CTRE

Center for Transportation
Research and Education

IOWA STATE UNIVERSITY

COMPENDIUM OF STUDENT PAPERS

Presented at
The 1997 Transportation Scholar's Conference
Iowa State University
November 14, 1997

Jennifer Guggisberg
The Third-Party Logistics Industry: A Discussion of Characteristics and Uses

Feng Yong Huang
Truck Drivers' Hours-of-Service

Heng Wei
A Study of Heuristic-Optimization Models for Service-Request Vehicle/Crew Routing with Time Windows in a GIS Environment

Matthew Eatherton
Enhancements in the Ductility of FRP Reinforced Beams Through the Use of Fiber Reinforced Concrete

Ayman Khalil
Out-of-Plane Distortion of X-Type Diaphragm Bridges: Revisited

Madaniyo Is Mutabazi
Safety and Operational Performance of Passing Lanes in Kansas

Jeff Gerken
A Methodology for the Creation, Calibration, and Utilization of a Micro-Simulation Model

Jennifer Guggisberg
Undergraduate Student
Business Administration
Iowa State University

The Third-Party Logistics Industry:
A Discussion of Characteristics and Uses

ABSTRACT

Third-party logistics is one of the fastest growing segments in the transportation and logistics industries. It is of increasing interest to both industry practitioners and academicians. The purpose of this paper is to define the industry, discuss the providers, and develop reasons for a customer to use a third-party logistics provider. Discussed are the services outsourced to third-parties and steps to assist the customer in choosing the correct provider. Once the correct provider is identified, the focus moves to implementation of the outsourcing -- success of the third-party's plan, challenges facing third-party logistics providers, and characteristics used to determine the success of the implementation. Finally, current industry trends are examined, industry growth areas are explored, and the future of the third-party logistics industry is considered.

The primary sources of information involve both the academia and trade literature. Additionally, I have drawn heavily upon my summer intern experience at Dart Logistics and Dart Intermodal in Eagan, Minnesota. As part of my internship, I conducted a brief survey of more than one hundred third-party logistics firms. The information and insights from this project are reflected in this paper.

INTRODUCTION

Third-party logistics is one of the fastest growing segments in the transportation and logistics industries. It is of increasing interest to both industry practitioners and academicians. The purpose of this paper is to define the industry, discuss the providers, and develop reasons for using a third-party logistics provider. This paper will also explore steps for the successful implementation of outsourcing logistics functions, and consider the third-party logistics industry -- both in its current state and in the future.

WHAT IS THIRD-PARTY LOGISTICS (3PL's)?

Many definitions exist for third-party logistics. Academia to industry and beyond have their own idea of what third-party logistics really is. Some believe third-party logistics should encompass the entire supply chain from shipper to purchaser; while others believe the provider should focus on a specific area of the supply chain they excel at managing. Several definitions are available to uphold these various points-of-view. The definition by the Council of Logistics Management states, "[Third-party logistics] encompasses the entire supply chain, from inbound raw material to after-sale service." (*1*) Arnold Maltz, professor at Arizona State University, and Robert Leib, professor at Northeastern University, define a third-party logistics provider "as a company which supplies/coordinates logistics functions across multiple links in the logistics supply chain. The company thus acts as a 'third party' facilitator between seller/manufacturer [the 'first party'] and buyer/user [the 'second party']." (*1*) Frederick Beyer, professor of Logistics at the University of Minnesota's Carlson School of Management, stated, "Third-party logistics [providers] are specialists, a new middle man in the distribution process. They contribute their specialty and provide transactional efficiency for the customer." (Beier, Frederick - unpublished date) With all these different views, it can be -- and is -- difficult to distinguish between third-party logistics providers and those who claim to be third-party logistics providers.

WHO ARE THIRD-PARTY LOGISTICS PROVIDERS?

Third-party logistics assistance can be found in a variety of locations. Depending on the customer and situation, any number of logistics activities can be outsourced to a third-party provider. Warehouses provide the ideal partner for managers looking to outsource their warehousing function and reduce the costs of holding inventory within their company. Truckload carriers have knowledge about various industries. By serving as a partner in third-party logistics, carriers hope to "provide more comprehensive services (to customers), meet demands of key customers, increase revenues, meet service offerings of key competitors, and attain more efficient use of assets and labor." (*2*) Carriers believe customers outsource some or all of their logistics activities to "focus on core business, lower cost, improve customer service, attain greater flexibility, improve operational efficiency, and attain improved market knowledge and data." (*2*) Freight forwarders, customs brokers and less-than-truckload (LTL) carriers attempt to consolidate freight for their customers. Some even consolidate the freight of two or more customers to make costs more economical. Airfreight and express carriers believe they can shorten the lead time for their customers' deliveries, thereby making customers' products available much faster. However, a trade-off for this faster service exists in the cost of the transportation. Information systems companies are also entering the third-party logistics arena. These companies can update computer systems of their customers from inventory management to shipping lanes to purchasing instructions and beyond.

WHY USE A THIRD-PARTY LOGISTICS PROVIDER?

First and foremost, everyone in today's society is looking to cut costs. Outsourcing logistics activities can cut the cost of managing and carrying out a specific logistics function. A third-party provider offers "niche expertise" (*3*) or "expertise, talent and resources that don't exist internally." (*4*) This niche expertise can allow a company to gain the competitive advantage in their industry. A company may want to add value to its product. Value-added services could include, but are not limited to: form utility -- having the product in the desired condition for the consumer; place utility -- having the product in the desired location for the consumer; and time utility -- having the product available when the consumer needs it. By adding value to its product, the company can also increase its customer service level. Using a third-party logistics provider also allows "the company to focus on its core competency which it has determined is not logistics." (*4*) A third-party logistics firm may also offer technological advantages to its customer by improving the customer's current technology and information systems. Other benefits not directly related to logistics include access to specialists in logistics-related fields and possible downsizing of a firm to meet management's demands to cut costs.

SERVICES OUTSOURCED TO THIRD-PARTY LOGISTICS PROVIDERS

Services that should, or could, be outsourced are not always agreed upon. Some suggested areas to outsource include: transportation management and services; warehousing management and operations; value-added services; dedicated contract carriage; fleet management and operations; shipment consolidation; inbound transportation management; carrier selection and rate negotiation; interfacility and outbound transportation; and logistics information, information systems and communications. (*2, 6, 7, 8*) As with any "new" idea, warnings exist about areas that should never be outsourced. These include: customer service; materials management, and supplies replenishment and scheduling; inventory management and control; customs clearance; order processing; freight audit and payment services; procurement of raw materials; and international procurement. (*8, 9*) Overlap occurs between what some believe should be outsourced and what others believe should never leave the control of the individual company. Each firm must decide for itself what it wishes to control internally and what it can afford to have managed externally.

CHOOSING THE RIGHT THIRD-PARTY LOGISTICS PROVIDER

1. Customers Must Know Themselves

The decision to outsource part or all of the logistics process should not be taken lightly. A customer has many things to consider when making this decision. The first item to be considered is why would the customer want to outsource its logistics function. Will it save money, time, and space? What objectives does the customer have for outsourcing? What does the customer hope to accomplish by outsourcing? Customers need to consider what a third-party logistics firm can provide for them. Another item of consideration is what area(s) of the firm the customer is handling well and what they need assistance with. Once the customer can identify its reasons for outsourcing and what area(s) it wishes to outsource, it can choose the most qualified provider to carry out the logistics activities. Choosing the most qualified provider can be based on a variety of details, and is dependent on the specific needs of the customer.

2. **Choosing the Most Qualified Provider**

David Clancy of *Transportation & Distribution* provides a list of questions to consider when choosing a third-party logistics provider. First, he suggests dropping by for a plant trip – unannounced. Then, look around the organization. Examine how employees dress; if floors are free of pock marks and holes; condition of lift trucks; if storage racks are free from scrapes, dents and damage; if products on shelves are dusty; who is using the facility (besides the provider); what amount of technology is used; what type of security system is used; how accessible is the facility (paved roads); what type of signs are on bulletin boards; and examine financial statements, damage records, and a list of references. When finished looking around, talk to employees and customers of the potential third-party logistics provider. (*10*)

3. **Choose the Third-Party Provider with Care**

After doing thorough research on potential providers, a customer must find a provider who offers specifically what it is looking for and will help them achieve its goals. The customer must bring the final candidate(s) back for more questions. Examining information discovered when researching providers is essential at this stage. The customer must know what skills are needed for successful implementation of outsourcing, and if the final providers offer these skills. The customer must look at financial strength, business experience, business development, support services, business arrangements, location, high and improving standards, and integrated capabilities, according to *Purchasing* magazine. (*11*) Other areas to explore include industry experiences of the provider, the provider's abilities to set-up and successfully operate a third-party logistics service for the customer, how the customer and provider will communicate, and what advantages the customer will recognize once it grants control of its logistics activities to the provider. Customers should beware of typically made mistakes when choosing to outsource: not being a team player, holding back (information), focusing on the small picture, seeing the service provider as a threat, and hiring a service provider as a consultant when (the customer) does not really want its advice. Providers should be able to anticipate problems with implementation by drawing on past experiences, and eliminate as many as possible. Providers should have an idea of the time frame of when the outsourced logistics activities will be up and running, and what types of value, service, and cost-reduction they will provide to their customer. The most important part of the outsourcing decision is the communication between provider and customer – the customer should make sure communication lines are open and information on activities of the outsourced functions is available at all times. It is essential to "develop an atmosphere for continuous improvement" (*12*) between the buyer and the seller of the logistics services.

IMPLEMENTATION OF THE OUTSOURCING DECISION

After a provider is chosen, the customer and provider must work together to make the implementation process work smoothly. The customer and provider need to form a working partnership in order to create successful outsourcing for the customer. This may not be as easy as it sounds. In the *Journal of Business Logistics*, Robert Lieb and Hugh Randall suggest several problems with implementation of third-party management of logistics functions. These include overcoming (internal) resistance to change, difficulty in teaching third-party personnel about the company's requirements and systems, cultural differences between the two companies, and the need to integrate computer and information systems. (*7*) Other problems include inability of providers to respond to changing requirements, provider's lack of understanding of the buyer's business goals, and difficulty changing suppliers. (*9*) As implementation begins, communication must continue and the providers must be willing to change their proposed plans to meet the customer's needs and wants. Throughout implementation, communication is vital, and a constant evaluation of the third-party's management is necessary. Finally, it is important for the customer to find ways to maintain company morale throughout the implementation. Employees of the customer need to be aware of, and involved in, the changes. Their input and training is valuable to both the provider's knowledge and the success of the outsourcing relationship.

HOW CAN A THIRD-PARTY LOGISTICS PROVIDER SUCCEED?

A third-party logistics provider must do many things in order to succeed and avoid being flushed out by other more successful firms. The third-party logistics provider must look for new accounts. Many third-party logistics firms continue to look at the large companies as their only customer base. Small and medium sized firms are also looking to outsource. This concept is known as "niche marketing" – looking for an area where the provider can succeed, and creating a reason for a customer to consider the provider through a sound marketing scheme. Third-parties should consider increasing their logistics offerings, but only if they are capable of handling the new activities well. The provider must first look at their core competencies, evaluate their service levels on these, and decide if they can branch off from there. If they feel their service levels will fall as a result of adding new activities and functions, they should not accept them at the current time. The third-party logistics provider must attract, develop and retain skilled personnel in the sales and marketing, systems, and operations areas. Finding these skilled personnel requires a recruiting strategy involving university programs. (*1*) The provider must be flexible. Realizing what your customer is looking for and helping them achieve that goal is crucial to retaining the customer. Providing everything the customer is looking for may not always be easy or feasible. Providers may need to form alliances with other providers (who have different core competencies) to offer the best possible service to their customer. The provider must also manage the relationships for profit and continuous improvement by putting true "partnership" arrangements in place. (*1*) Other tips to keep in mind include building for the long term; being creative, pro-active, open, and driven; and doing the outsourcing right the first time! (*13*)

CHALLENGES FOR THIRD-PARTY LOGISTICS PROVIDERS

Just as the customer faces the decision to outsource, the providers face difficult obstacles with each customer and within the overall third-party logistics industry. The providers must be able to manage the outsourced function successfully. They must ask questions and work to understand what their customer is expecting of them. The third-party must show they are decreasing the cost of the logistics function by running it for their customer, rather than the customer running the logistics function alone. They must be able to show where these savings are coming from. The provider must compete against entrenched internal groups (*1*) who do not believe the provider can do as good of a job managing the logistics function as they currently do. Third-party logistics providers also have an identity crisis within the industry to solve. Many companies are inserting "logistics" into their name, but they are not a true logistics provider. They could be a transportation center, a warehouse, an intermodal manager, or information systems specialist. A true third-party logistics provider offers a wide-range of services to their customer (or is capable of finding what their customer is looking for), not just a specialized section of logistics. Logistics providers have not proven that they can attain long-term profitability. In order to attain long-term profitability, the provider must preserve the relationship with their customer before increasing their own profits (*1*). Many logistics providers also have a parent company who is helping them get off the ground. For example, Werner Logistics is supported by Werner Enterprises, Dart Logistics is supported by Dart Transit and Fleetline, Inc., and Ryder Integrated Logistics is supported by Ryder. The provider also must prove to this parent company they are a worthwhile investment and the logistics area of the company should continue receiving support.

DETERMINANTS OF SUCCESSFUL THIRD-PARTY RELATIONSHIPS

After the implementation is complete, the relationship between the provider and the customer must be evaluated. Several areas are stressed in this evaluation process to determine the success of the relationship. Because outsourcing transportation and logistics is a major decision for a shipper, there is fairly extensive literature on what determines a successful relationship between third-party logistics providers and the customer. The following are some of the key determinants identified in the literature:

1. *Change orientation (innovation)* – the provider can easily adapt to a changing business environment and develop contingencies to minimize system breakdowns.
2. *Access of parties to latest technology* – allows the service buyer to use the latest technology and equipment of the provider without the burden of financial investment.
3. *Channel perspective* – all parties (i.e. both the provider and the customer) view the relationship from the system perspective of the overall channel or supply chain.
4. *Provider's knowledge of the external or competitive environment* – the provider has knowledge of competitors, industry regulations, political and market conditions.

5. *Customer orientation (responsive to customer needs)* – a philosophy that customer service is a process that results in value added to the service exchanged. This includes the provider's ability to customize or tailor its services to the buyer's needs.
6. *Control and performance appraisal* – there is agreement between the provider and customer on performance measurement standards. The agreement should include specific criteria for on-time delivery, freight claims and other crucial service issues. The agreement should mandate periodic reporting by the provider, emphasizing whether service expectations are being met.
7. *Emphasis on long-term relationship* – relationships between the provider and buyer are characterized as contractual rather than transactional in nature.
8. *Improved service* – providers can perform the outsourced tasks at the same, or higher, service levels.
9. *Management expertise* – the provider employs experienced professionals to manage all aspects of the supply chain.
10. *Number of services offered* – the providers offers a comprehensive set of value-added services to meet customer needs.
11. *Sharing of benefits and risks* – an incentive program in established which involves the sharing of benefits and risks between the provider and buyer for any cooperative efforts.
12. *Financial strength* – ensures that the provider's and customer's financial positions warrants a commitment of resources and that each party has the staying power to withstand economic conditions.

13. *Good communications* – the provider and customer openly discuss their requirements and expectations and talk through their problems.
14. *Confidentiality* – make sure the third party and its underlying service providers will protect the customer's sensitive data on products, shipments and their customers.
15. *Guidelines exist to resolve issues or disputes* – procedures have been established to identify and discuss matters, or issues, of interest to both parties.
16. *Provider's knowledge of customer operations and vice versa* – each party has a clear understanding of the capabilities and limitations of those involved.
17. *Sharing of common goals (value consistency)* – matching of the provider's and customer's corporate cultures and philosophies.
18. *Sharing of relevant information* – establishing information systems, procedures, and meetings that involve the sharing of information between the customer and provider.
19. *Total organizational involvement* – there are multiple levels of commitment by both the provider and customer (including commitment of top management).
20. *Subcontractors* – the customer must give the third-party clear criteria for subcontractors, including minimum levels of liability and insurance coverage, for selecting carriers and other underlying providers.

(*14, 15, 16*)

CURRENT TRENDS IN THE THIRD-PARTY LOGISTICS INDUSTRY

At the moment, the third-party logistics industry is growing rapidly. Anyone can enter the third-party logistics industry because the entry costs and barriers are low and there is no clear definition of using the term "logistics" in the name of a company. Advertising can be done via the World Wide Web – searches come up with over four hundred names of companies claiming to be third-party logistics providers. *Purchasing* magazine offers additional reasons for expected growth in third-party logistics such as "management focus on core business, pressure to reduce cycle times and inventories, pressure to cut costs, more complex supply chains, and remembering success breeds success." (*11*) As some current companies continue to grow and improve their service and offerings, a shake-out is predicted in this industry. Those who can prove they are doing well will continue as a third-party logistics provider, while those who have only one or two customers will probably fail. This prediction of a shake-out comes from many sources, both in academia and industry. The shake-out can already be seen in third-party logistics. Yellow Logistics was closed down because its parent company, Yellow Freight Systems, did not believe it was successful. Several other logistics firms are facing the same problem. Competition is fierce. Third-party providers have to convince their customers to continue to work with them, and continue to improve their logistics activities. Providers who are just starting up must convince customers they can do the same, or better, job than the "big" names currently existing in the third-party industry.

GROWTH AREAS FOR THIRD-PARTY LOGISTICS

As successful third-party logistics firms continue development, numerous growth areas are available to them. According to James Cooke of *Logistics Management*, these include: continued globalization, further information systems development, further integration of supply-chain activities, broader service offerings, transportation management, broader warehouse applications, and conversion of private fleets to contract transportation. (*6*) As firms grow, develop, and excel in these areas, they will be able to increase their customer service and overall customer base.

THE FUTURE OF THIRD-PARTY LOGISTICS

The future of third-party logistics looks bright for those firms who can provide exactly what their customers are looking for. If a firm examines all the information a customer must consider before hiring a third-party provider and develops it to their advantage, they should succeed. Firms should also combine all their logistics activities under one area rather than breaking it up into a logistics department, an intermodal department, an information systems department, a warehouse department, and a brokerage department -- to name a few. When all of a firm's logistics functions are located together and able to communicate effectively, they can begin to develop long-range goals for themselves and long-range plans with their customers. However, smaller firms need to find and establish their corner in the market to avoid the inevitable shake-out that will occur in the industry. The future of third-party logistics is still quite uncertain in this infant industry. Predictions abound, but nothing is definite. Watching the industry during the next decade will provide interesting insight and knowledge about the growth of a new era in the transportation world.

ACKNOWLEDGMENTS

Thank you to:

Crum, Dr. Michael	for assisting me with the final draft of my paper.
Weideranders, Sharon	for correcting grammar and technical errors.
Dart Logistics and Dart Intermodal	for the opportunity to gain from my internship experience and apply the skills in my academic development.

REFERENCES

1. Maltz, Arnold B., and Robert C. Lieb. The Third Party Logistics Industry: Evolution, Drivers, and Prospects. Presentation at Annual Meeting of the Council of Logistics Management.
2. Crum, Michael R., and Benjamin J. Allen. A Longitudinal Assessment of Motor Carrier-Shipper Relationship Trends, 1990 vs. 1996. Research at Iowa State University, Spring 1997. Publication scheduled for next edition of *Transportation Journal*.
3. Dollar, Tony. The Power of Third Parties. *Distribution*, Vol. 94, March 1995, pp. 34-44.
4. Craig, Tom. Outsourcing: Let the buyers beware. *Transportation & Distribution*, Vol. 37, May 1996, p. 102.
5. Cooke, James Aaron. On the up and up (and up)! *Traffic Management*, Vol. 35, January 1996, pp. 49-51.
6. Cooke, James Aaron. 3PL's look toward more realistic growth. *Logistics Management*, Vol. 35, December 1996, pp. 29-32.
7. Lieb, Robert C., and Hugh L. Randall. A Comparison of the Use of Third-Party Logistics Services by Large American Manufacturers, 1991, 1994, and 1995. *Journal of Business Logistics*, Vol. 17, no. 1, 1996, pp. 305-320.
8. Bonney, Joseph. What makes Bob Delaney nervous? American Shipper, Vol. 35, December 1993, pp. 40I-40J.
9. Bradley, Peter. Third Party Logistics: Third parties gain slow, cautious buyer support. *Purchasing*, Vol. 118, 18 May 1995, pp. 51-52.
10. Clancy, David. Stop! Look, and Evaluate Third Parties. *Transportation & Distribution*, Vol. 31, August 1990, pp. 24-25.

11. Third Party Logistics: Cozy up, but Stay tough. *Purchasing*, Vol. 116, 17 March 1994, pp. 47-51.

12. Can't get a handle on freight costs? Give up Trying! *Purchasing*, v. 119, 23 November 1995, pp. 35-36.

13. Beargie, Tony. Want to Succeed as a Third Party? *American Shipper*, November 1993, p. 62.

14. Leahy, Steven E., Paul R. Murphy, and Richard F. Poist. Determinants of Successful Logistical Relationships: A Third-Party Provider Prospective. *Transportation Journal*, Vol. 35, Winter 1995, pp. 5-13.

15. Divorce: Third Party Style. *Distribution*, Vol. 94, November 1995, pp. 46-51.

16. Cooke, James Aaron. How to build a solid third-party relationship. *Logistics Management*, Vol. 35, August 1996, pp. 39-41.

Feng Yong Huang
MS Student
Transportation and Logistics
Iowa State University

Truck Drivers' Hours-of-Service

INTRODUCTION

The Federal Highway Administration (FHWA) has considered a rule-making that could result in rewriting the current hours-of-service regulations for truck drivers (1). The FHWA addresses the concern of the trucking industry that the current hours-of-service laws may not be helping to counter fatigue (2). An understanding of what the truck driver think about the changing of current hours-of-service is important to the general public, government, and business. This report includes sections covering (a) Hours-of-service's background, (b) Current hours-of-service regulations, (c) Other countries' hours-of-service regulations, (d) Hours-of-service opinions, (e) Limitations of the survey, (f) Methodology of the survey, (g) Results, (h) Summary of the findings, and (i) Recommendations. The research project is focused on a survey of truck drivers employed at Adrian Carriers, Inc. The survey focused on the drivers' subjective preference regarding the possible changes of current hours-of-service, and the problems they have on the road with the current hours-of-service regulations.

BACKGROUND

In the late 1920s, low rates forced truckers to work longer hours and to drive more miles to remain solvents (3, p. 74). With competition from major freighting firms that paid low wages that allowed them to offer low rates, truckers were left at the mercy of the shippers to stay alive (3, p. 75). In 1933, several reports said the average wage earned by truckers was $24 per week, but the hours needed to earn this amount ranged from 50 to 99 (3, p. 76-8). After the passage of the National Industrial

Recovery Act in 1933, working conditions and pay improved for many interstate drivers employed by trucking firms. A code of fair competition aimed at reducing work hours and increasing pay was instituted in 1934 for the trucking industry (3, p. 81). Drivers were allowed to work up to a maximum of 108 hours in any two-week period, with overtime pay at one and one-third their normal salary for more than 48 hours worked in one week. Moreover, drivers were to be given two days off each week, and minimum wages were set according to geographical areas. However, the good intent of the federal government did not reduce the hours worked by, nor increase the wages for, the independent trucker (3, p. 82).

During the summer of 1935, Congress passed the Motor Carrier Act that gave the Interstate Commerce Commission (ICC) the power to regulate the trucking industry (3, p. 82). Congress gave the ICC power to investigate and determine if it was necessary to put in the rules and regulations for hours-of-service (4, p. 31). In order to make the highways safer, a provision was added which give the Commission authority to establish similar requirements with respect to the hours-of-service of the employees of trucking operators. The investigation permitted the Commission not only to determine whether there was need for regulation, but also to establish requirements adapted to the special conditions surrounding the different types and conditions of operation. The original bill conferred upon the Commission power to regulate the safety of operating carriers. The Commission was empowered to use funds and avail themselves of other federal agencies to conduct research and tests pertaining to the safety of life and health of employees employed in the motor industry (4, p. 33).

According to a survey made by the National Safety Council in 1935, fatigue exceeded all other causes of accidents. The councils' major findings were:

1. Many motor vehicle accidents occurred because of driver fatigue. These fatigue caused accidents were more likely to occur to truck drivers than to those of private passenger cars.
2. Drowsiness may be complicated by other factors, such as alcohol, carbon monoxide, and starting trips after considerable periods of wakefulness.
3. Although most states had regulations limiting the hours-of-service for certain classes of drivers, there were only a few places where these rules were enforced.
4. Violations of hours-of-service rules were common in long-haul, for-hire trucking.
5. The total hours on-duty, including time for loading, unloading, and waiting, were the important, not just the hours behind the wheel.
6. Most of the well-run truck fleets who wanted to reduce accidents had already adopted safety measures voluntarily. The effects of enforced legislation would be "reduce competition from and chance of collision with trucks whose drivers are working dangerously long hours" (4, p. 34).

In October 1936, the reduction of hours-of-service marked one of the early confrontations between the trucking industry and the strengthened Teamsters Union. The conflicts focused as much upon economic control as upon safe operations. Union representatives wanted an eight-hour workday, which would restrict the distances over-the-road haulers could cover. This would make it difficult for over-the-road truckers to make local deliveries. The Teamsters lost this battle, as the American Trucking

Associations, Inc. (ATA) attacked the proposal as too conservative and offered a substitute—sixty-hour weeks and the use of sleeper cabs. (Sleeper cabs allowed one driver to rest on a bunk behind the cab while another drives the vehicle). Effective December 1, 1938, a new regulation allowed interstate truckers to work ten hours per day before they had to take a mandatory eight-hour rest, but no trucker could work more than sixty hours in one week. The ten-hour rule included loading, driving, and unloading the truck. One year later, after additional hearings, the commission made the rules more lenient, allowing drivers to work 15 hours per day, consisting of 5 hours loading or unloading and 10 hours driving, up to the sixty-hour limit per week. Union leaders protested that the ATA program would decrease the number of trucking jobs, still a matter of concern as the Depression wore on toward the 1940s (5, p. 163-4).

To enforce these new hours-of-service regulations, all interstate truckers were required to maintain a current daily logbook that is still used today. The logbook contains pages for each day of the month, and each page has space in a graphlike form to record the driver's activities such as driving, loading or unloading, inspection, eating, sleeping or off-duty time; see Appendix A. As with any rule there will be "violators as some drivers carry fake or duplicate logbooks, or falsify their records" (5, p. 164). This is something state policemen and the highway patrol check to make sure driver logs are complete and up to date during routine stops (5, p. 164).

CURRENT HOURS-OF-SERVICE REGULATIONS

The new hours-of-service regulations, under Title 49, Code of Federal Regulations part 395, were promulgated by the ICC to limit the hours-of-service of interstate truck drivers engaged in for-hire service (6, p. 257). Amendments to these regulations, made on March 1, 1939, were based on the findings of an investigation and report by the United States Public Health Service of the problem of fatigue and hours-of-service of drivers of commercial vehicles operating in interstate commerce (6, p. 258).

10 Hours Driving Law

Drivers cannot drive more than 10 hours following 8 consecutive hours off-duty. Drivers cannot operate for more than 10 hours in the aggregate in any period of 24 consecutive hours; unless such driver be off duty for 8 consecutive hours during or immediately following the 10 hours' aggregate driving and within the stated period of 24 consecutive hours (7, p. 494).

There are two exceptions to these driving regulations, those are adverse driving conditions and emergency conditions. Adverse conditions include snow, sleet, fog, and others such as the highway being covered with snow or ice, or other unusual traffic conditions, that were not apparent on the basis of information known to the person dispatching the move at the time it began (8, p. 320). The driver who encounters those conditions and cannot, because of the conditions, complete his or her run within the 10-hour maximum driving time permitted may drive up to but not more than 2 additional hours to complete the run or to reach a safe place. In the case of an emergency, a driver may complete his or her run without being in violation of the regulations, if the run could have reasonably been completed in absence of the emergency (8, p. 317).

15 Hours On-Duty Law

Drivers may have a 15 hour on-duty work day, no more than 10 of which can be driving, following 8 consecutive hours off-duty (8, p. 323). On-duty time includes all of the time after a driver begins to work up to the time the driver is relieved of responsibility for performing work. This includes time waiting to be dispatched or spent preparing the vehicle for operation, loading or unloading the drivers' vehicle, or performing any other work (9, p. 5).

60/70 Hours-of-Service Law

Drivers must not drive after accumulating 60 hours on-duty during any 7 consecutive days or 70 hours on-duty time in any 8 consecutive days. Drivers may continue to perform non-driving duties after reaching these limits and not be in violation. For example, a driver who works on the 70-hour/8 day schedule would add the hours worked during the last 7 days (day 1 plus the preceding 6 days). If it totals 70 hours or more, the driver has no driving hours available for the next day. However, the driver still can perform non-driving activities after reaching the 70-hour limit and not be in violation (9, p. 5). Table 1 gives a clear view of the current hours-of-service regulations.

TABLE 1 Hours-of-Service Regulations

Driving time limitation	10 hours
On-duty time limitation	15 hours
Off-duty time minimum	8 hours
7-day on-duty time maximum	60 hours
8-day on-duty time maximum	70 hours

Duty Log Book Record

As explained above, a driver must keep a logbook, and this log is maintained in duplicate for each day of the month. Operators of farm trucks do not have to maintain driver's logs. The original of these records is retained by the motor carrier for one year and furnishes the basis for necessary reports to the ICC. The driver keeps his copy for one month (7, p. 495). Drivers operating within a 100 air-mile radius of their normal reporting location may be exempt from the logging requirement. A driver must be back to the work reporting location within 12 hours and have 8 consecutive off-duty hours before working another 12 hours. The driver also cannot exceed the 10 hours maximum driving time and must comply with the 60/70 hours of service rule (9, p. 9). The driver could be found in violation of the regulations if he or she submitted a log that indicated too many hours worked (5, p. 164).

The Congress of the United States has been entrusted with the enactment of proper legislation to regulate interstate commerce. "This includes not only the truck owner and truck driver but the innocent public, led to believe that in the purchasing of an automobile the highway can be traveled with reasonable safety" (4, p. 35).

Hours-of-Service Opinions

The National Private Truck Council (NPTC) states that the optimum hours-of-service program should be tailored to each different segment of the trucking industry. At the same time, they do acknowledge it will be difficult for officers conducting roadside inspections to differentiate between the different classes of truckers. Ideally, the hours-of-service regulations need to be simple, effective, workable, and enforceable (10). The NPTC agrees with the 60 hours in seven days and 70 hours in eight days rule, but it feels the more suitable hours worked in a day would consist of 12 hours driving, three hours on-duty without driving, and nine hours for rest. This hours format will "better fit the 24-hour circadian rhythm" of the human body. The current rules based on an 18-hour cycle with 10 hours driving and 8 hours sleeping causes irregular sleep patterns for drivers. The accumulative effect is that the driver is forced to sleep at different times every day as the work week goes on. Results of a Driver Fatigue and Alertness Study concluded that this disruption of the body's sleep pattern is a greater contributor to fatigue than the amount of time one spends on duty. Safety Director Jim York of the NPTC says that the majority of NPTC members do favor keeping the current cumulative driving hours intact. NPTC feels the Federal Highway Administration should make adjustments to hours-of-service rules that better suit the drivers health requirements and at the same time allow them to provide the service freight customers need (10).

In the article of "Re: HOS Regulations," Oldtimer recommended not increasing truck driver work hours because the rules provide protection and safety for the truck driver. He said that the rules should increase drivers' pay, so they do not have to work long hours to make it (11). In another article, Kniefel argues that drivers' working hours should be regulated under the Fair Labor Standards Act that requires employees who work in excess of forty hours in any calendar week be compensated for those excess hours at a rate of 1 1/2 times. Truckers should not be kept outside the protection of the law given to workers in other industries (12).

OTHER COUNTRIES' HOURS-OF-SERVICE REGULATIONS

Australia

Hours-of-service regulations in Australia are different from the United States. Most of Australia's states current regulations allow truck drivers to work up to 18 hours per day that includes 12 hours driving time. The maximum of working hours is 72 hours per week and drivers can work for four consecutive days until the limitation of 72 hours a week. There are two proposed policies that could change truck drivers' hours of service. First, drivers would be allowed to work the maximum 18 hours per day and 72 hours per week. However, drivers would drive 14 hours behind the wheel per day until 72 maximum hours per week. Second, trucking companies have developed a Fatigue Management Scheme that would allow drivers to drive up to 18 hours per day for four consecutive days without exceeding 72 hours per week (13, p. 1).

Canada

Hours-of-service rules in Canada are also different from those in the U. S. All truck drivers must carry and fill out a log book. Truck drivers can drive 13 hours after 8 straight hours off, or 16 hours in a 24 hour period but drivers must have 8 straight hours off after the first 13 hours of driving. Drivers must take 8 straight hours off after 15 hours on duty. Once in any 7 consecutive days drivers can reduce their off duty time to no less than 4 hours, but they must increase their next 8 hours off by whatever amount that shortened the first 8, e.g., 4 hours off and then 12 hours off (14, p. 1).

FATIGUE EFFECTS

Safety

A study by the National Transportation Safety Board of the United States disclosed a frightful statistic that 30 percent of all truck accidents are fatigue related (15, p. 12); the biggest problem trucking companies faced was fatigue (16, p. 26). Fatigue results when working hours are long but also when drivers begin at unusual times (17, p. 22). For example, a fully loaded semi-trailer traveling over 55 miles per hour ran into the rear of a school bus. The truck driver received only minor injuries while 4 of the school bus passengers were fatally injured, 4 received serious injuries, and 15 students received minor injuries. The safety Board found that the truck driver had been on duty for 26 hours preceding the accident. He had falsified his daily log book to indicate 7 hours of off-duty time. In addition, it was found that he had violated hours-of-service laws at least four times in the 3 days before the accident (18, p. 4).

Drivers know fatigue is an uninvited and unwelcome passenger on any journey. They use many methods to battle this passenger like consuming caffeine drinks, eating spicy foods, or talking on the CB radio. Preparation for each trip is the most important part. The following is a list of ways to counteract the danger of fatigue (17, p. 23):

1. Get proper sleep before leaving.
2. Do not rely on stimulants.
3. Take rest periods regularly, exercise to limber up.
4. Drink plenty of fluids, but avoid alcohol.
5. Do not start a journey hungry. Train yourself in good eating habits, a light and healthy diet is best suited for travel.

Industries are in the development phase of being able to market technical aids that will warn drivers when they are falling asleep. According to *Awake* magazine, a Japanese firm has an idea using a video camera that monitors how frequently the driver blinks his or her eyes. Too many long blinks and a prerecorded voice warn the driver that it is time to stop and rest. In Europe, drivers are working on an apparatus that detects when the vehicle is swaying back in forth. If this is happening, a warning message sounds in the cab telling the drivers they need some rest (17, p. 23). It may be sometime before instruments like these are in production.

There are some questions that drivers need to recognize the warning signs of fatigue. If a driver answers yes to the following questions, it means that he or she needs to take a rest (17, p. 22).

- Do you have burning eyes or drooping eyelids?
- Do you imagine things or find yourself daydreaming?
- Does the road seem to be narrower, causing you to drive along the middle line?
- Is your recollection of certain parts of the journey missing?
- Is your use of the steering wheel and brakes more jerky than normal?

Driver Turnover

There are some reasons for the driver shortage and the shrinking labor pool. Fuller and Walter cited reports of driver turnover rates exceeding 100 percent annually (19, p. 42), for higher than in manufacturing turnover of 12 percent (20, p. 15). The primary reason for such high turnover rates is the low level of drivers' compensation. There are some additional factors that relate to the turnover rates, such as the drivers' daily schedule is ever changing, because the loads are not ready, or the customer unloads only during certain hours, or traffic conditions. Another common problem occurs when a person's personal life at home is not amiable and it becomes increasingly difficult to be away from home (21, p. 25). The rules associated with acquiring a Commercial Drivers License (CDL), procedures for transporting hazardous materials, drug and alcohol testing, and the lack of necessary literacy skills are all contributing factors of the shrinking labor pool of qualified drivers (19, p. 42).

Common practice in the trucking industry is to offer current drivers a cash reward for finding new drivers to join the company and complete the 90-day probationary period. According to James Beaham, a truck driver at Adrian Carriers, Inc., this is incentive for drivers to present a favorable picture of the company they drive for, even it's not true. A driver may be susceptible to the sales pitch and leave one company for another in the hopes of finding a better workplace. Everyone wants to work for a company that provides added benefits, such as many paid holidays and weeks of vacation. However, these are rare in the trucking industry that usually only provides 1-week vacation, 6 major holidays, 401K, health and dental plans (Personal interview with James Beaham, a Truck Driver at Adrian Carriers, Inc., Milan IL, August 1997). Therefore, better pay and benefits may reduce drivers turnover rate.

TRUCK DRIVERS HOURS-OF-SERVICE SURVEY

Limitations of the Survey

Participation in the survey was limited to truck drivers employed by Adrian Carriers, Inc., a company with 100 drivers including part-time drivers. Participants included over-the-road drivers, who travel only within a 500-mile radius of the home terminal and city drivers who do not exceed a 100-mile radius. City drivers, who do not need to log miles or hours driven and part-time drivers were also included.

Methodology

Hours-of-service regulations is an issue of interest since the federal government is considering changes. The intention of the survey was to study truck drivers' opinions about possible changes of hours-of-service regulations. The development of a Truck Drivers' Hours-of-Service data base began as a project supported by Adrian Carriers, Inc., which operates both as a common carrier and a contract trucking company.

The survey included items regarding the preference on changes in hours-of-service, the problem with hours-of-service, years of truck driving experience, reasons for changing employers, and age. The survey was designed to maintain the voluntary and confidential nature of the project. The researcher was available by phone to answer any inquiries about the survey (see Appendix B).

The plan was to distribute the surveys at the company in a very brief period, not to exceed two weeks. A total of 100 questionnaires were distributed through the drivers' mailboxes at the terminal. Questionnaires were returned to a box marked "Iowa State University Survey Drop-Box" in the drivers' lounge at the company, ensuring that answers would remain anonymous.

Fifty-three responses were received at the survey box in ten days; 51 were usable which is 51 percent of the total (Although some of the recommendations were not related to the change in hours-of-service). Nearly every survey was fully completed and useful; one of the drivers provided his name, such identification was removed before the data were used. Only a few responses were insincere or attempted humor.

Results

Preferred in hours-of-service regulations

Many recent articles talk about changing trucking hours-of-service rules, so drivers were expected to be conversant in this topic. When drivers were asked the preference in changing hours-of-service, 35 percent preferred no change from current regulations (10 hours driving, 8 hours off-duty; 15 hours on- duty, 8 hours off-duty; 60 hours in 7 days; 70 hours in 8 days), see Figure 1. Twenty-five percent preferred 12 hours on duty and 12 hours off-duty. Twenty percent chose 14 hours driving per day. Eight percent responded 10 hours on driving and 10-12 hours off-duty. Six percent liked 13 hours driving per day and six percent did not answer this question.

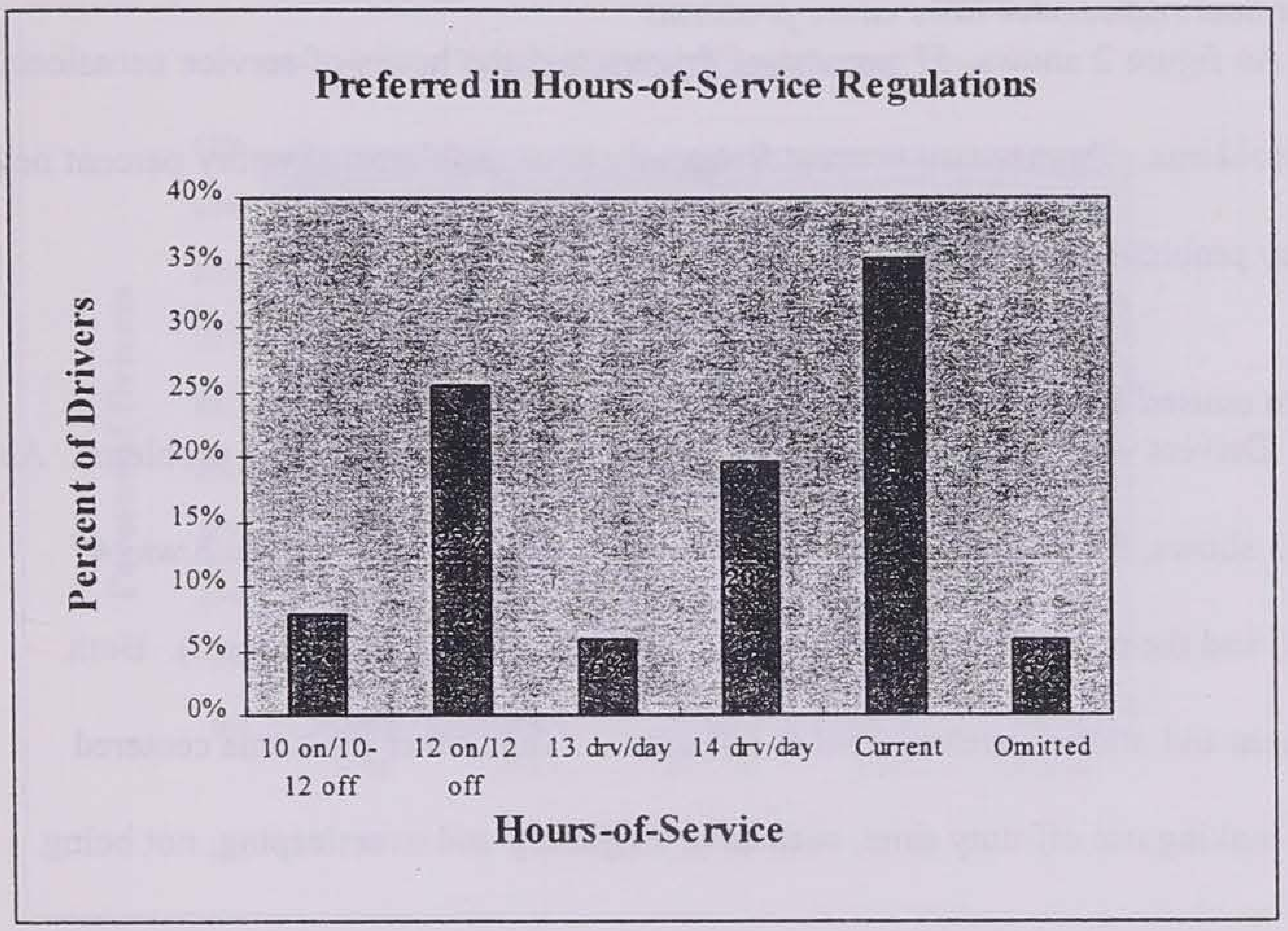


FIGURE 1

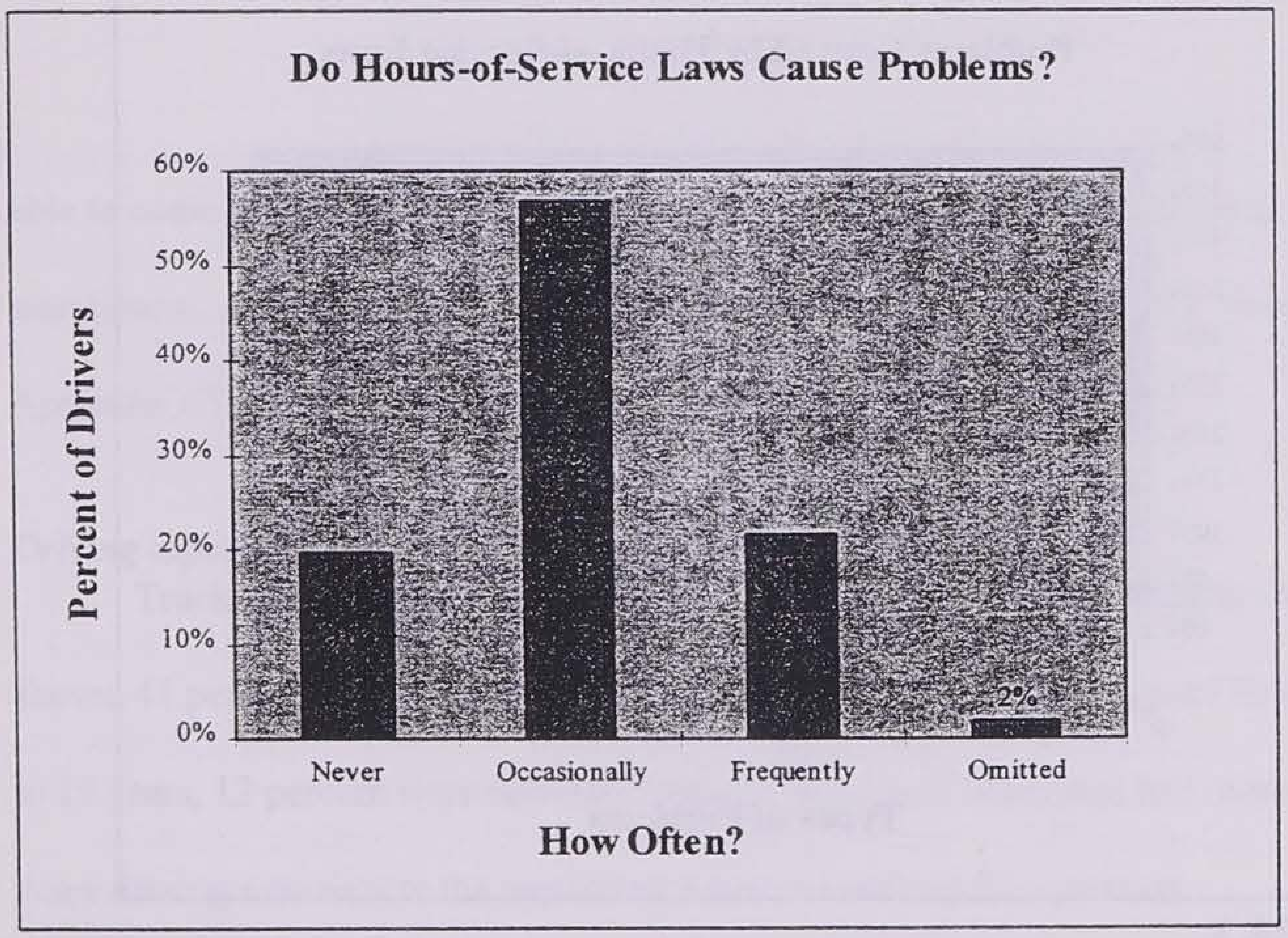


FIGURE 2

Current hours-of-service laws cause problems

As figure 2 shows, 57 percent of drivers said the hours-of-service occasionally cause problems. Twenty-two percent frequently have problems. Twenty percent never have any problem and 2 percent omitted the item.

Problem caused by hours-of-service laws

Drivers were asked why the hours-of-service laws have caused problems. As Figure 3 shows, the main problems are tight schedules, bad weather (each was 47 percent) and the need for more income by working long hours (45 percent). Both equipment and others were reported at 16 percent. Then other problems centered around making use off-duty time, such as getting sleep and oversleeping, not being

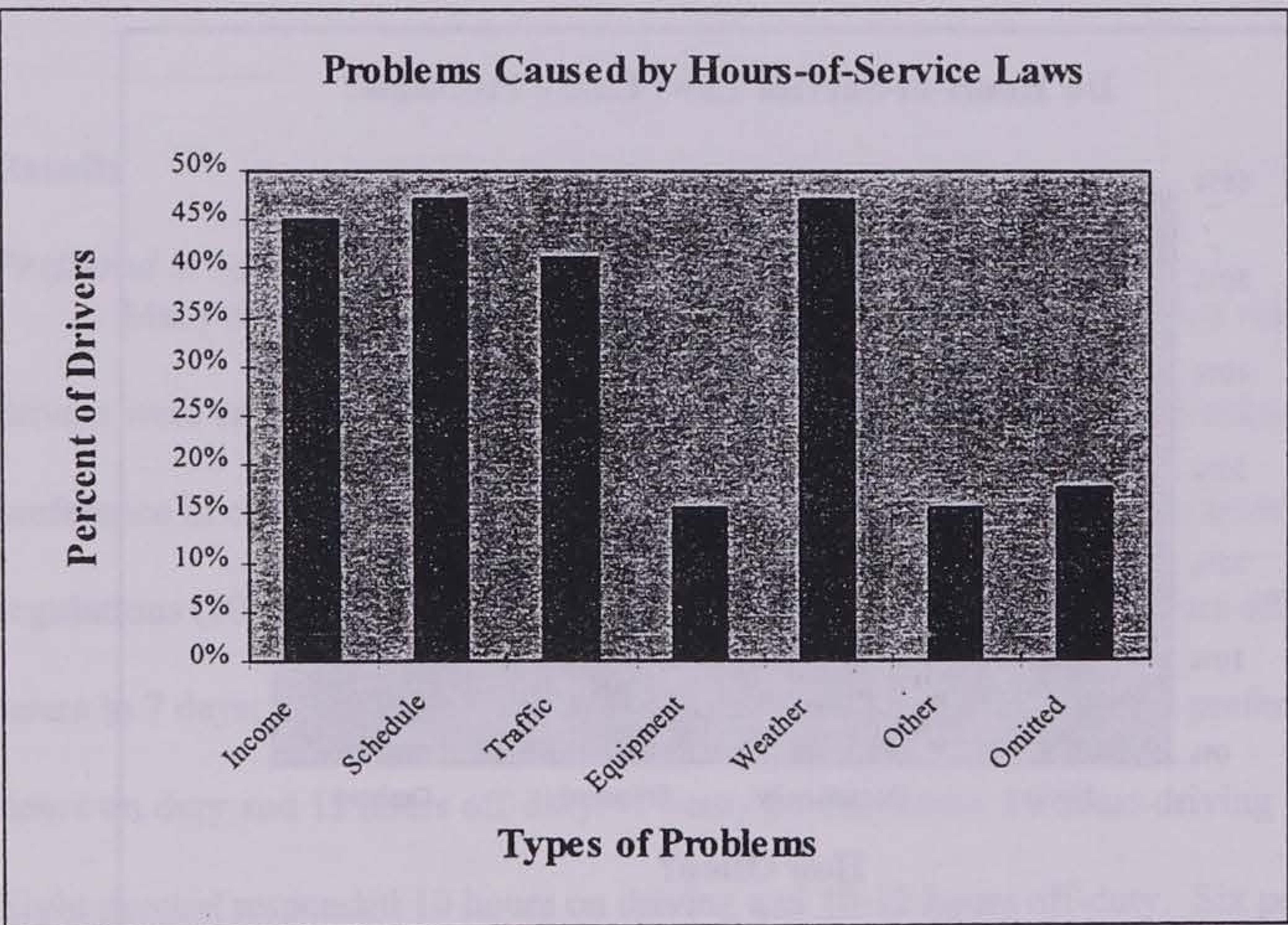


FIGURE 3

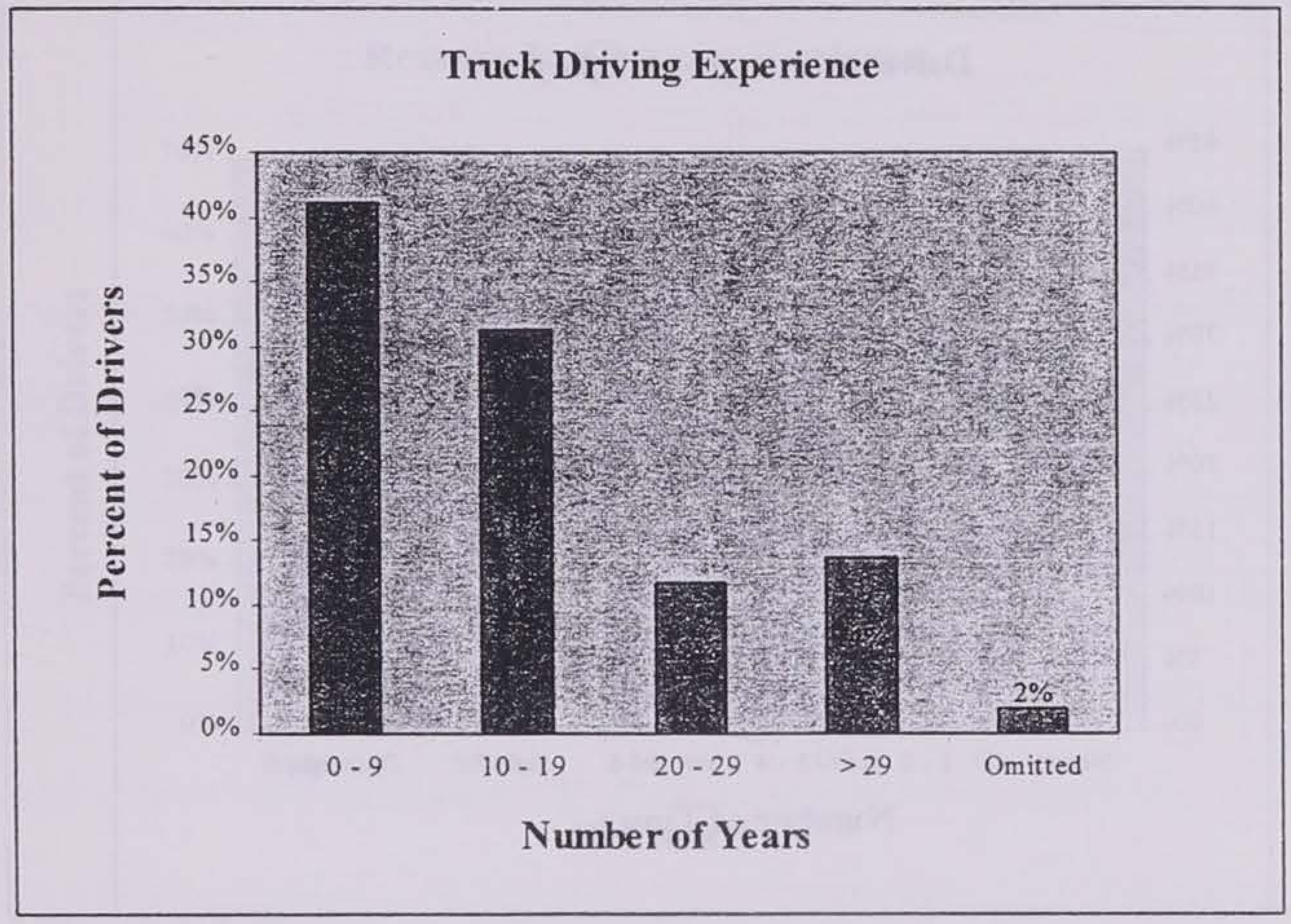


FIGURE 4

able to come home because of layovers, lost time waiting to load or unload at big warehouses, and requirements to deliver customers' freight "just-in-time" (see Appendix C).

Driving experience

Truck drivers were asked how many years they have driven a truck. As figure 4 shows, 41 percent had driving experience of 0 to 9 years, 31 percent were between 10 to 19 years, 12 percent were between 20 to 29 years, and 14 percent had more than 29 years driving experience; the remaining 2 percent omitted this question.

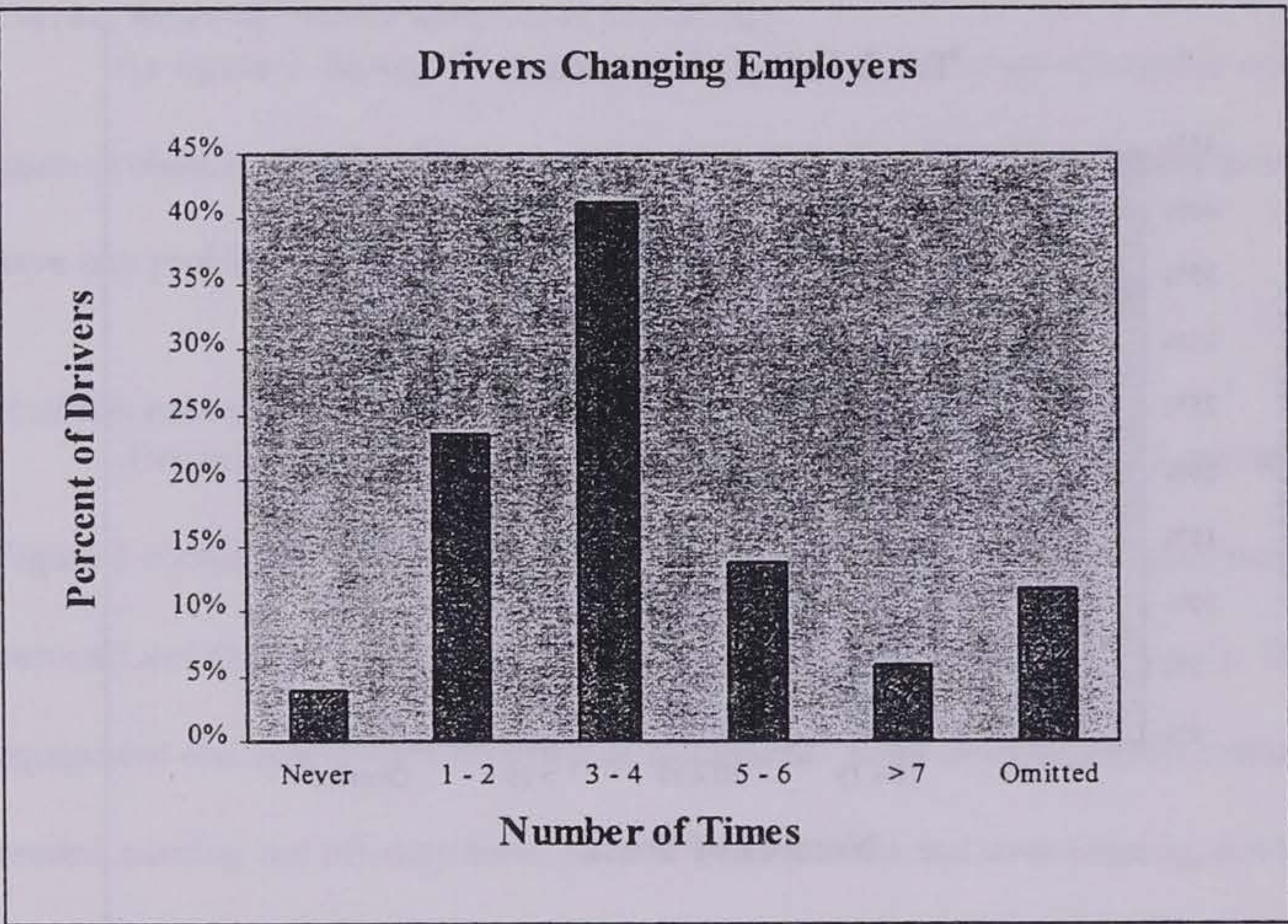


FIGURE 5

Changing employers

As Figure 5 shows, 4 percent of drivers have never changed employers, but the remainder had changed employers at leave once. Twenty-four percent had changed 1 to 2 times; 41 percent changed 3 to 4 times; 14 percent had changed 5 to 6 times, and 6 percent changed 7 or more times. The remaining 12 percent omitted the item.

Reasons for changing employers

According to Schulz, compensation is the primary reason drivers give for leaving their jobs. Figure 6 supports this statement, as 67 percent of the drivers indicated income as the reason for changing employers. Thirty-three percent said schedule and 31 percent responded equipment. There were 25 percent who indicated other reasons, such as wanting to be home more often, changing to higher job position,

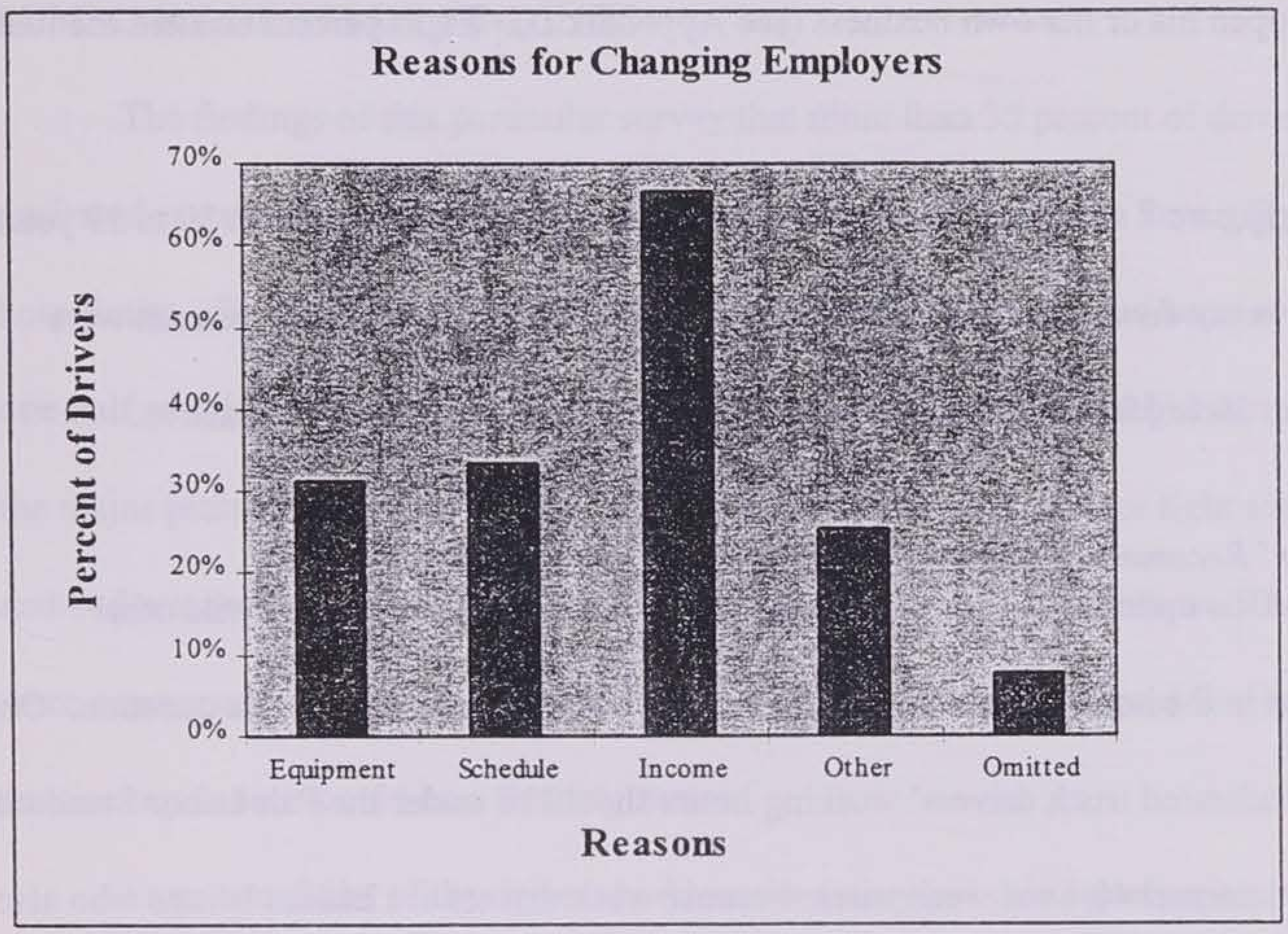


FIGURE 6

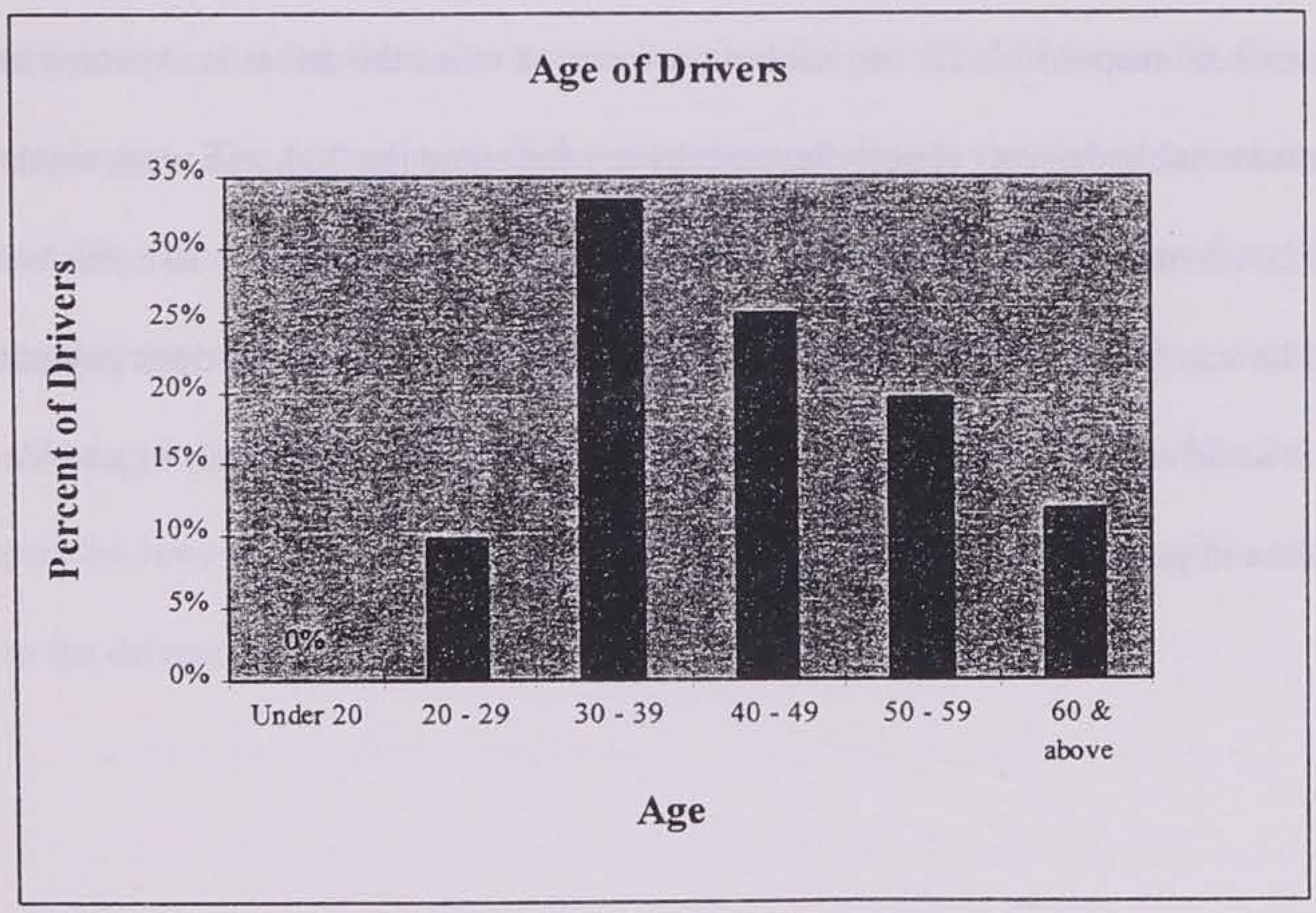


FIGURE 7

and to open his or her own business (see Appendix D). Eight percent omitted the item.

Age

Figure 7 shows that 33 percent of the drivers' age were between 30 to 39 years old. Twenty-five percent were between 40 to 49 years of age, and 20 percent were between 50 to 59 years of age. The rest, 12 percent, were aged 60 and above.

Drivers' Recommendation Other Changes in Hours-of-Service Laws

One optional question on the survey was for drivers to recommend other changes in the hours-of-service laws. Twenty percent responded to this question. One driver indicated truck drivers' working hours should be under the Fair Labor Standards Act, the normal 40-hour work week, because truck drivers are human beings who also work hard to make a living. Shippers and consignees should be more conscious of pick-up and delivery times and the way they relate to current hours-of-service laws, or have them held responsible for any violations incurred when the driver is expected to meet unreasonable delivery times. Several drivers welcome the 70 hours work week with 12 hours on-duty and 12 hours off-duty or being able to start a new 70 hours week after 24 hours off duty. Other responses were related to money, such as dock pay rate the same as driving rate, more money per hour, and raising the speed limit to provide an increase in pay based on miles driven (see Appendix E).

SUMMARY OF STUDY FINDINGS

The findings of this particular survey that more than 35 percent of drivers preferred current hours-of-service regulations compared to any of the new suggested hour limits. The remaining 65 percent of driver were split in their preferences. Over one-half of drivers occasionally had problems with hours-of-service regulations, with the major problems being caused by uncontrollable circumstances like tight schedules and bad weather conditions (both are almost one-half) or problems with traffic. Drivers were concerned with their income, as the response of 45 percent showed that hours-of-service regulations could be a limiting factor.

Over two-fifths of the drivers had less than ten years driving experience and the same portion of drivers had changed employers between 3 or 4 times. Income was the reason for changing jobs for more than two-third of the drivers. Scheduling and equipment considerations also were incentives for one-third of drivers to change their employers. The age majority of the drivers responding to the survey were between 30 and 49. One-fifth of the drivers recommended other changes in hours-of-service regulations, such as a 40-hour work week, shippers and receivers' being responsible for adhering to current hours laws, and increasing wage and speed limits. For the most part the laws associated with hours-of-service are thought to be reasonable, according to the drivers surveyed.

RECOMMENDATIONS AND CONCLUSIONS

Hours-of-service regulations include a special rule allowing two extra hours driving time associated with bad weather and traffic tie ups; allowing extra hours for drivers who have time problems while on-duty but waiting to be loaded would be consistent with this provision. Their extra hours would not be charged against driving time if the driver had the ability to rest while waiting. Also, shippers need to be concerned with the extra work load they are placing on the driver. They should be willing to compensate the driver for money lost while waiting, and offer any extra help to see that the driver can use this time to rest up for the trip.

The researcher also recommends if at anyone choosing the occupation of driving a truck to make a living needs to know the physical burden and responsibility associated with trucking. Truckers need to use this information to promote their own personal health, but also to help make our public highways a safe place to travel. The most important preparation for each trip is to get the proper sleep. Second, drivers should be encouraged to develop an exercise routine into their daily schedule before they start and when they take a break. Third, drivers need to eat a light and healthy diet that is most appropriate for travel.

In summary, this researcher found out how difficult it is to make the hours-of-service regulations to suit all different types of truck drivers. In my opinion, the FHWA needs to review the hours-of-service regulations to ensure they are set a level that balances the needs of all involved: truck drivers, shippers, receivers, and for the safety of the general public.

ACKNOWLEDGMENTS

The authors would like to thank Dr. Clyde K. Walter, Mark A. Walkup, and other people's assistance in the preparation of this paper.

REFERENCES

1. McNamara, J. "Hours-of-Service Rulemaking Nears." *TT News*, 23 September 1996: http://www.ttnews.com/daily.archive/09.23.fp.html

2. Lewis, J. "Trucking Chief Welcomes Start of Proposed Rulemaking for Hours of Service," *News Releases*, 6 November 1996: http://www.trucking.org/press/hours.html

3. Thomas, J. H. *The Long Hall,* Memphis: Memphis State University Press, 1979.

4. Wagner, W. H. *A Legislative History of the Motor Carrier Act, 1935*, Denton, MD: Rue Publishing Company, 1935.

5. Childs, W. R. *Trucking and the Public Interest*, Tennessee: The University of Tennessee Press, 1985.

6. Hudson, W. J. *Motor Transportation*, N.Y.: The Ronald Press Company, 1958.

7. Taff, C. A. *Commercial Motor Transportation*, Homewood: Richard D. Irwin, Inc., 1955.

8. *Federal Motor Carrier Safety Regulations Pocketbook*, Wisconsin: J. J. Keller & Associates, Inc., 1997.

9. *A Driver's Guide to the Daily Log*, Wisconsin: J. J. Keller & Associates, Inc., 1995.

10. Brandt, C. "Driving Time for Private Trucking." *Transport Topics*, 14 July 1997: p. 25.

11. Oldtimer, "Re: HOS Regulations." *Break One-Nine*, http://www.roadking.com/Breaking1-9/messages/891.html

12. Kniefel, B. "Hours of Service Another Opinion." http://www.yondar.com/writers/hosbob2.html

13. "Truck Driver Hours." *NRMA Today*: http://www.nrma.com.au/articles/library/trukhrs.htm

14. "Hours of Service (Canada)." http://www.cgo.wave.ca/~smcgrath/hours.htm

15. Schulz, J. D. "Are Shippers the Next Target?" *Traffic World*, 14 October 1996: pp. 12-13.

16. Schulz, J. D. "Trucker Faces 35-year Prison Term in Fatigue Case." *Traffic World,*" 1 January 1996: pp. 26-27.

17. "Fatigue--an Unseen Trap for Truckers." *Awake!* 8 August 1997: pp. 21-23.

18. *Safety Study*, Washington, D.C.: National Transportation Safety Board Bureau of Field Operation, 12 October 1988.

19. Fuller, N. P. and C. K. Walter. "Job Satisfaction of Iowa Truck Drivers." *Journal of The Transportation Research Forum*, Transportation Research Forum, v. 33, n. 2, 1993: pp. 42-55.

20. Taylor, G. S. and G. B. Turner. "Driver Turnover and Management Policy: A Survey of Truckload Irregular Route Motor Carriers." *Transportation Journal*, v. 33, n. 2, Winter 1993, pp. 15-21.

21. Schulz, J. D. "Survey Identifies Reasons for High Driver Turnover." *Traffic World,* 25 March 1991: pp. 25-26.

1. Listed below are some possible changes to the hours-of-service regulations. Which one do you prefer?
   - ☐ 10 hours driving, 10 to 12 hours off-duty
   - ☐ 12 hours on duty and 12 hours off-duty
   - ☐ 13 hours driving per day
   - ☐ 14 hours driving per day
   - ☐ No change from current regulations (10 hours driving, 8 hours off-duty; 15 hours on duty, 8 hours off-duty; 60 hours in 7 days; 70 hours in 8 days.)

2. Have the current hours-of-service laws caused you problems?
   - ☐ Never (if never, please go to # 4)
   - ☐ Occasionally
   - ☐ Frequently

3. Why have the hours-of-service laws caused you problems? Please check all that apply.
   - ☐ Limits opportunity for more income
   - ☐ Tight schedule
   - ☐ Traffic jams
   - ☐ Equipment breakdown
   - ☐ Bad weather
   - ☐ Others, such as ______________________________

4. How many years have you driven a truck? ___ years

5. Have you changed employers since you became a truck driver?
   - ☐ Yes (if yes, how many times? ____ times)
   - ☐ No (if no, please go to # 7)

6. What was the reason for changing employers?
   - ☐ Equipment
   - ☐ Schedule
   - ☐ Income
   - ☐ Other ______________

7. Please indicate your age:

☐ Under 20	☐ 40 to 49
☐ 20 to 29	☐ 50 to 59
☐ 30 to 39	☐ 60 and above

8. Optional: If you can recommend other changes in the hours-of- service laws, please write them on the back. Thank you again for your help.

APPENDIX C

Survey question number 3: drivers' responses to "other."

1. Possible over sleeping
2. Off duty time
3. Speed laws different ineach state and way they are enforced state by state
4. Poor shipping & receive
5. Sitting (waitting) to load or unload: on duty/not driving. Big warehouses can be hours to wait.
6. Lay overs not being albe to drive home
7. Lack of sleep on regular basis
8. Customers don't think realistically about how much time it take to move their freight. Everybody expects everything done overnights or yesterday. Pushing trucking companies to turn noncompliant to get the job done.

APPENDIX D

Survey question number 6: drivers' responses to "other."

1. Employers who aren't willing to comprimise such as hours or schedules
2. Went out of business
3. Bought own truck
4. Dispatcher & home time
5. More home time
6. Local work
7. Fired
8. To be home more often
9. Personal
10. Management opportunities

APPENDIX E

Survey question number 8, drivers' recommendations for hours-of-service regulations.

1. 12 on & 12 off then go back to 70 hrs available--
2. You wirk 8 hrs go home, work eight more tomorrow ect. and make a living. Why can't I? It seams all trucking Co. want 70 hrs 8 days. I say get real!
3. Increase truck speed limits
4. Companies should be monitered closing because they ignore all regulations Anyway!
5. I like the idia of starting 70 hr. after 24 hr.off
6. Shipper and receiver should provide labor for loadding and unloading
7. Pay on dock the same as driving
8. The shippers and consigners should be held accountable as well for violations, accidents, fines, etc... due to non-compliance of Hours of Service. Maybe then they will be more realistic about when they want their frieght and won't choose non-compliance companies to handle their fritght. In time alll companies will be more compliant or go out of business.
9. There just like a comic book. There a real Joke!!
10. More money per hour.

Heng Wei
PhD Student
Civil Engineering
University of Kansas

A Study of Heuristic-Optimization Models for Service-Request Vehicle/Crew Routing with Time Windows in a GIS Environment

A Study of Heuristic-Optimization Models for Service-Request Vehicle/Crew Routing with Time Windows in a GIS Environment

HENG WEI

This paper addresses the construction of effective heuristic-optimization models for the Service-Request Vehicle/Crew Routing with Time Windows (SRVCRTW) problem. Three basic models and the development of a software package for SRVCRTW problem in a Geographic Information System (GIS) environment are presented. Among three basic models, Hard-TW Model improves Solomon's model in terms of insertion criteria and defines the double-objective for SRVCRTW problem. Impacts of contributing factors on route solutions are analyzed and a set of appropriate values for these parameters are suggested based on tests carried out in a real case study; Second, Negotiable-TW Model and Division-Duty Model are proposed based on the demand of real-life service-request problems. Finally, the software package developed in a GIS environment provides an effective and convenient tool to SRVCRTW problem. With the use of good programming procedures and attention to related database structure, excellent performance and functionality was experienced.

The Service-Request Vehicle Routing with Time Windows problem (SRVCRTW) is concerned with the design of minimum-cost crew routes to service a set of customers with desired service periods, or so-called Time Windows (TW), originating and terminating at one or more central depots. Utility service, for instance, including regular or emergency examination and repair of utilities requested by customers, is one of applications of SRVCRTW.

Similar with general Vehicle Routing Problem with Time Windows (VRPTW), the objective of SRVRPTW is to service all customers while minimizing the number of vehicles and travel cost without violating the time constraints. Meanwhile, it has to deal with some specific time constraints except for customer requested time windows, such as crew's morning and afternoon break time, lunch time and overtime, and etc.. In addition, on-line requests and emergency calls may force rescheduling parts of initial routes or already-in-service routes. Consequently, in order to minimizing crew's waste time, which is usually caused by waiting time, some customers may have to violate their time windows if insert additional unrouted customers. This arrangement with violations of time windows needs negotiations with those special customers. In the real world, this kind of negotiable way is potentially useful to make an effective and efficient arrangement of an individual crew's route for routing the maximum number of customers.

Professional crews usually have different responsibilities because of their professional skills and territory distribution of their duties. For example, electricity, water or gas utility services require workers or technicians trained in corresponding fields. Accordingly, crews in different territories may be in charge of service for specific groups of customers. On the other hand, no need to pick up or delivery exists in SRVCRTW, so capacity constraints and size of the vehicle fleet will be ignored. Therefore, it is very necessary to distinguish this type of real-life routing problem from conventional VRPTW, defined as the Service-Request Crew Routing with Time Windows (SRVCRTW) problem in this paper.

Three basic models for SRVCRTW are proposed in the paper: Hard-TW Model which results in a route without violation of time windows; Negotiable Model that produces solutions with negotiable time windows, i.e., arrival time at some customers may be permitted beyond time window but targeted minimum violation; and Division-Duty Model in which each crew has responsibility to each specific territory, and also has opportunities to serve remained unrouted customers of adjacency territories if his current routing schedule allows him to do so using above two models. The findings of Solomon, Koskosidis, Russel, Thangiah [Solomon 1986 &1987, Koskosidis 1992, Russle 1995 and Thangiah 1996] indicate that Heuristic algorithm have been quite successful in dealing with large-scale vehicle routing problems with time windows and have so far offered the most promising results for solving realistic size problems. With the adoption of basic principles of Heuristic algorithm proposed by Solomon, the basic model of SRVCRTW algorithm, Hard-TW Model, is established with new structure of heuristic insertion criteria for double objectives, i.e., minimize total route travel cost with maximum routed customers. The studies of Thangiah and Potvin [Thangiahand etc. 1996, Potvinour etc. 1993] and the author's research indicate that "seed" impacts significantly on route solutions, particularly in terms of number of routed customers. Based on double objectives, optimal solution is produced among all "seed" alternatives. The concept of "Soft" time window [Koskosidis 1992] gave authors insight into design of the Negotiable Model of SRVCRTW algorithm. Referring to multiple crew routes, Division-Duty Model is designed according to the demand of real-life service-request problems.

Heng Wei, Doctoral Student, Transportation Center, 2011 Learned Hall, The University of Kansas, Lawrence, Kansas 66045

Geographic Information System (GIS) provides an excellent platform for the storage, analysis, and presentation of abstract transportation network and analysis results. Some advanced GIS packages (e.g. MapInfo) provide application development environments.

One of the advantages to being in the GIS environment is the availability of data required to support transportation applications. Street level maps are available from the TIGER files, CTPP files or commercially available street map providers. These vendors support all of the popular platforms, or one can find translators that will convert from one format to another. Other critical information such as block group and census tract maps and data are readily available. Transportation related GIS are rapidly becoming available at significantly reduced costs.

Therefore, the graphics and database engines found in GIS software can easily and efficiently manipulate the data into the format required by the transportation models. Since the collection and processing of transportation data required to support the transportation models is very time consuming and expensive, the use of existing data can have a significant impact on project costs. This feature is a major improvement in the efficiency of transportation officials. The generation of the models with the original transportation software packages was cumbersome and costly.

Regarding availability of GIS and its advantages of dealing with spatial data analysis, a software packages for SRVCRTW was developed in a GIS environment. The author is working in three different development environments: MapInfo, MapBasic/Visual Basic and Visual C++. MapInfo is used for spatial database management and results display; MapBasi/Visual Basic for data processing and transferring and user interfaces; and Visual C++ for numerical calculations.

This paper addresses the construction of effective heuristic-optimization models for the Service-Request Crew Routing with Time Windows (SRVCRTW) problem. Three basic models and the method of their software package development in a GIS environment are presented, including test examples and software's functionality. Finally, summaries and conclusions are stated, which also gives author's plan for further research on this topic.

DEVELOPMENT OF BASIC MODELS FOR SRVCRTW ALGORITHM

Notations

The rotations below will be used in following parts:

$\mu_{ijpk} = 1$, if vehicle k travels directly from customer i to customer j on route p; 0, otherwise on route p;

at_{ipk} : crew/vehicle k's arrival time at customer/order i on route p;

at_{lpk}, at_{jpk} : crew k's new arrival time at customer l and j due to customer u's insertion on route p, $at_{jpk} = at_{ipk} + tc_{iu} + LS_u + tc_{uj}$;

BK_{endk} : end time of break/lunch period for crew k;

B_{jpk} : buffer at customer j, limits to range of increase due to insertion of u immediately precede j so as to not violate any of routed customers' time windows;

BK_{stk} : begin time of break/lunch period for crew k;

d_{ij} : shortest path distance form customer i to j;

E_j : earliest time window requested by the customer/order j;

k: a given vehicle or crew ID; i,j,s represent customer in models;

L_o : end time of crew's whole work period;

L_j : latest time window requested by the customer/order j;

Ls_u : length of service at customer u;

$rn_{pk}(s)$: total routed customers/orders on route p for vehicle k if the "seed" is customer s;

s^*: the largest $rn_{pk}(s)$ value among all possible seeds (s = 1, 2, ...,M), M is total number of customers;

st_{ipk} : crew/vehicle k's starting work time;

$TC(s)_k$: total travel time cost of vehicle k on route p if seed is s;

tc_{ij} : shortest path travel time from customer i to j;

tv_{pk} : total violation of time windows on route p for crew k;

tw_{pk}: crew/vehicle k's total waiting time on route p;

Heuristic-Optimization Model with Hard Time Window (Hard-TW Model)

Hard-TW Model results in a route with correspondence to requirements of objective and time window constraints. In other words, its optimal solution absolutely has no violation of time windows, called Hard Time Window (Hard-TW). According to Solomon's insertion heuristic [Solomon 1986], a seed customer is selected to initialize a route and then insert unrouted customers one by one based on insertion criterion with satisfying all routed customers and inserted-to-be customer's time window and break/lunch constraint. Table 2-1 shows mathematical expression of Hard-TW Model. The insertion heuristic is described step by step below:

Step 1: Select a seed customer s among all unrouted customers. Now the initial route is from depo to the seed and then bake to depo.

Step 2: Suppose that customer i and j is a pair of two immediate adjacent customers on current route with direction form i to j. Try each unrouted customer u to insert between all possible i and j on the initial route. First of all, check if u and j satisfy their time windows and break/lunch constraints. Then, check if j violates his "Buffer" constraint due to u's insertion. Customer u's insertion will cause j and all those routed customers who are following j on current route to postpone their arrival time at the length of $at_{jupk} - at_{jpk}$. Each routed customer j in fact has tolerance of the largest postponement of his arrival time due to u's insertion, that is, $L_{jp} - at_{jupk}$. The Buffer of customer j is defined as $B_j = min\{(L_{lp} - at_{lupk}); j = 1, 2, \ldots, M, l = j, j+1, \ldots, M\}$; If all above time window constraints are satisfied, proceed to Step 3; otherwise go start Step 2 again.

Step 3: For each unrouted customer u, compute its best feasible insertion place (marked u^* in the math model) in the emerging route as the First Insertion Criterion as described in Table 2-1. For each u^*, the best customer u^{**} to be inserted in the current route is chosen as the one which satisfies the Second Insertion Criterion described in Table 2-1.

Step 4: Go back to Step 2 until all unrouted customers are examined. Then the best feasible customer u^{**} is finally inserted into current route so that a new initial route is generated.

Step 5: Repeat Step 2 through Step 4 until either all unrouted customer are routed or no more unrouted customer can be inserted. The route for seed **s** is generated, and called **s**-route.

Table 2-1. Mathematical Expression of Hard-TW Model

Objective: $\min TC(s^*)_k = \min\{\text{total travel cost of a route } s^*_k\}$,
$(s^*_k = \max\{rn_{pk}(s)\ i,j,s=1,2,\ldots,M\})$;

Subject to:

initial route:	*select a unrouted customer s as seed;*
time window constraint:	$E_j \le st_{jk} \le L_j$ $(j = 1, 2, \ldots, M)$;
"buffer" constraint:	$at_{jpk} \le \{\min(L_j, B_j);\ B_j = \min\{(L_{lp} - at_{lupk});\ j=1,2,\ldots,M,\ l=j, j+1, \ldots, M\}$;
break/lunch constraint:	$BK_{endk} \le at_{jpk} \le BK_{stk}$ $(j = 1, 2, \ldots, M)$;
first insertion criterion:	$C_{1pk}(i(u^*),u,j(u^*)) = \min\{C_{1pk}(i,u,j);$ *all possible pairs of i and j on current route*$\}$;
	$C_{1pk}(i,u,j) = \{(P_{11}C_{11pk} + P_{12}C_{12pk} + P_w tw p_k);\ P_{11}+P_{12}+P_w=1,\ P_{11}, P_{12}, P_w \ge 0\}$;
	$C_{11pk} = \{(d_{iu} + d_{uj} - d_{ij})$, *all possible pairs of i and j on current route*$\}$;
	$C_{12pk} = \{(at_{jupk} - at_{jpk} + Ls_u)$; *all possible pairs of i and j on current route*$\}$;
	$tw_{pk} = \sum \max\{(0, E_{jp} - at_{jpk});$ *all routed j plus u*$\}$;
second insertion criterion:	$C_{2pk}(i(u^{**}),u^{**},j(u^{**})) = \min\{C_{2pk}(i(u^*),u^*,j(u^*))$; *all possible pairs of i and j on current route*$\}$;
	$C_{2pk}(i(u^*),u^*,j(u^*)) = TC(s)_k = \{\sum tc_{ij}\,\mu_{ijpk}\}$; *all possible pairs of i and j on current route*$\}$;

Table 2-2. Testing Waiting Time Factor's Contribution to the Insertion Heuristic

Test group #	Total customers in the group	Total routed customers on route given by model #1	Total routed customers on route given by model #2
2	11	11	10
3	14	12	11
7	15	12	11
8	13	13	12
11	10	10	9
12	10	10	9
13	11	10	9
15	12	11	10
16	13	12	11
17	12	10	9
18	12	11	10
23	12	10	9
25	9	8	7
Other 12 groups		these groups' results are same	
Total difference		model #1 totally services 13 more customers than model #2 to test samples	

Note: 1). in model #1: P_{11}=0.25, P_{12}=0.40, P_w=0.35; in model #2: P_{11}=0.45, P_{12}=0.55;
2). all customers in each of 25 groups were picked up randomly from Solomon's Instance R107;

Table 2-6. Example: Crew #10's Routing Schedule by Negotiable-TW Model

Order_No	Order_ID	Start_T W	End_TW	Arrival_ Time	Actual_ Start	Waiting_ Time	Service_ Time	Violation
0 (depot)	0	800	1300	800	800	0	0	0
1	205	800	900	808	808	0	12	0
2	211	815	1000	828	828	0	11	0
3	201	800	930	842	842	0	10	0
4	213	900	1100	858	900	2	10	0
5	208	900	1100	920	920	0	12	0
6	204	930	1040	939	939	0	8	0
7	210	930	1100	955	955	0	10	0
8	203	1000	1100	1016	1016	0	10	0
9	209	930	1200	1032	1032	0	7	0
10	212	1040	1240	1052	1052	0	15	0
11	202	930	1100	1123	1123	0	12	23
12	206	1100	1200	1147	1147	0	11	0
13	207	1130	1200	1206	1206	0	10	6
14	214	1200	1300	1220	1220	0	10	0
0 (depot)	0	800	1300	1240	0	0	0	0

Step 2 through **Step 4** are the same as Hard-TW Model except:

• In Step 2, only check Break/Lunch and Crew's work hour constraints;

• In Step 3, total violation of time windows tvp_k replaces the total waiting time twp_k in the first insertion criterion.

Step 5: Repeat Step 2 through Step 4 until either all unrouted customer are routed or no more unrouted customer can be inserted. The route with negotiable time windows is generated, and all customer with whom the schedule manager needs to negotiate about violating their desired time windows are called Negotiable Customers.

Figure 2-1 shows the result of an example by Hard-TW Model. Provided that there are 14 customers need utility inspection service within their desired period of time. All of them are located in City of Lawrence, Kansas. The task here is to propose a minimum-cost routing schedule for Crew #10 to provide service with time window constraints. 13 of total 14 customers are routed by Hard-TW Model. Customer/Order #212 is not routed due to his time window's restriction. Table 2-5 indicates the routing solution including each customer's basic information such as location, time window, arrival time, waiting time and service time. Crew's back time is 12:20 PM, earlier 40 minutes than his scheduled work hour. Additionally, total waiting time at customer #213, #207 and #214 is 23 minutes (shadow areas in Table 2-5). It implies that the crew is still capable of serving more customers.

Figure 2-6 shows the solution of the same example by Negotiable-TW Model, in which the initial route is given by Hard-TW Model, as demonstrated by Figure 2-1. An additional unrouted customer #212 is inserted into the initial route and causes two routed customers' time windows (#202 and #207) negotiable (shadow areas in Table 2-6). Customer #202 has a 23 minutes of violation, i.e., the crew's starting work time is scheduled at customer #202 to be 23 min later than his desired. Similarly, 6-minute delay is caused at customer #207's schedule. It is also noticed that total waiting time goes down to 2 minutes since customer #212's insertion, which means that new solution enhances the efficiency of crew's schedule if negotiable time windows at customer #202 and #207 reach agreement. In Figure 2-1 and 2-2, thick solid lines/polylines represent real road route between customers while the thin straight lines between customers show the direction of the route or the service order.

In the practical execution of the computer program, an information board will appear on the screen after the Hard-TW and the Negotiable-TW Model have been gone through, as illustrated as Figure 2-3. It helps operator to have a first glimpse of comparison of routing schedules between above two models, and make a quick response for negotiation and decision-making. The program can save those separately, in graphs and tabular tables in a GIS environment, or MapInfo platform.

Division-Duty Model for Multi-Crew Routing

In the real world, professional crews usually have different responsibilities because of their professional skills and territory distribution of their duties. For example, electricity, water or gas utility services require workers or technicians trained in corresponding fields. Accordingly, crews in different territories may be in charge of service for specific groups of customers within a given territory. Division-Duty Model is proposed here to deal with this type of routing problem. In Division-Duty Model, each crew has responsibility to each specific territory, and also has opportunities to serve remained unrouted customers of adjacency territories if his current routing schedule allows him to do so using above two models. Its procedure is described as the following:

Step 1: Produce routes for each appointed crew of every territory using Hard-TW Model.

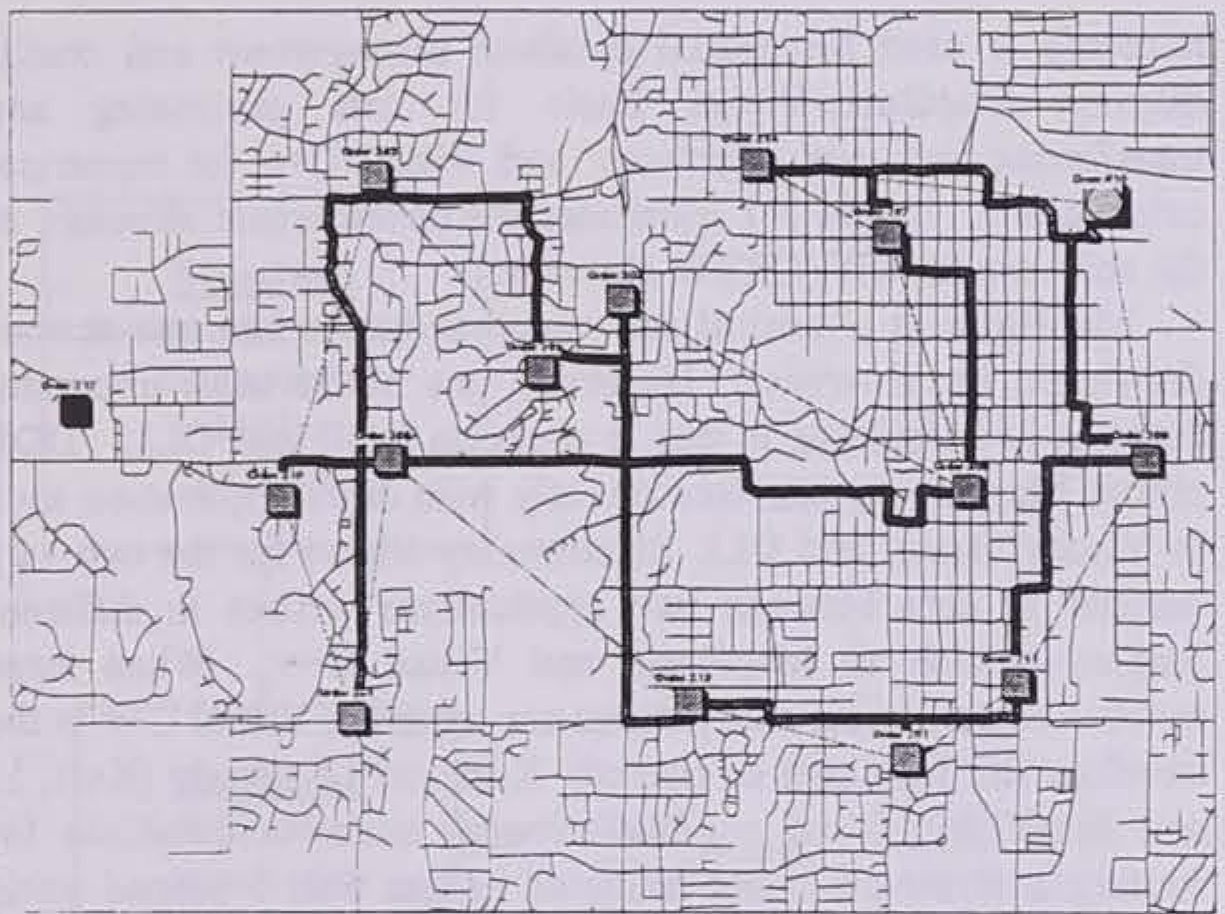


Figure 2-1. Crew #10's Routing by Hard-TW Model

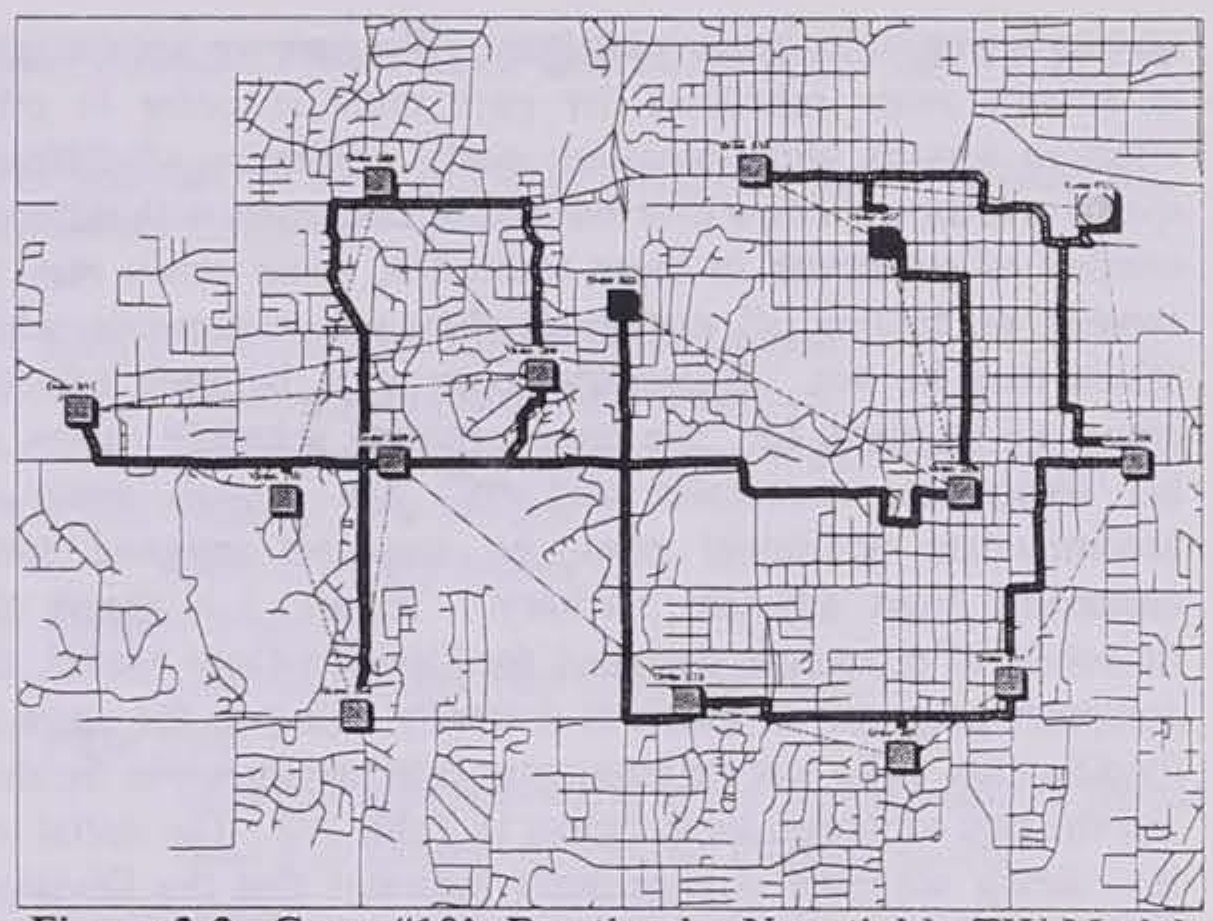


Figure 2-2. Crew #10's Routing by Negotiable-TW Model

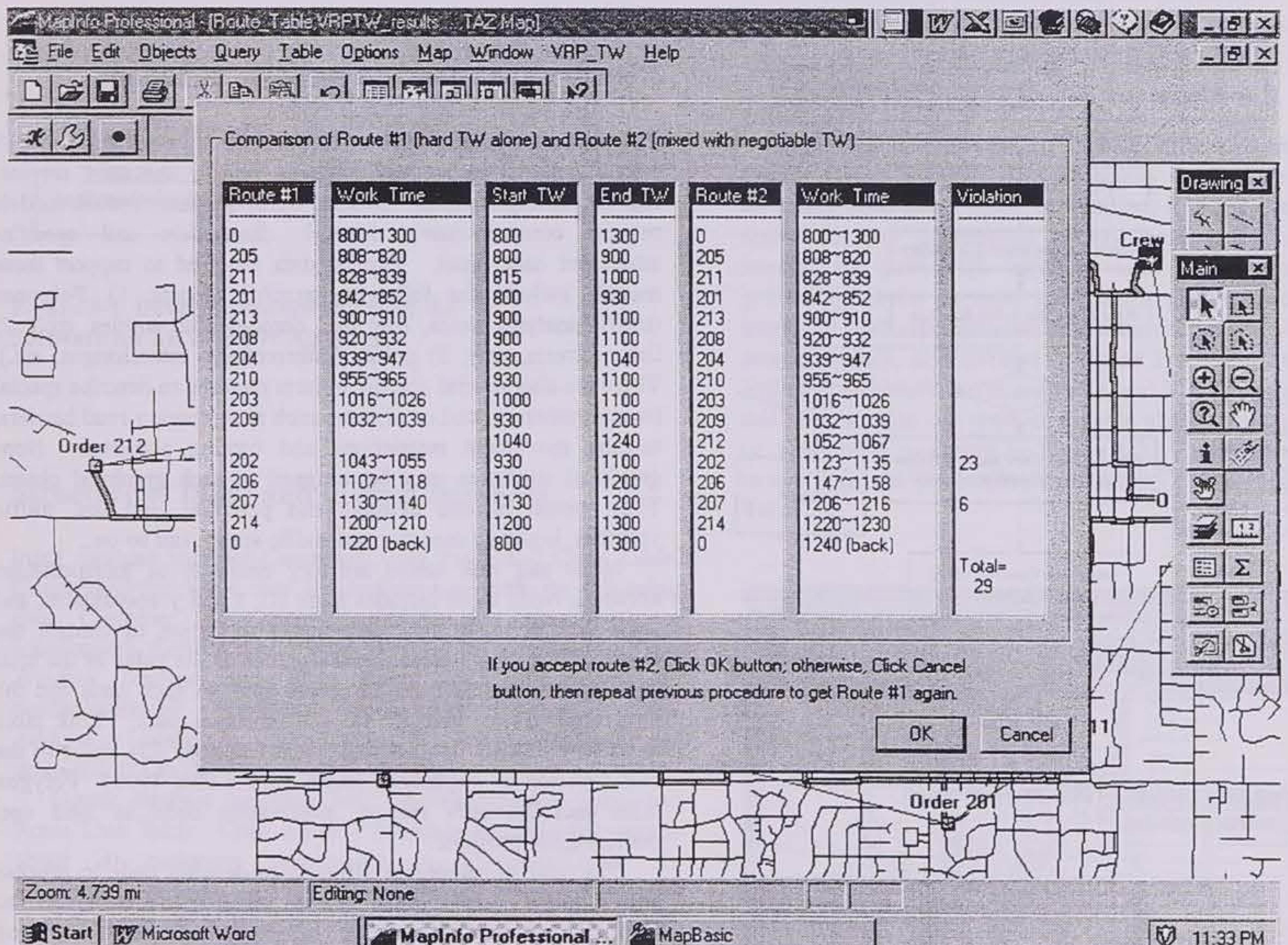


Figure 2-3. Quick Glimpse of Routing Schedules between Hard-TW & Negotiable models

Step 2: If the route is not filled full out of crew's whole work hour period, add unrouted customers of adjacent territories using Hard-TW first till no more can be inserted.

Step 3: If unrouted customers still exist, then insert more unrouted customers till the crew's schedule is full, using Negotiable Model in necessary.

A test study was conducted using a real record of customers' order list with time windows for a city in Texas, which was provided by a utility company in Texas. There are ten territories with one crew each. A list of customers who request utility service is available for each territory. The task we are facing is to arrange route schedules for each crew in order to offer effective service with minimum costs. Because of different spatial and time window distributions of customers with different number of customers in these territories, some crews may be capable of serving all customers they are responsible while others may be not. Necessary cooperation between adjacent crews are required, i.e., if a crew's routing schedule covers all his responsible customers and still has enough room to accommodate additional ones, he may be assigned some customers from adjacent territory. Figure 2-4 shows the flowchart of procedure designed for Division-Duty Model, the computer program of which is currently being in the stage of modification. The test for parameter determination was finished and the part of its results is shown in Table 2-2. The initial test for routing schedule arrangements indicates that the Division-Duty Model is potentially very practical. More details about this case study will be discussed in another paper.

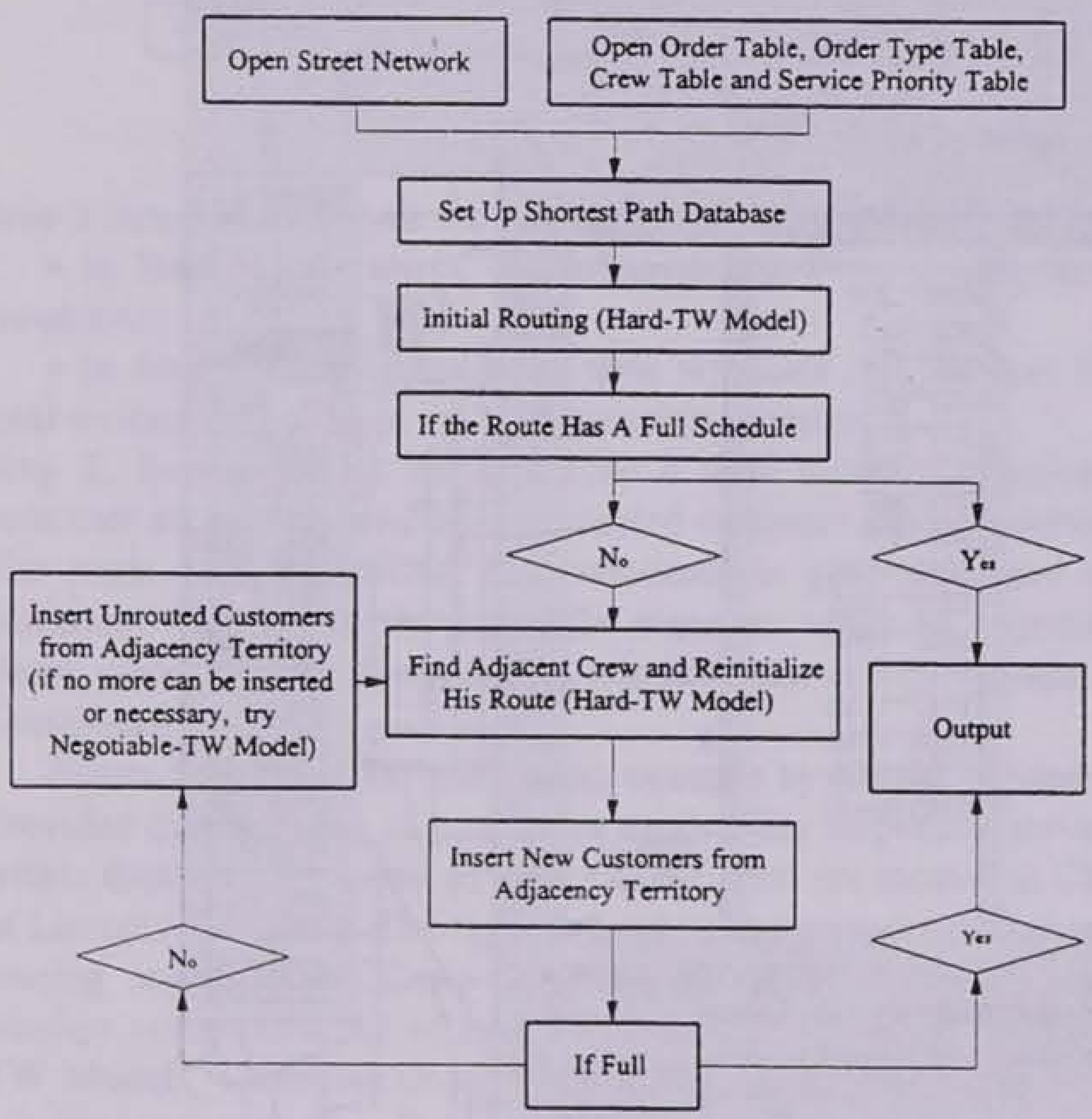


Figure 2-4. Flowchart of Procedure Designed for Division-Duty Model

DEVELOPMENT OF THE SOFTWARE IN A GIS ENVIRONMENT

Development Environments

The author is working in three different development environments: MapInfo, MapBasic/Visual Basic and Visual C++. MapInfo is used for spatial database management and results display; MapBasic/Visual Basic for data processing and transferring and user interfaces; and Visual C++ for numerical calculations. Figure 3-1 illustrates the development structure of the software for SRVCRTW algorithm.

MapBasic is a critical environment but it has one serious drawback, i.e. slowness. However, one of the most important features of MapBasic is that it supports DDE and DLL. DDE allows MapInfo to interface directly with other application such as Visusal Basic, and DLL functionality allows for the two way transfer of data between two applications written in different languages such as MapBasic and Visual C++. When large number of numerical calculations are required, Visual C++ is the development language of choice. Kurt and Li's study [Kurt, Li and Zhu 1995] found out that network over 100,000 links for routing analysis are being analyzed in less than 5 second using C++ while MapBasic would take 13 hours to analyze a network of approximately 3500 links. Therefore, improvement of analysis speeding results from using Visual C++.

Network Creation and Its Basic Functions

The network model provides the basis for an application of GIS into transportation analysis such as vehicle and crew service-request routing analysis. General transportation network models require comprehensive network description and specific-structured data input. Typical data required to support these models include the following graphic objects: 1). Polygons (traffic analysis zones, land use, demographic entities, etc.); 2) links (streets, etc); 3) points (intersections, interchanges, etc.). There are also special graphic objects required to describe special transportation related conditions such as temporary road barriers, turning movement restrictions and turning penalties. Non-graphical attributes may be assigned to each graphical object. They would include existing and potential land use, traffic volumes, highway capacity and traffic speed, and so on.

Node and link tables are key elements of transportation network. Node table includes node ID, x and y coordinates, and room that is ready for additional information to contain the results of network analysis models, such as the value of the total cost, or impedance, from an origin point to each node and the next node ID or link ID on the optimum path. Link table includes a link ID (start node ID and end node ID), value of the cost function or impedance [Kurt, Li and Zhu 1995). Polygon table includes area related information such as land use, demographic profiles.

The next development effort is to develop code to process above spatial data. Some spatial function are developed to handle transportation specific information, such as defining penalties and restriction, temporary barriers. Finally, the function of the shortest path between any two points is developed. It will be used frequently in a routing analysis. The basic principle of Dijkstra's algorithm [Balakrishnan 1995] is employed in the development of the function of shortest path; however, the algorithm must be modified skillfully to fit data structure provided by the GIS environment, i.e., MapInfo here. The speed operating this function directly influences the speed of operating the whole program for SRVCRTW.

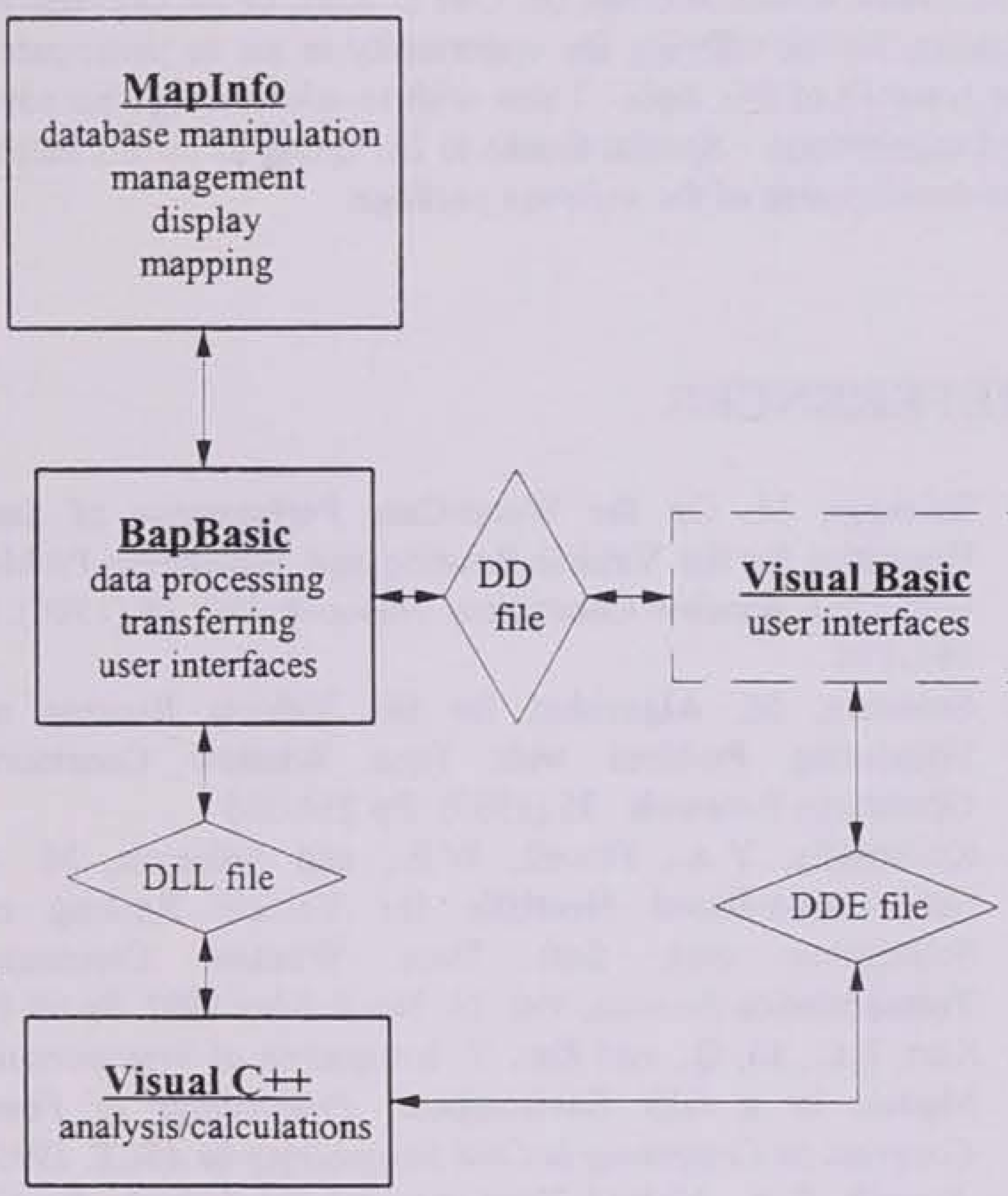


Figure 3-1. Development Structure of the Software for SRVCRTW Algorithm

Structure of Input and Output Database

Input database includes Customer/Order Table and Crew Table. Customer/Order Table may be characterized with the following data: Customer ID, Customer Address or Location (x, y coordinates), Service/Work Type, Priority (if necessary), Time Window (earliest and latest time), and Service Length needed/estimated; The Crew Table consists of Crew ID, Crew Address or Location (x, y coordinates), Break Time (begin and end time) and its Length, Crew Duty (work type);

Output database includes Crew Routing Schedule Table and Route Link Table. Crew Routing Schedule includes information about all customers represented by Customer/Order ID, arrangement of a service order with arrival and starting work time at each customer, as well as Waiting Time, Work Type, Service Length; Route Link Table consists of all links or street segments the route goes through and information about route direction (e.g., where turn left or right).

All elements in above tables correspond with and connect with graphic objects on the street map of a study area. That means that the map in fact store all information of input data and output data after implementation of SRVCRTW algorithm, and some of them can be visualized.

Functions of Software Developed for SRVCRTW

The software for SRVCRTW developed by author includes the following functions:

- Single Vehicle/Crew Optimization Models
  - Routing with Hard Time Windows
  - Routing with Negotiable Time Windows
- Multi-Vehicle/Crew Models
  - Division-Duty Model
- Create Network
  - Convert a street map into a Network
- Input Data
  - Data linked to real-world street map in MapInfo format
  - Data with Debase format (no graphic objects)
- Modify Input
  - Update Customer/Order Input: add, delete & edit
  - Update Crew Input: add, delete and edit
- GIS functions (provided by MapInfo platform)
  - create, edit, manipulate, display and visualize data or map including data graphing; query (select and SQL select, etc)

In a GIS environment, it is with easy to manipulate and display input and output data, especially to visualize output data on a real-word street map. In addition, it is very convenient to search for any information of any items (e.g., customer) of interest by query/SQL query. GIS is characterized with geocoding tabular database and graphic objects. Consequently, users can read visualized routing solutions and tabular database simultaneously, as illustrated as Figure 3-1. For input data not linked to real-world street map, if X and Y coordinates available, this program also can produce graphic object on each customer's (x, y) location, as shown by Figure 3-2. This function was used to test Solomon's examples some results of which are shown in Table 2-2.

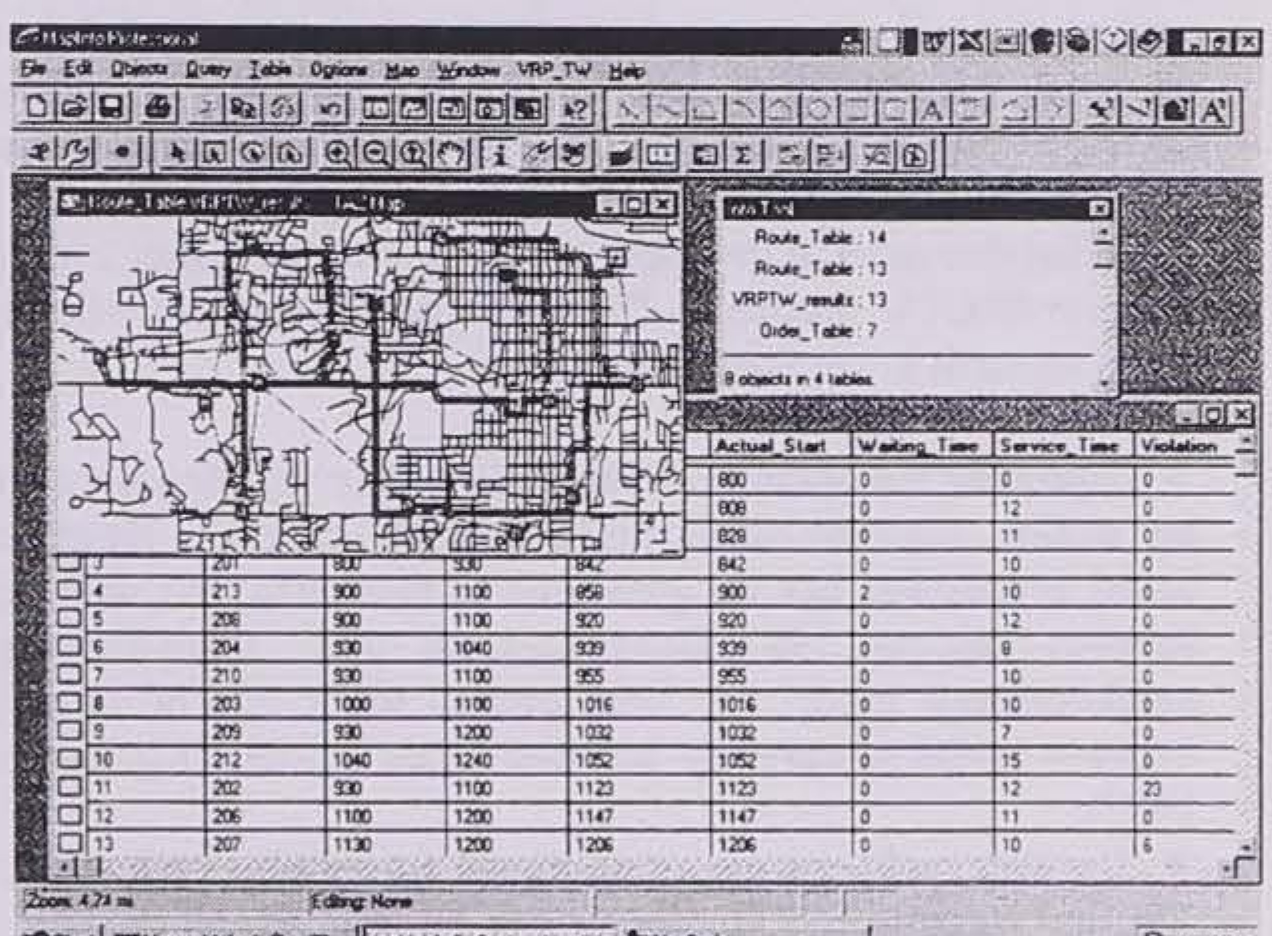


Figure 3-1. Display of Results

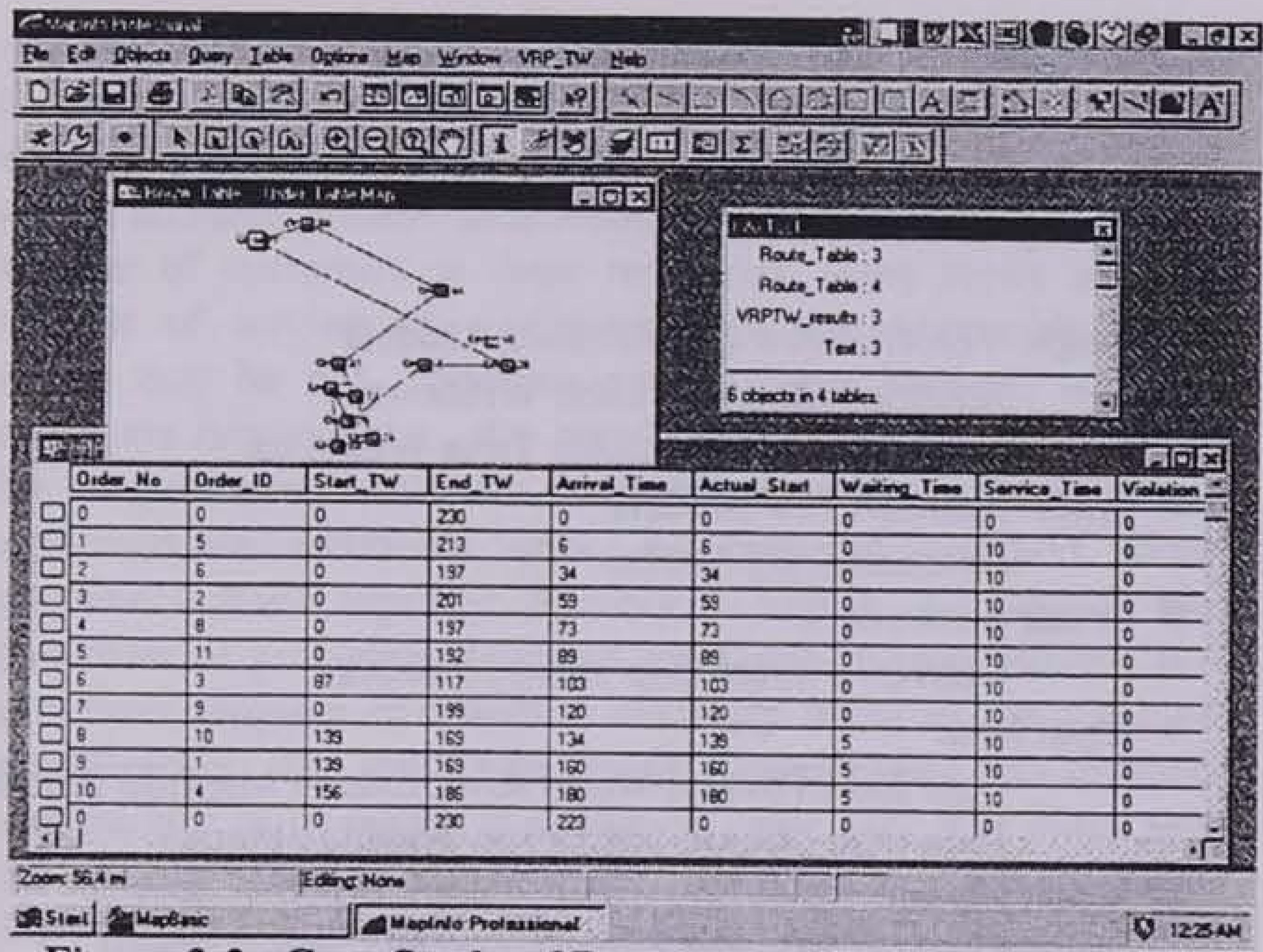


Figure 3-2. Case Study of Data not Linked to Street Map

SUMMARIES AND CONCLUSIONS

This paper addresses the construction of effective heuristic-optimization models for the Service-Request Vehicle/Crew Routing with Time Windows (SRVCRTW) problem. First, Hard-TW Model improves Solomon's model in terms of insertion criteria and defines the double-objective for SRVCRTW problem. Impacts of contributing factors on route solutions are discussed and a set of appropriate values for these parameters are suggested based on tests carried out in a real case study; Second, Negotiable-TW Model and Division-Duty Model are proposed based on the demand of real-life service-request problems. They are potentially useful and practical in route scheduling targeted at maximum number of customers and multi-route problem. Finally, also a very important contribution this paper made to solve SRCTW problem is the development of a software package. This package was already successfully applied in a real project conducted in last summer. With the use of good programming procedures and attention to related database structure, excellent performance and functionality was experienced.

What discussed in the paper is referring to the author's initial study in SRCTW problem. The author plans to make further in-depth research in the future, including:

- Improving the optimum solution for single vehicle/crew route by adding edge-exchange neighborhoods model. Heuristic-based approaches has no guarantee to reach the real optimum solution [Solomon 1987; Desrochers, etc 1988]. Edge-exchange neighborhoods model has been proved to be one of ways to improve initial solution by heuristic-based models [Kindervater 1997].
- Develop multi-vehicle route model for single depot. Hard-TW and Negotiable-TW Models can be used as sub-models or sub-directories for multi-vehicle/crew problem. In fact, Division-Duty deals with multi-vehicle route problem for multi-depots.

ACKNOWLEDGMENT

The author wishes to thank Dr. Carl E. Kurt, of the University of Kansas, for his offering the opportunity to me to participate in the research of this topic. I also wish to acknowledge his advice and suggestions. Special thanks to Dr. Qiang Li for his helps to the development of the software package.

REFERENCES

1. Solomon, M. On the Worst-Case Performance of Some Heuristics for the Vehicle Routing and Scheduling Problem with Time Window Constraints. *Network*. Vol. 16 (1986). Pp 161-174
2. Solomon, M. Algorithm for the Vehicle Routing and Scheduling Problem with Time Window Constraints. Operations Research. 35 (1987). Pp 254-265
3. Koskosidis, Y.A., Powell, W.B., and Solomon, M. An optimization-Based Heuristic for Vehicle Routing and Scheduling with Soft Time Window Constraints. Transportation Science, Vol. 26. No. 2. May 1992. Pp 69-89
4. Kurt, E.C., Li, Q., and Zhu, Y. Integration of Transportation Models in a GIS Environment. *Proceedings of Fourth Congress on Computing in Civil Engineering by ASCE. 1995*
5. Russell, R.A.. Hybrid Heuristics for the Vehicle Routing Problem with Time Windows. *Transportation Science*. Vol. 29, No. 2, May 1995. Pp 156-166
6. Potvin, J.V., and Rousseau, J.M. A Parallel Route Building Algorithm for the Vehicle routing and Scheduling Problem with Time Windows. *European Journal of Operation Research* 66 (1993) Pp 331-340
7. Thangiah, S.R., Potvin, J.V., and Sun, T. Heuristic Approaches to Vehicle Routing with Backhauls and Time Windows. Draft submitted to *the International Journal of Computer and Operations Research*. 1996
8. Thangiah, S.R., Osman, I.H., and Sun, T. Hybrid Genetic Algorithm, Simulated Annealing and Tabu Search Methods for Vehicle Routing Problems with Time Windows. Draft. 1996
9. Thangiah, S.R., Osman, I.H., Vinayagamoorthy R., and Sun T. Algorithms for the Vehicle Routing Problems with Time Deadlines. American Journal of Mathematical and Management Science. 13(3&4). Pp 323-355
10. Desrochers, M., Lenstra, J.K., Savelsbergh, M.W.P., and Soumis, F. Vehicle Routing with Time Windows: Optimization and Approximation. *Studies in Management Science and Systems*. Vol. 16 (Vehicle Routing: Methods and Studies). 1988. Pp 65-84
11. Balakrishnan, V.K., *Network Optimization*. CHAPMAN & Hall, 1995
12. Kindervater, G.A.P and Savelsbergh, M.W.P. Vehicle Routing: Handling Edge Exchanges. *Local Search in Combinatorial Optimization*. John Wiley & Sons 1997. Pp 337-36.

Matthew Eatherton
Undergraduate Student
Civil Engineering
University of Missouri at Columbia

Enhancements in the Ductility of FRP Reinforced Beams Through the Use of Fiber Reinforced Concrete

Abstract

Chloride and de-icing salt-related corrosion observed in conventional steel rebars does not occur for fiber reinforced polymer (FRP) rebars. As a result, research interest using FRP reinforcement for concrete has grown over the last few years. There are, however, other issues that have to be addressed before use of FRP bars as an alternate to steel rebars, for some structural applications, can become acceptable. One of the main concerns while using FRP is it's brittle nature of failure. Most FRP rebar act elastically up to failure, without exhibiting any significant inelastic deformation. When used compositely with concrete, another brittle material, there is very little warning, and comparatively low energy absorption during failure.

Another relatively new technology in structural materials is fiber reinforced concrete (FRC). FRC has been proven to improve the energy absorption characteristics of concrete. Consequently, using FRC in conjunction with FRP is expected to enhance the ductility of the FRP concrete structure. This premise was the basis for the experimental program reported here.

Four beams were tested, two with polypropylene fibers and two without fibers, all reinforced with FRP reinforcing bars. The results are also compared to those from the previous tests of three steel reinforced concrete beams of similar dimensions. Differences in the load-deflection response, cracking characteristics, energy absorption and failure are discussed and compared. It is concluded that the addition of fibers enhances the ductility of FRP reinforced beams and alters the failure mechanism by preventing bond-splitting fracture.

I - Introduction

In the past few decades the deterioration of the nation's infrastructure has prompted the investigation of new technologies for certain structural applications. One issue that is of great concern is the corrosion of reinforcing steel. Corrosion is a major problem in concrete structural elements, especially in bridge decks and parking structures where de-icing salts are used. One potential solution to this problem receiving research attention, is the use of fiber reinforced polymers (FRP) instead of steel as reinforcement.

Fiber reinforced polymers consist of synthetic or organic high-strength fibers impregnated with a resin matrix. The fibers, which have a high tensile strength and high modulus of elasticity, are the load-bearing component in FRP. The resin is the bonding material used to hold the fibers together, prevent shear between them, and to protect the fibers against adverse chemical attack. While the fibers, like glass, may be vulnerable to alkaline environments, the resin can be engineered so that FRP does not exhibit corrosion of the same nature as steel.

For structural applications, however, the brittle failure of most FRP demands attention. FRP acts elastically up to failure, exhibiting virtually no inelastic deformation. Concrete also exhibits a brittle failure, and as a result the FRP reinforced concrete element is generally brittle. FRP reinforced concrete beams absorb less energy during failure than properly-designed steel reinforced concrete beams and do not provide as much warning prior to failure.

Fiber reinforced concrete (FRC) is another relatively new structural material. It has been proven that FRC can absorb more energy during failure than normal concrete. As a result of this increased toughness, using fibers in the concrete mix is expected to increase the ductility of the FRP reinforced concrete elements. The experimental program described in this report was based on this idea.

Four beams were tested. Two beams contained polypropylene fibers in the concrete mix and two were cast with normal concrete. All beams were reinforced with FRP rebars. The performance of the beams tested was compared with that of three similar beams reinforced with conventional steel reinforcement, tested by Ghazavy [1]. Parameters compared were the load-deflection response, cracking characteristics, energy absorption and failure.

II - Background Information

The addition of randomly distributed fibers to a concrete mix has been observed to improve toughness, impact resistance and fatigue endurance of concrete by transferring stress across cracks. Fiber reinforced concrete (FRC) also exhibits a more ductile failure than concrete that is not reinforced with fibers. As a result it is expected that the failure of an FRP-FRC structural element would be more ductile than one that contans only FRP reinforcement.

A limited number of studies on the use of fiber reinforced concrete in conjunction with FRP are available in publicized literature [2,3,4]. Nawy tested 20 beams using four different reinforcement ratios [2]. For each reinforcement ratio, two beams with FRP and normal concrete, one beam with FRP reinforcement using FRC, and one beam with steel reinforcement in normal concrete were tested. The FRP bars utilized glass fibers, however, no surface treatments or helical fiber wrap was mentioned. The fibers in the concrete matrix were 31.8 mm long crimped round steel wire. The fibers were added at a dosage of 1.25% by weight. No increase in ultimate load capacity was noted for the FRC and FRP beams. No measure of energy absorption, or ductility was attempted. Nawy noted in the article, however, that for the FRP with chopped wire in the concrete beam the cracking pattern branched out more and was more jagged, suggesting that the chopped wire was contributing to resisting the tension stresses.

In the study by Banthia et al. [3] four square slabs were tested. Three of the slabs were reinforced with an FRP grid. The fourth slab was reinforced with steel rebar and served as a control slab. Of the three FRP reinforced slab, one was made with normal strength concrete, one with high strength concrete, and one with 28 mm long hooked end steel fibers mixed in normal strength concrete. Center point deflection and ultimate load experienced by the fiber reinforced slab were larger than the non fiber reinforced slab. Banthia concludes from his study that the use of fiber reinforced concrete improves the ultimate load-carrying capacity and the energy-absorption capability of slabs reinforced with FRP grids. The fibers improve the strain capacity of the concrete and delay the formation of large cracks, and thus assist the low-modulus FRP reinforcement in achieving its full potential.

Jeong and Naaman [4] tested five prestressed concrete beams prestressed with carbon fiber composite cables. Two beams were under reinforced T-beams using CFCC (carbon fiber composite cables), two were over reinforced rectangular beams using CFCC. One of the over reinforced rectangular beams contained fibers, and one of the T-beams also contained nonprestressed steel reinforcement. The last beam was a T-beam reinforced with steel strands. The fiber reinforced beam exhibited a much more ductile behavior than that of the non fiber reinforced concrete beams. Jeong and Naaman concluded from their study that the use of a fiber reinforced concrete matrix is a successful method to improve structural ductility.

The present study is aimed at studying in detail the potential enhancement in structural ductility that can be achieved through the incorporation of fibers, even while using relatively brittle FRP rebars.

III - Experimental Program

The experimental program consisted of the casting and testing of four FRP reinforced concrete beams. Two beams were cast with polypropylene fiber reinforced concrete (FRC-FRP) while the other two beams were cast with normal unreinforced concrete (FRP-normal). The two beams without fibers are referred to as FRP 1 and FRP 2. The two beams with fibers are referred to as FRP 3 and FRP 4.

All beams were reinforced with two number six E-Glass type FRP bars. The FRP bars have a nominal diameter of 3/4" (19.05 mm), the diameter of a conventional number six steel reinforcing bar. The actual diameters of the FRP bars tested were between 0.75" (19.05 mm) and 0.825" (20.96 mm) due to the surface coating of sand. The FRP bars were also wrapped helically with glass fibers to simulate deformed rebars and thus enhance bond characteristics.

Four tensile tests were done on specially prepared number six E-Glass type FRP bars that were supplied by the manufacturer, Hughes Brothers Inc. The average measured tensile strength for the number six bars was 88,567 psi (610.7 MPa). The average measured modulus of elasticity was 8.06×10^6 psi (55.6 GPa). The average measured maximum elongation was 1.11%.

The concrete mix was designed to have a compressive strength of 5,000 psi (34.48 MPa). The beams were cured in a curing room for 28 days (98% RH, 70° F). The fibers used were 52.5 mm long polypropylene meshes, manufactured by the FiberMesh Co. of Chattanooga, TN. The fibers made up 0.437 % of the concrete mix by volume. Polypropylene fibers were used in this study to maintain the magnetic transparency and the non-conducting nature of the beams.

All beams were tested with a clear span of 48" (1.219 m) between supports and a distance of 8" (203.2 mm) between load points in a four point bending setup. The a/d ratio used was 2.5. The beams were tested on a 110 kip closed loop MTS machine. The testing was controlled by the ram displacement. The dimensions of the beam are shown in Figure 1.

An LVDT was set at the mid point of the beam and was supported by a metal frame which rested on top of the concrete beam directly above the supports. This LVDT measured the deflection of the mid point of the beam as referenced to the beam at the supports. This deflection will be referred to as the net-deflection. A strain gage was attached to the compression face of the concrete beams near the midpoint of the beam. The load as measured by a load cell and the ram displacement was also recorded throughout the test. The experimental setup is shown in Figure 2. The instrumentation used during the test is also schematically illustrated in the inset of Figures 3 and 4. The crack patterns were also recorded after the failure of each beam.

IV - Results and Discussions

FRP 3 and FRP 4, which contained fibers, both sustained higher concrete compressive strains than the non fiber reinforced beams. The FRC-FRP beams also reached a higher load level before failure as can be seen in Table 1. The average ultimate load for the FRP-normal beams was 18,750 lbs (83.40 kN) while the average ultimate load for the FRC-FRP beams was 22,550 (100.3 kN). This represents a 20.3% increase in the ultimate load capacity of the beams.

The energy absorbed by the reinforced concrete beams during testing was calculated at first crack and at a net-deflection of 0.20 inches (0.00508 mm), and averaged for each series. The energy absorption results are shown in Table 2. The FRP-normal beams absorbed 37 lb-in (4.2 N-m) and 2495 lb-in (281.9 N-m) respectively. The FRC-FRP beams absorbed 34 lb-in (3.8 N-m) and 2710 lb-in (306.2 N-m) respectively. The steel reinforced beams absorbed 27 lb-in (3.1 N-m) and 2781 lb-in (314.2 N-m) respectively. At a net-deflection of 0.20 inches (5.08 mm) the FRC-FRP beams exhibited nearly the same amount of energy absorption as the steel reinforced beams, while exceeding the energy absorption of the FRP-normal beams by 8%.

It should be mentioned, however, that while the behavior of FRP 3 and FRP 4 were quite similar under loading, the behavior of FRP 1 and FRP 2 were not. FRP 1 cracked at a much higher load, 7520 lbs (33.5 kN), than the other three beams, 5810 lbs - 6150 lbs (25.8 kN - 27.4 kN). FRP 1 failed at an expected concrete compressive failure strain of under 0.0035. FRP 2, on the other hand, sustained a concrete compressive strain of almost 0.005. This failure strain is much larger than would be expected of normal strength concrete.

Even with the high strain capacity of FRP 1, the average maximum concrete compressive strain for the FRP-normal group was 0.0045 in/in. The average maximum concrete compressive strain for the FRC-FRP group was 0.0058 in/in. This represents an increase of 22% in the ultimate concrete compressive strain with the addition of fibers in the concrete mix.

The beams with fibers also demonstrated several qualitative properties under loading which were different than the non fiber reinforced beams. The failure of the FRC-FRP beams were not explosive in nature like the failure experienced with the FRP-normal reinforced beams. As can be seen in Figures 5 and 6 portions of FRP 1 and FRP 2 were dislodged, while FRP 3 and FRP 4 remained intact.

It can also be seen in Figures 5 and 6 that FRP 3 and FRP 4 sustained more cracks and that those cracks exhibited more branching. The crack widths however, remained smaller than those experienced by the FRP-normal beams. This branching and distribution of cracks shows that the fibers are in fact bridging the cracks and transferring the tensile load across the cracks.

The beams referred to as BNW 21, BNW 22 and BNW 23 in Figures 3 and 4 were tested by Ghazavy [1]. BNW 21 - BNW 23 were steel reinforced beams of the same dimensions as the FRP reinforced beams, except that the overall length was 56" (1.42 m) instead of 53.25" (1.35 m). From Figure 4 it can be seen that all 7 beams reacted very similarly up until first crack. Until first crack the stiffness of the FRP reinforced beams is lower than that of the steel reinforced beam. This is due to the low modulus of FRP rebar which is about a quarter of that of steel rebar. The steel reinforced beams then go on to display an ultimate load between that of the FRC-FRP beams and FRP-normal beams. The major differences in the response of the steel reinforced sections versus the FRP reinforced sections is the lower net deflections at ultimate and the residual strength after ultimate. It should be noted, however, that all three steel reinforced beams failed by diagonal tension in the shear zone.

Figure 3 shows that the concrete compressive strains at ultimate for the steel reinforced beams were less than a quarter that of the FRP reinforced beams, again highlighting the fact that the steel reinforced beams did not fail in flexure. This demonstrates the difference in the expected failure modes of the two types of beams. For the steel reinforced beams the steel is supposed to yield before the concrete crushes, whereas the FRP reinforced beams were designed so that the FRP would not fracture before some other type of failure occurred.

To complete a thorough investigation into the effects of fibers in FRP reinforced concrete a greater number of specimens would need to be tested. A testing program needs to be done which varies the type and percentage of fibers as well as the beam's reinforcement ratio. An in depth study of this sort would be capable of determining the optimum FRP reinforcing ratio and optimum fiber content in the concrete mix.

In this study all of the FRP reinforced beams exhibited an ultimate failure related to bond. It is evident that the characteristics of the bond between these FRP bars and concrete needs further study.

V - Conclusions

- There was a 20.3% increase in the load capacity of the beams with the inclusion of polypropylene fibers in the concrete mix.
- The FRC-FRP beams exhibited 8% more energy absorption at a net-deflection of 0.20 in (5.08 mm) than the FRP-normal beams.
- The fiber reinforced concrete sustained 22% more concrete compressive strain than the normal concrete.
- The failure of the FRC-FRP beams exhibited a much less explosive failure than the FRP-normal beams.
- The FRC-FRP beams showed more cracking and more branching of cracks than the FRP-normal beams.

VI - Acknowledgements

This experimental program was conducted under the direction of Dr. Vellore S. Gopalaratnam. The author would like to thank Dr. Gopalaratnam for all his time and guidance during the course of this study. Thanks go to Mr. Doug Gremmel of Hughes Brothers Inc for supplying the FRP used in this study. The funding provided by Mid-America-Transportation Center (MATC/UMC 97-2) to the author's advisor was also greatly appreciated.

VII - References

1. Ghazavy, Khorasgany. "Shear Failure of Normal and High Strength RC Beams." PhD Dissertation, University of Missouri - Columbia. December 1994

2. Nawy, Edward G. Neuwerth, Gary E. Phillips, Charles J. "Behavior of Fiber Glass Reinforced Concrete Beams." Journal of the Structural Division - ASCE Sept 1971 p 2203-2215.

3. Banthia, N. Al-Asaly, M. Ma, S. "Behavior of concrete slabs reinforced with fiber-reinforced plastic grid." Journal of Materials in Civil Engineering. v 7 n 4 Nov 1995. p 252-257.

4. Jeong, Sang-Mo Naaman, Antoine E. "Ductility of Concrete Beams Prestressed with FRP Tendons" Restructuring - America and Beyond: Proceedings of Structures Congress XIII ASCE. Boston, Massachusetts, April 2-5 1995. p 1466-1469.

VIII - Tables and Figures

	Energy Absorbed							
	At first crack		Average at first crack for group		At $\delta_n = 0.20$ in. (5.08 mm)		Average at $\delta_n = 0.20$ in. for group	
Beam	(lb-in)	(N-m)	(lb-in)	(N-m)	(lb-in)	(N-m)	(lb-in)	(N-m)
FRP 1	51	5.8			2580	291.5		
FRP 2	22	2.5	37	4.1	2410	272.3	2495	281.9
FRP 3	33	3.7			2703	305.4		
FRP 4	34	3.8	34	3.8	2717	307.0	2710	306.2
BNW 21	28	3.2			2838	320.6		
BNW 22	27	3.1			3179	359.2		
BNW 23	27	3.1	27	3.1	2327	262.9	2781	314.2

Table 1 – Tabulated values of energy absorption at first crack and at a net deflection of 0.20 inches (5.08 mm) for all beams.

	First Crack Load		First Crack Net Deflection		Maximum Load		Maximum Net Deflection		Maximum Strain
Beam	(lbs)	(kN)	(in)	(mm)	(lbs)	(kN)	(in)	(mm)	(in/in)
FRP 1	7520	33.45	0.01027	0.2609	19800	88.07	0.2069	5.255	0.003383
FRP 2	5860	26.07	0.00654	0.1661	17700	78.73	0.2191	5.565	0.005525
FRP 3	6150	27.36	0.00676	0.1716	24200	107.64	0.2245	5.702	0.005599
FRP 4	5810	25.84	0.00989	0.2511	20900	92.96	0.2120	5.385	0.005945
BNW 21	6152	27.36	0.00716	0.1819	19336	86.01	0.2741	6.962	0.000796
BNW 22	6494	28.89	0.00692	0.1758	19140	85.13	0.2051	5.210	0.001655
BNW 23	6104	27.15	0.00811	0.2060	16504	73.41	0.2898	7.361	0.001221

Table 2 – Characteristics of the loading response for all beams.

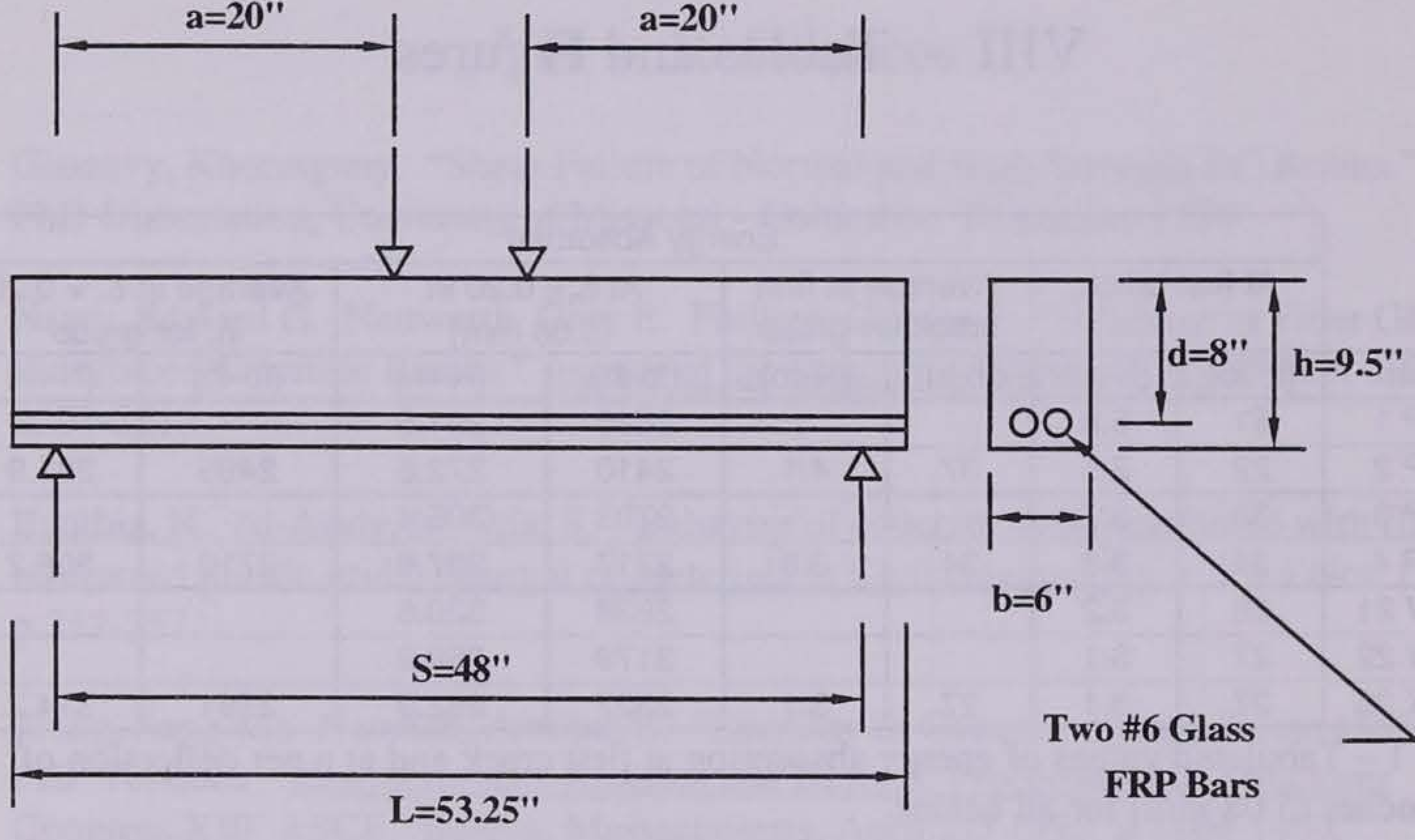


Figure 1 - Diagram of beam dimensions for beams FRP 1 – FRP 4. Beams BNW 21 – BNW 23 had the same dimensions, except L=56" and steel reinforcement.

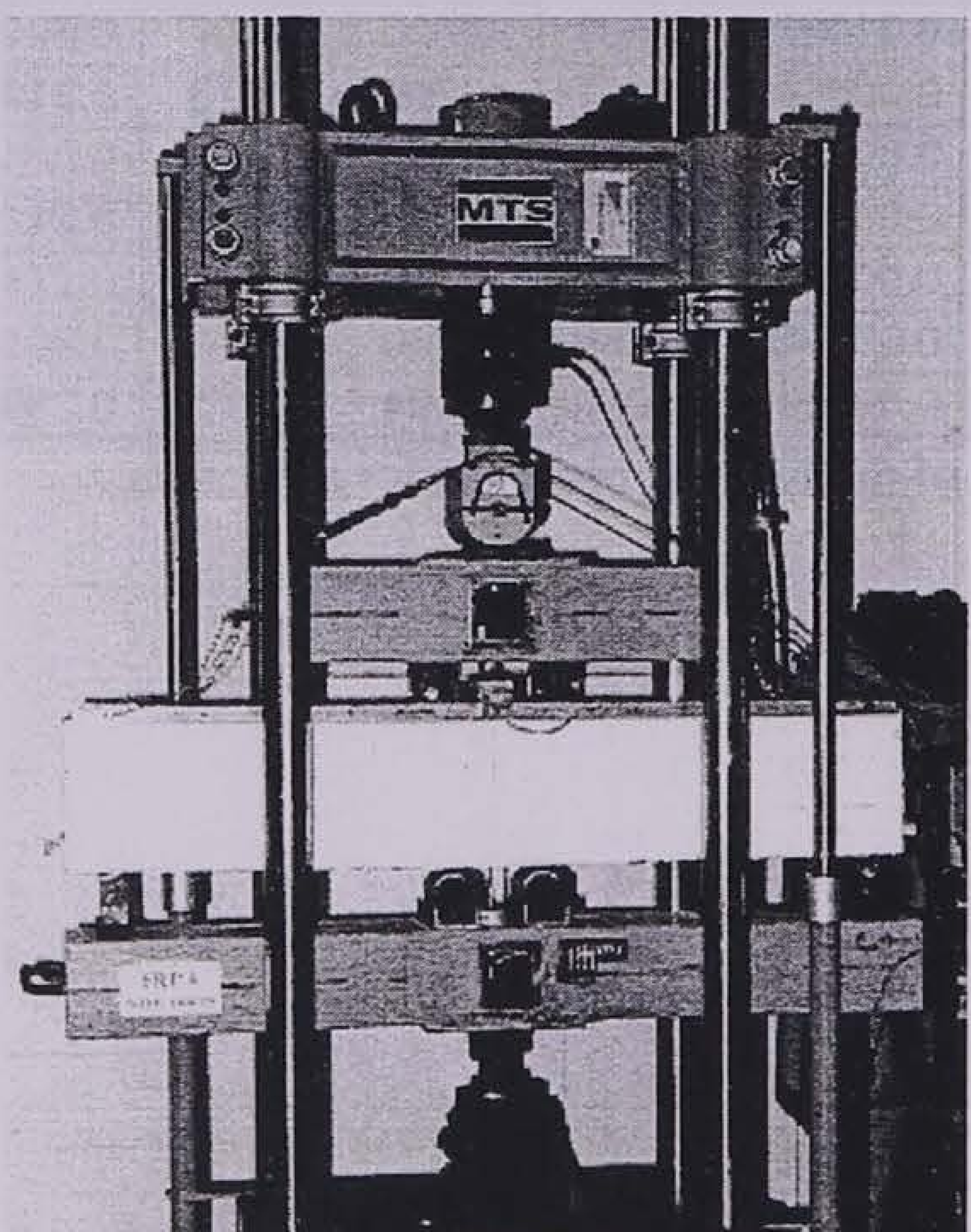


Figure 2 – Picture of the experimental setup.

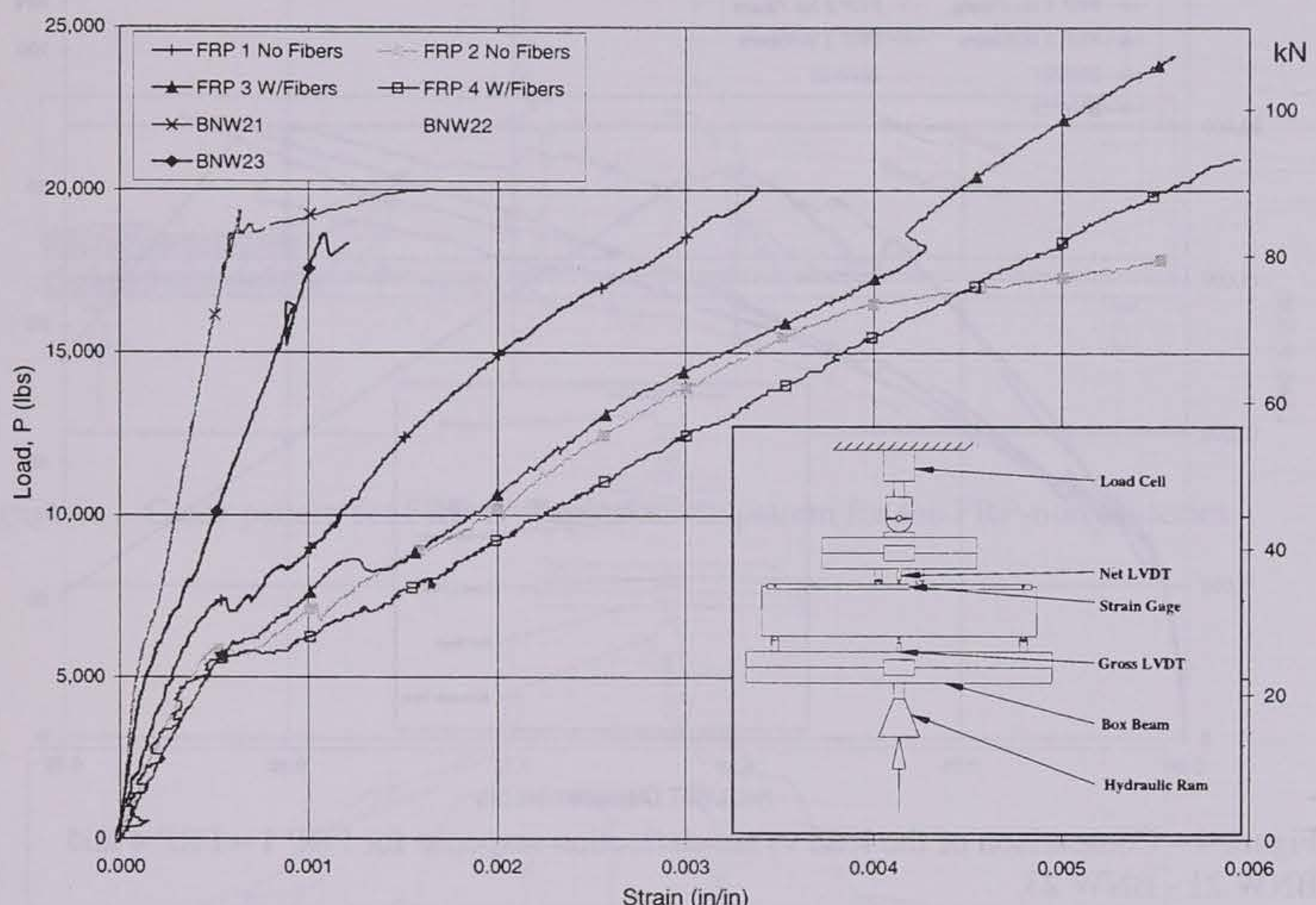


Figure 3 – Comparison of the load vs concrete compressive strain response for FRP 1 – FRP 4 and BNW 21 – BNW 23.

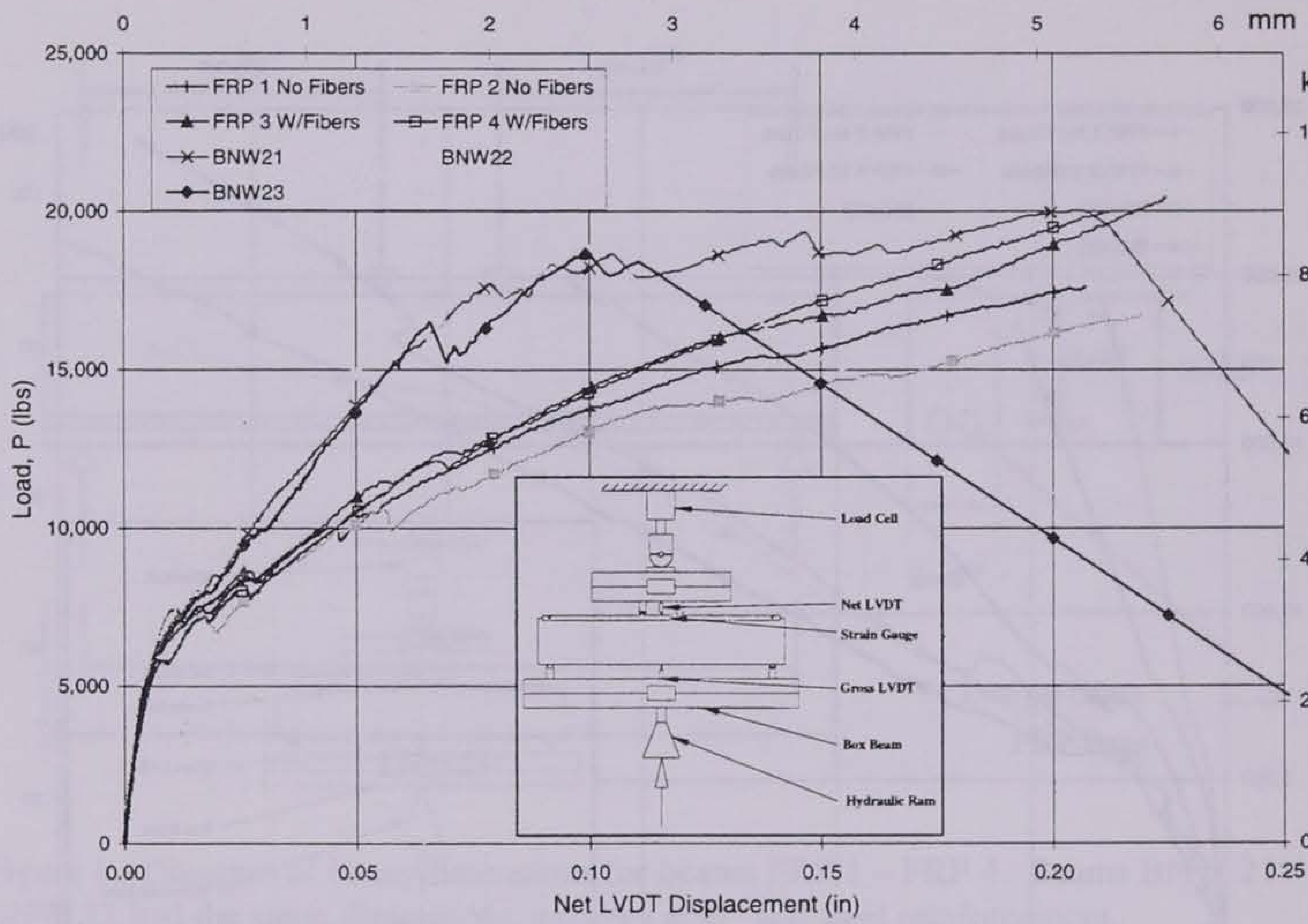


Figure 4 – Comparison of the load vs net-deflection response for FRP 1 – FRP 4 and BNW 21 - BNW 23.

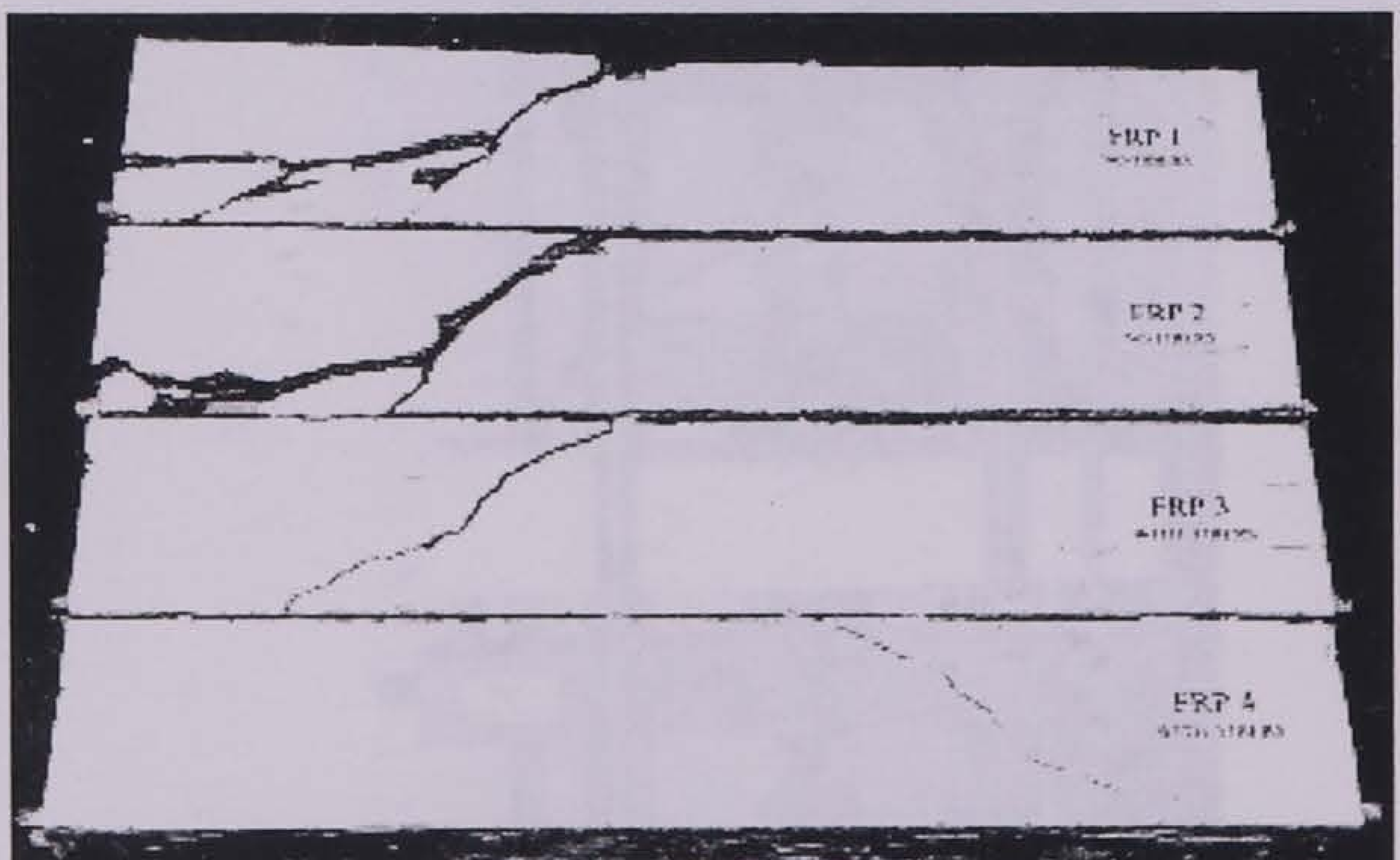


Figure 5 – Picture of the four FRP reinforced beams after testing.

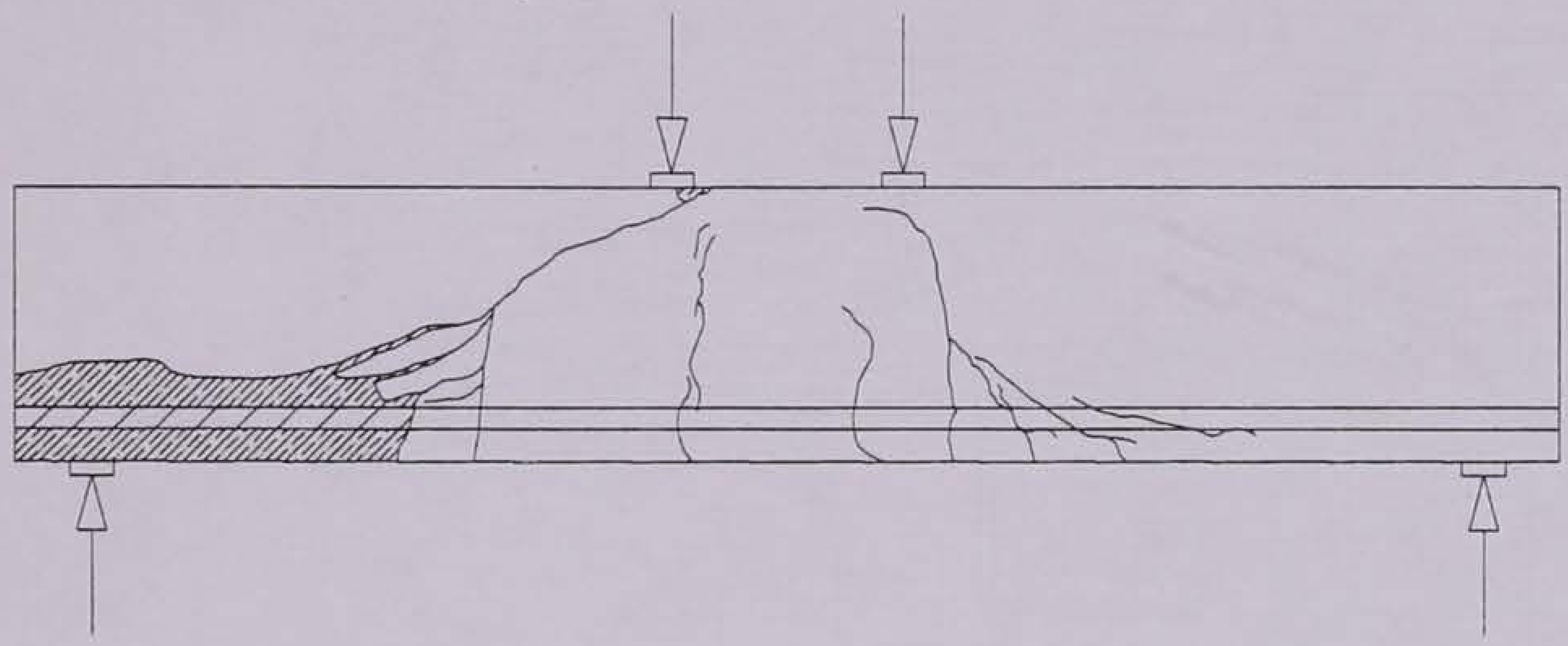


Figure 6a – Crack pattern for FRP 1. Typical crack pattern for the FRP-normal series.

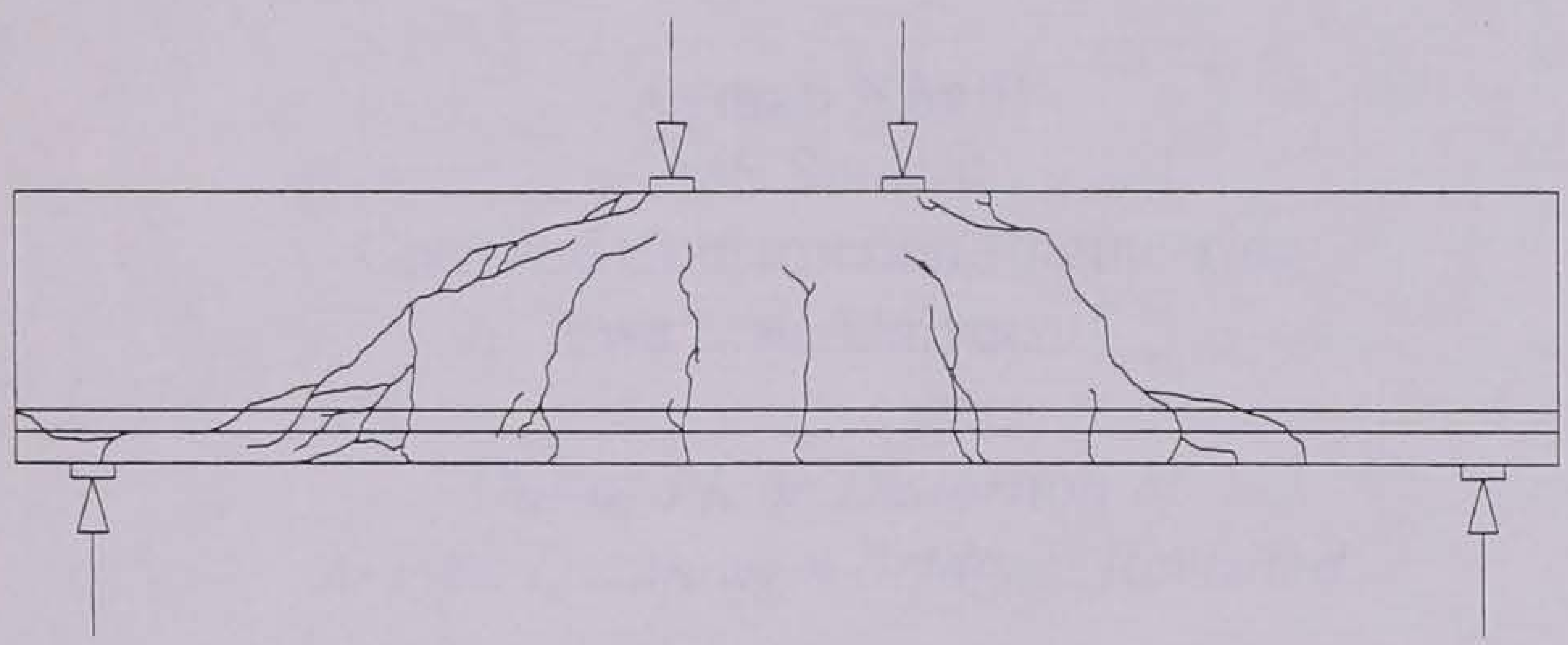


Figure 6b – Crack Pattern for FRP 4. Typical crack pattern for the FRC-FRP series.

Ayman Khalil
MS Student
Civil and Construction Engineering
Iowa State University

Out-of-Plane Distortion of
X-Type Diaphragm Bridges: Revisited

ABSTRACT

Some of the Iowa Department of Transportation (Iowa DOT) welded continuous steel plate girder bridges have developed cracking in the negative moment regions at the web gaps with diaphragm connection plates. A research program was initiated to investigate the problem in bridges with X- and K-type diaphragms. This research included a literature search to identify current retrofit methods and an experimental investigation of the problem in X- and K-type diaphragm bridges. The research is still in progress and the results, conclusions, and recommendations are thus preliminary.

Three retrofit techniques have been suggested: drilling holes, increasing web gap length, and providing rigid attachment. Drilling holes at the crack tip locations is the one on which the Iowa DOT relies primarily to prevent crack extension.

Three bridges with X-type diaphragms were tested. During the summers of 1996 and 1997, these bridges were instrumented using strain gages and displacement transducers to obtain the response at various web gaps and diaphragm elements. Bridges were subjected to truck loading in different lanes with speeds varying from crawl to 96 km/h (60 mph).

Due to a 222-kN (50-kips) truck, the maximum computed stress range was 50 mPa (7.25 ksi). The hole-drilling technique did not enhance the web gap behavior provided that the holes were close to the connection plates. It is recommended to continue careful inspection of web gap details even after drilling-hole retrofit method is used.

1.

INTRODUCTION

A number of localized failures have developed in steel bridge components due to fatigue during the past several decades. Some of these have resulted in brittle fracture. Out-of-plane distortions in small gaps at the diaphragm connection plates are the cause of the largest category of cracking in bridges (1). The problem has developed in different types of bridges, including suspension bridges, girder floor beam bridges, multiple girder bridges, tied arch bridges, and box girder bridges.

Figure 1 shows a schematic of the out-of-plane distortion at the end of transverse connection plates (stiffeners) in plate girder bridges with X-type diaphragms. Under typical vehicle loading, differential vertical deflection of adjacent girders causes forces to develop in the diaphragm elements, which cause the out-of-plane loading on the girder web (Detail A). Without the stiffener attachment to the top flange and with the top flange rigidly connected to the bridge deck, these forces pass through girder web causing out-of-plane distortion and, hence, bending of the web gap immediately adjacent to the top flange (Detail B). In the negative moment regions, high cyclic stresses due to this distortion cause cracking in the web gap region typically parallel to the longitudinal tensile stresses (2).

Diaphragms serve several functions including: (1) transferring lateral wind load from the bottom of girders to the deck slab and from the deck slab to the support system, (2) providing stability of the top compression flange in positive moment regions during construction, providing stability of the bottom compression flange under various types of loads, (3) distributing vertical loads among girders, (4) providing transverse integrity in cases of extreme events (bridge being hit by a passing vehicle or vessel) and (5) providing stability for the top flange during deck replacement.

The scope of the investigation included: (1) studying the cracking problems occurring at the diaphragm/plate girder connections in negative moment regions of continuous plate girder bridges, and (2) identifying existing methods of crack preventation, and testing three bridges with X-type diaphragms to evaluate the general deformational behavior of different web gap configurations (with or without diaphragm, at exterior or interior girders, at negative or positive moment regions, with or without cracks).

2. OUT-OF-PLANE DISTORTION AND RETROFIT METHODS

Fisher et al. (3,4) investigated causes of, and possible retrofit techniques for, distortion-induced cracking of steel girder bridges with web gaps. The field measurements indicated that most distortion-induced fatigue cracking develops in the web gap regions. Usually, cracking occurs within the first 10 years of service. However, some extreme cases reported cracking due to wind induced vibration before the bridge opened. The authors predicted that crack propagation rate might decrease as it grows. Different retrofit procedures for the connection plates were examined through laboratory testing.

Drilling holes at the crack tip has been successfully used in many different applications to arrest fatigue cracks. As suggested by the authors (3,4), this technique should be used alone or with any other method to minimize crack extension. The method can not be used to prevent crack initiation. Hole-drilling method may be satisfactory alone if the crack has propagated into lower stress regions.

Another retrofit technique depends on increasing the web gap length to increase the flexibility of the connection anticipating that would reduce the bending stresses in the web plate. Adopting this technique may cause greater distortion at the connection and was not successful in preventing crack initiation in some cases.

Field tests have shown that providing positive attachment is the most effective. Current AASHTO Specifications (5) require a positive attachment between transverse connection plates for the diaphragms and both girder flanges. For many in-service bridges, however, the connection plates are welded only to the web and the compression flange as bridge specifications, at the time these bridges were constructed, discouraged welding of connection plates to the tension flange. For existing bridges, attaching the stiffener to the top flange involves an overhead field weld, which can be adversely affected if traffic continues during welding. As a result, this method is seldom used for existing bridges.

The above methods are destructive in nature. The Iowa DOT has proposed a new nondestructive method to prevent cracking due to the out-of-plane distortion at diaphragm/plate girder connections; the method is still under investigation.

3. DESCRIPTION OF BRIDGES

The experimental phase of the study involved testing three bridges with X-type diaphragms. Each bridge has a reinforced concrete deck slab with composite construction between the girders and the deck slab. In the negative moment regions, the stiffeners are welded to the bottom (compression) flanges and the webs; whereas, they are closely fitted to the tension flanges.

The Boone River Bridge is located approximately 2 km (1.25 miles) south of U.S. 20 on Iowa Highway 17 (IA 17) in Hamilton County. It carries the north and southbound traffic over the Boone River. In Figure 2(a, b, c), an overall view for the bridge as well as schematic drawings for the bridge are shown. The bridge was constructed in 1972. The 203 m (8 in.) reinforced concrete deck slab is supported on five plate girders of spans 29.72, 38.10, 29.72 m (97.5, 125, and 97.5 ft), respectively. At intermediate locations, X-type cross frame diaphragms brace girder webs at approximately 6.10-m (20-ft) intervals. This bridge had no recorded history of fatigue cracking.

The Des Moines River Bridge carries Iowa Highway 210 (IA 210) over the Des Moines River to the west of Madrid in Boone County. The bridge was opened to traffic in 1973. It has five continuous spans; the exterior spans are 53.64 m (176 ft) each and the interior spans are 67.06 m (220 ft) each. An overall view and schematic drawings are presented in Figure 3(a, b, c). The bridge is skewed 29° with four piers and two abutments. Between supports, the girders are braced using X-type cross frames at spacing of 6.71 m (22 ft). No fatigue cracking has been reported in the Des Moines River Bridge.

The I-80 Bridge No. 7804.080L is located in Pottawattamie County (Iowa), 5.92 km (3.7 miles) west of the junction of Interstate 80 (I-80) with U.S. 6 road. It carries the westbound traffic of I-80 over an abandoned railroad (Figure 4(a)). The bridge has three spans of 27.89, 35.66, and 27.89 m (91.5, 117, 91.5 ft), respectively (Figure 4(b)). The superstructure is skewed 30° with its supporting two piers and two stub reinforced concrete abutments. Between the supports, girders are braced using X-type diaphragms at an approximate spacing of 6.71 m (22 ft). Fatigue cracks have been detected in the web gap region at nine locations (see Figure 4(b), Figure 5). As a retrofit, holes were drilled; however, the cracks extended beyond the drilled holes in some of these locations. Crack extensions were treated by drilling holes at the new crack tip locations.

4. TEST PROCEDURE, LOADING, AND INSTRUMENTATION

The Iowa DOT provided two loaded rear tandem axle trucks for each bridge with dimensions and weights that were consistently similar. The gross truck weight ranged from 218.05 kN (49 kips) to 235.85 kN (53 kips). Table 1 describes the number of trucks, truck speed, and truck position during different tests.

For both the Boone River Bridge and the Des Moines River Bridge, nine tests were conducted. During testing, traffic was restricted on the bridges. To assess the quasi-static response, a single truck traveling in different lanes and shoulders at crawl speed was used. The dynamic response was recorded for a single truck traveling only in the driving lanes at speeds of 48 km/h (30 mph) and 80 km/h (50 mph). Due to the high volume of traffic on the I-80 Bridge, shutting down the traffic was not possible and, hence, tests were only conducted with the loaded trucks running at the traffic flow speed. Three tests were conducted for the I-80 Bridge. Additional data were collected due to heavy truck from normal traffic.

Two types of instrumentation were used: displacement transducers and strain gages. Displacements were measured with Trans-Tek series 240 DC-DC displacement transducers (DCDTs) with confidence of accuracy 0.013±0.005mm (0.0005±0.0002 in.). Foil strain gages were mounted at the locations described in the following paragraphs. Data from the instrumentation were collected, processed, and stored using an Optim Electronics Megadac data acquisition system (5108DC Megadac).

In the Boone River Bridge, measurements were taken in three locations A, B, and C (see Figure 2(d)). At Location A, the strains were measured at the web gap, and at both diaphragm diagonals (D1, D2). Displacement transducers were mounted at Locations A and B to record out-of-plane distortion. A web gap in the positive moment region at Location C was instrumented with two strain gages and a displacement transducer.

In the Des Moines River Bridge, measurements were obtained at Locations A, B, and C (see Figure 3(d)). The web gap and diaphragm diagonal strains (D1) were measured at Location A. At Location B, the web gap strains were measured using three strain gages. Displacement transducers were mounted at Locations A, B, and C to record the out-of-plane distortion of the web gap.

In the I-80 Bridge, the strains in the web gap and diaphragm diagonal (D1) were measured at Location A. The diaphragm diagonal (D1) connected to the exterior girder (G1), near its top flange was instrumented using three strain gages. At Location B, the strains in the web gap of the interior girder (G2) were recorded with three strain gages. Two strain gages were affixed at location C adjacent to one of the drilled holes. Out-of-plane distortion of the web gaps of G1 and G2 were recorded at Locations A, B, and C using displacement transducers (see Figure 4(d)). Other measurements were taken; however, they are outside the scope of this paper.

5. FIELD TEST RESULTS

5.1 Web Gap Strains And Stress Range

Figure 6 shows the strain readings of the 4 gages installed in the web gap at Location A (Boone River Bridge) during Test 5. Like all strain plots, it is characterized by a single maximum value followed by a small rebound strain. During Test 5, the maximum recorded strain for Gage 1 was 160 micro-strain (32.0 mPa-4.64 ksi). Figure 7 shows the effect of transverse truck position and truck speed on the vertical profile of the maximum strains recorded in the web gap at Location A (Boone River Bridge) due to a single truck. The strain in the web gap region showed variation with truck speed with the highest strains during tests with 48 km/h (30-mph) speed. The strain in the web gap, however, showed greater variation with transverse truck position. The strain distribution shows double curvature bending of the web gap. The strains at Location C (at a positive moment region) were less than 1/10 of those recorded at Location A (at a negative moment region). This helps to explain why it is more likely that a web gap in the negative moment region would crack.

Figure 8 shows a comparison between the vertical profile of the strain in the web gaps of Locations A and B (web gaps with and without diaphragm connections, respectively in Des Moines River Bridge) during crawl speed tests. Apparently, the web gap behavior at Location A is unlike that at Location B, that is, the strain distribution at Location B shows a slight single-curvature bending behavior; however, that of Location A reflects double-curvature bending of the web gap. Further, the strains at Location A are approximately two times in magnitude those at Location B. This explains the effect of the diaphragm connection on the strains in the web gap.

The horizontal profile of the maximum strains in the web gap region at Locations A and C (web gaps at exterior girders without and with cracks, respectively in the I-80 Bridge) during Test 2 is shown in Figure 9. Although holes were drilled at Location C to relieve the strains, the strains in the web gap at that location were slightly higher than the corresponding values at Locations A or B. The local effect of the out-of-plane distortion is clearly shown as the strains increased towards the connection plate. At approximately 100 mm from the connection plates, the strain levels would be comparable in magnitude to those in web gaps without diaphragm connections.

The configuration of strain gages at Location A in I-80 Bridge allowed linear extrapolation of the recorded strains in both the vertical and horizontal directions to predict the strain values inside the web gap. The maximum extrapolated strain was at the weld toe connecting the stiffener to the top flange, with a value of 250 micro-strain (50 mPa-7.25 ksi). This might explain why most fatigue cracks resulting from out-of-plane distortion initiate at similar locations.

Strain plots were utilized to compute the strain range (Figure 6) and consequently the stress range. Stress range is the most important factor for determining fatigue life of welded joints. It had shown that fatigue strength of welded joints is governed by the applied stress range regardless of the type of stress or stress ratio (6). In Table 2, a list of the maximum computed stress ranges (without extrapolation) due to a 222-kN (50-kips) single truck is presented. Fatigue resistance of welded joints (in terms of cycles) is approximately inversely proportional to the cubic power of the maximum stress (5, 6). Considering the stress ranges in Table 2, fatigue life of the web gap detail without diaphragm connection could be up to 100 times that with a diaphragm connection. Data from the I-80 Bridge revealed that the stress range may reach greater values under normal traffic. Due to a heavily loaded semi-trailer, the maximum extrapolated stress range at the weld toe connecting the stiffener to the top flange at Location A was 129 mPa (18.7 ksi).

5.2 Web Gap Out-of-Plane Distortion

Table 2 shows the maximum out-of-plane distortion in the instrumented web gaps. The maximum out-of-plane distortion was 0.142 mm (0.0056 in.) at Location A (exterior girder) of the Boone River Bridge. The distortion at the interior girder of the same bridge (non-skew) was 0.028 mm (0.0011 in.) which is significantly less than that at the exterior girder. In Des Moines River Bridge (skew), the out-of-plane distortion at Location A (with diaphragm connection) was 0.056 mm (0.0022 in.) which was 10 times greater than that at Location B (with no diaphragm connection). Although, the stress range at Location A was only twice that at Location B. Factors such as flange out-of-plane rotation and web gap extension or compression may contribute to the stresses in the gap. In the I-80 Bridge, the maximum out-of-plane distortion at Location B (interior girder) was approximately equal to that at Location A (exterior girder); whereas, that at Location C (with cracks and drilled holes) is more than twice that occurred at Location A.

5.3 Diaphragm Diagonal Forces

The maximum force in D1 diagonals due to a single truck ranged from 5.03 to 6.23 kN (1.13 to 1.40 kips-see Table 2). A value of -7.34 kN (-1.65 kips) was computed for D2 in Boone River Bridge. Plotted in Figure 10 are the web gap out-of-plane distortion, the strain recorded using Gage 1, and the force in the diaphragm diagonal D1 at Location A in Boone River Bridge (Tests 1-4). A direct correlation is apparent between both the strains in the web gap region and the web gap out-of-plane distortion and the forces in the diaphragm diagonal (D1). That implies that the diaphragm diagonal force was the primary cause for web gap out-of-plane distortion and strains. Similar relations were noticed in the other bridges.

6. SUMMARY AND CONCLUSIONS

Due to a 222-kN (50-kips) truck, the maximum stress ranges computed in web gaps varied from 7.0 mPa (1.02 ksi), in a web gap without diaphragm connection, to a maximum of 40.0 mPa (5.80 ksi) in a web gap with diaphragm connection in the negative moment region. Extrapolated stresses at the weld toes were approximately twice these. With heavier trucks, the stress range may approach the yield strength of steel.

The results show that it is less likely to have cracking in web gaps with diaphragm connection in the positive moment regions near the bottom flange or at web gaps without diaphragm connections. Based on the results of the I-80 Bridge, drilled holes did not significantly affect the stress range and, hence, may not eliminate the problem of cracking due to out-of-plane distortion. Cracks would probably reinitiate if the hole locations are close to the connection plates (within 100 mm from the connection plates).

The maximum distortion was 0.142 mm (0.0056 in.) at a web gap of exterior girder in the negative moment region in Boone River Bridge. In non-skew bridges, the interior girders web gaps undergo considerably smaller amounts of out-of-plane distortion than exterior girder web gaps. In skew bridges, however, the distortion levels are of comparable magnitudes at exterior and interior girders, probably because of greater differential deflection between girders.

The study showed that other factors contribute relatively small effects to web gap stresses including the out-of-plane flange rotation and the web gap extension or compression due to direct load transfer from the deck slab to the girders.

Adopting the method of hole-drilling method appears not to yield satisfactory results if the cracks are detected close to the connection plates (within 100 mm). It is recommended to carefully inspect the web gaps with diaphragm connections even if cracks are detected and holes are drilled. It is advantageous to investigate new nondestructive retrofit techniques for the cracking problem in the web gaps.

7. ACKNOWLEDGMENTS

The research and results presented above are parts of the Project HR-393 funded by the Iowa DOT. The project is still in progress and, hence, the results, conclusions, and recommendations are preliminary. The author gratefully acknowledges the interest, help, and cooperation of Bruce Brakke in the initiation and continuation of this study. Without the efforts and support of several Iowa DOT personnel, this work could not have been completed. The author wishes to express his sincere appreciation to his major professors, Dr. Lowell Greimann and Dr. Terry Wipf, for their help and suggestions during this research. Appreciation is extended to Douglas Wood for his help during the experimental phase.

8. REFERENCES

1. Fisher, J.W., *Fatigue Cracking of Steel Structures: Volume III*, Publication No. FHWA-RD-89-168, Federal Highway Administration, U.S. Department of Transportation, 1990.

2. Fisher, J.W. *Fatigue and Fracture in Steel Bridges: Case Studies*. John Wiley & Sons, Inc., New York, 1984.

3. Fisher, J.W., and Keating, P.B. Distortion-Induced Fatigue Cracking of Bridge Details with Web Gaps. *Journal of Constructional Steel Research*, ASCE, Vol. 12, pp. 215-228, 1989.

4. Fisher, J.W., Jin, J., Wagner, D.C., and Yen, B.T. *Distortion Induced Fatigue Cracking in Steel Bridges*. NCHRP Report 336, TRB, National Research Council, 1990.

5 American Association of State Highway and Transportation Officials, *AASHTO LRFD Bridge Design Specifications, Customary U.S. Units, First Edition*, American Association of State Highway and Transportation Officials, Washington, D.C., 1994.

6 Maddox, S.J. *Fatigue Strength of Welded Structures: Second Edition.* Abingoton Publishing, Cambridge, England, 1991.

Table 1 Test arrangement for the three bridges

Test No.	Number of Trucks	Position of Truck: Boone River Bridge	Des Moines River Bridge	I-80 Bridge
Test 1	Single	West Shoulder-crawl	South Shoulder-crawl	South Lane-96 km/h
Test 2	Single	West Lane-crawl	South Lane-crawl	North Lane-88 km/h
Test 3	Single	East Lane-crawl	North Lane-crawl	Between lanes-96 km/h
Test 4	Single	East Shoulder-crawl	North Shoulder-crawl	
Test 5	Single	West Lane-48 km/h	South Lane-48 km/h	
Test 6	Single	East Lane-48 km/h	North Lane-48 km/h	
Test 7	Single	West Lane-80 km/h	South Lane-80 km/h	
Test 8	Single	East Lane-80 km/h	North Lane-80 km/h	
Test 9	Two	West Shoulder and Lane-crawl	South Shoulder and Lane-Crawl	

1 km/h = 0.625 mph

Table 2 Maximum stress range, out-of-plane distortion, and diaphragm diagonal forces due to a single test truck

Bridge	Web gap configuration (region-girder-diaphragm)	Stress Range (mPa)[a]	Out-of-plane Distortion (mm)[b]	Diaphragm diagonal and force (kN)[c]
Boone River Bridge	Negative-exterior-w/diaphragm-	40.0 (571%)	0.142 (2366%)	D1, 6.23
	Negative-interior-w/diaphragm-	-	0.028 (466%)	D2, -7.34
	Positive-exterior-w/diaphragm	4.00 (57%)	0.008 (133%)	
Des Moines River Bridge	Negative-exterior-w/diaphragm	15.6 (223%)	0.056 (933%)	D1, 5.92
	Negative-exterior-w/diaphragm	-	0.030 (500%)	
	Negative-exterior-w/o diaphragm	7.0 (100%)	0.006 (100%)	
I-80 Bridge No. 7804.8L080	Negative-exterior-w/diaphragm	28.6 (409%)	0.045 (750%)	D1, 5.03
	Negative-interior-w/diaphragm	30.7 (439%)	0.043 (717%)	
	Negative-w/diaphragm, cracks, and drilled holes	34.0 (486%)	0.107 (1783%)	

[a] amount in parentheses = (maximum stress range at the specified location / maximum stress range at the web gap with no diaphragm at the negative moment region of Des Moines River Bridge)%

[b] amount in parentheses = (maximum out-of-plane distortion at the specified location / maximum out-of-plane distortion at the web gap with no diaphragm at the negative moment region of Des Moines River Bridge)%

[c] positive means tension

1 mPa = 0.145 ksi, 1 mm = 0.0394 in., 1 kN = 0.2247 kips

Figure 1 Description of out-of-plane girder web distortion in the gap region

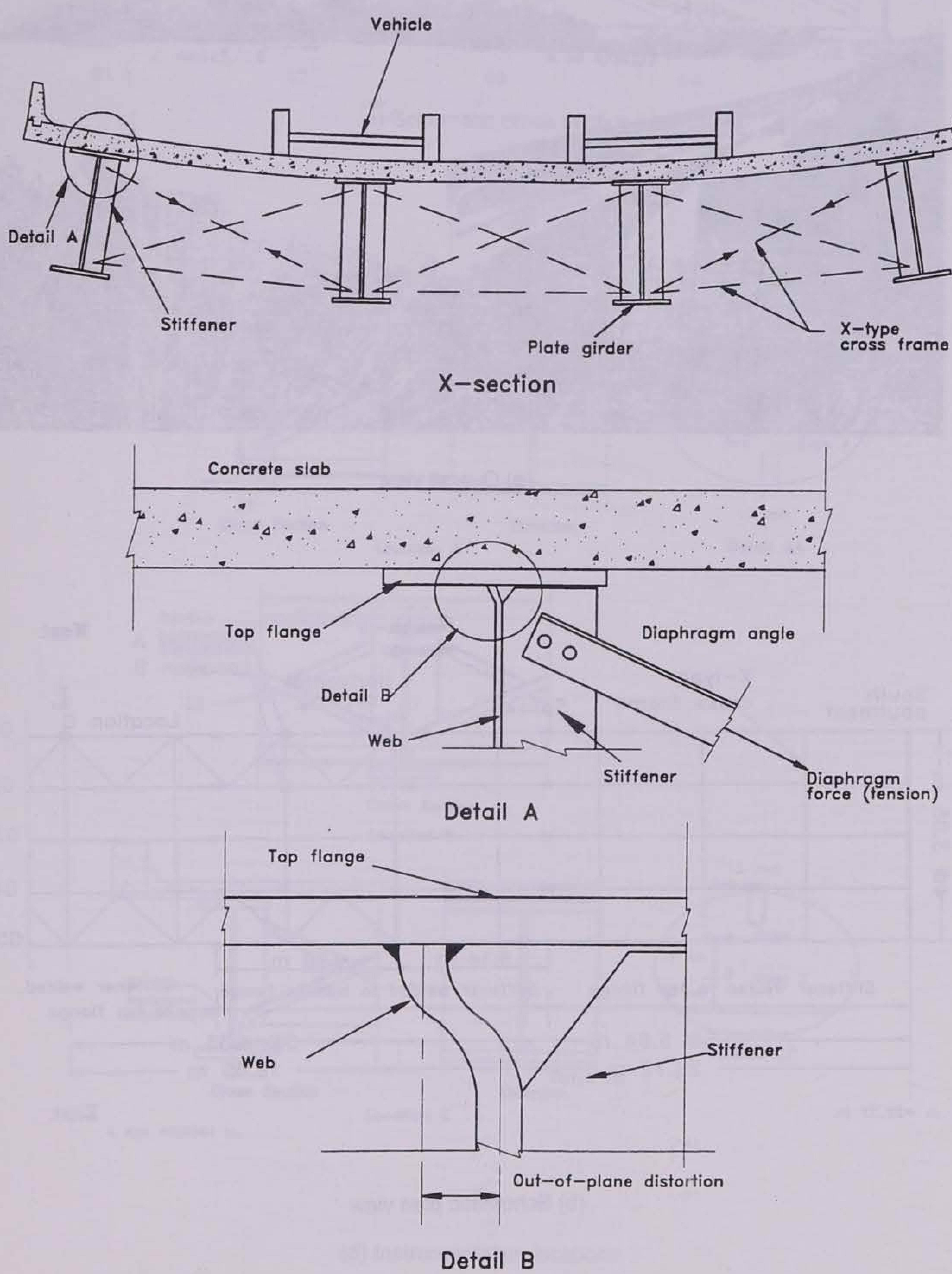
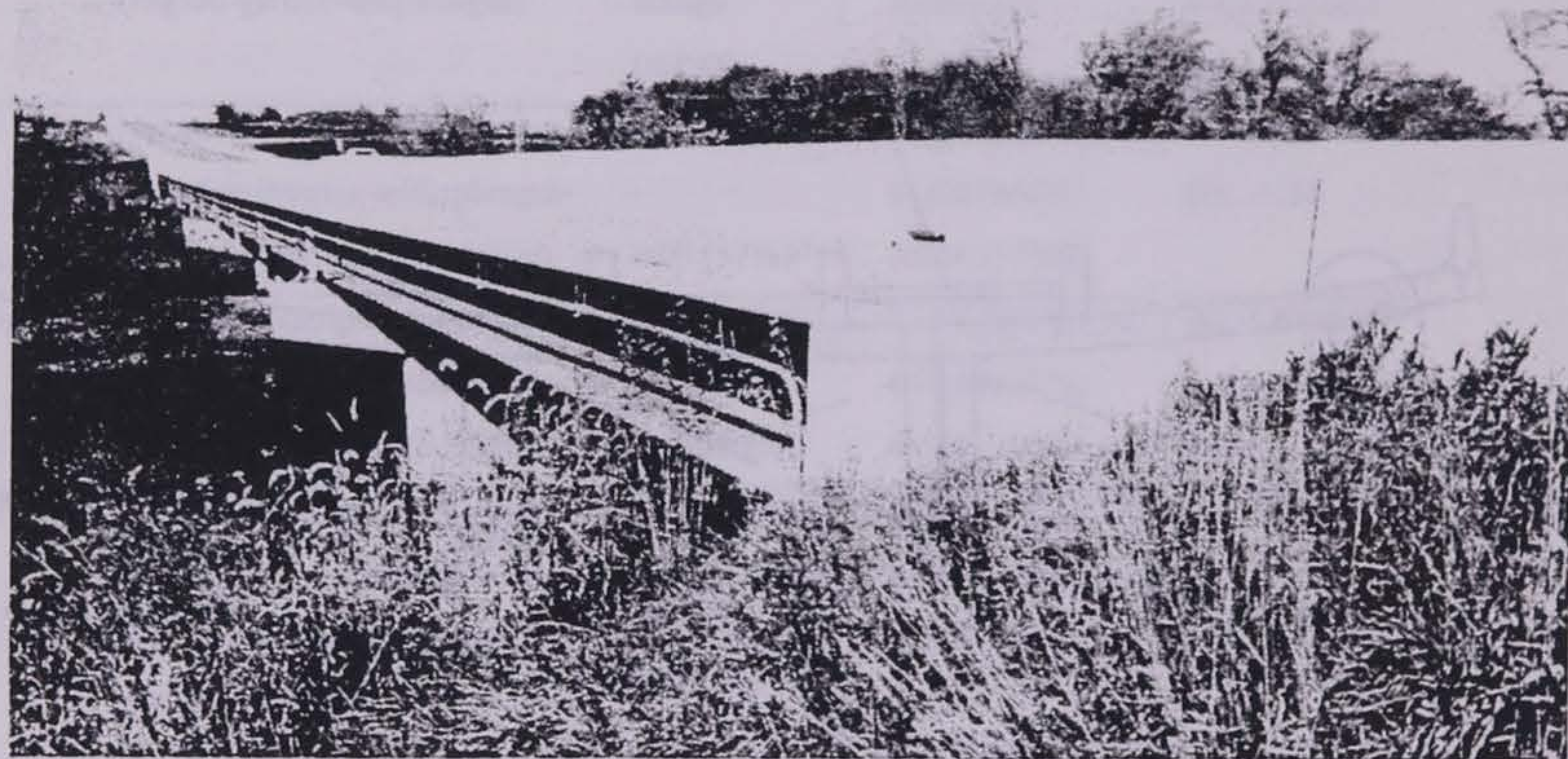
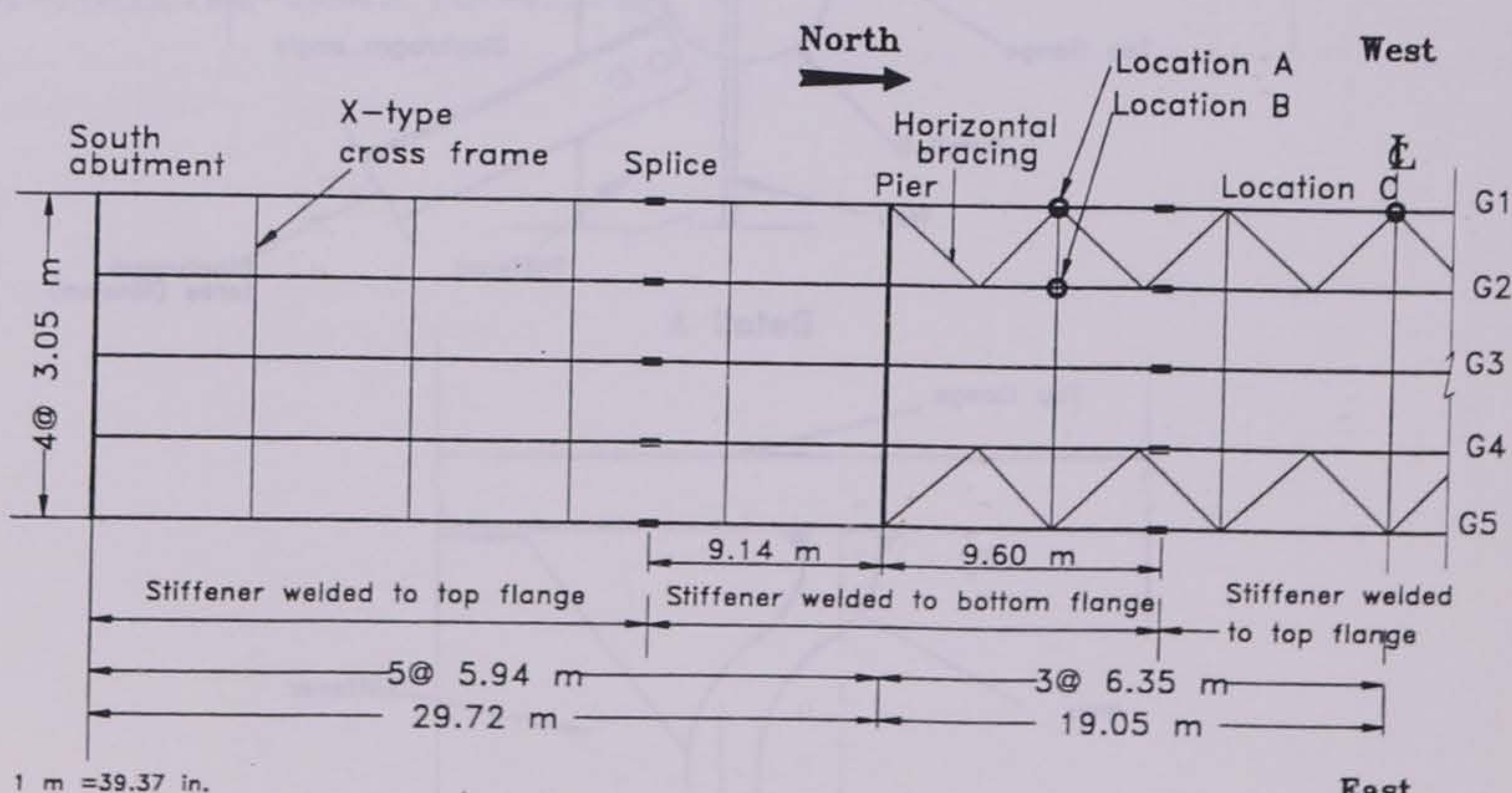


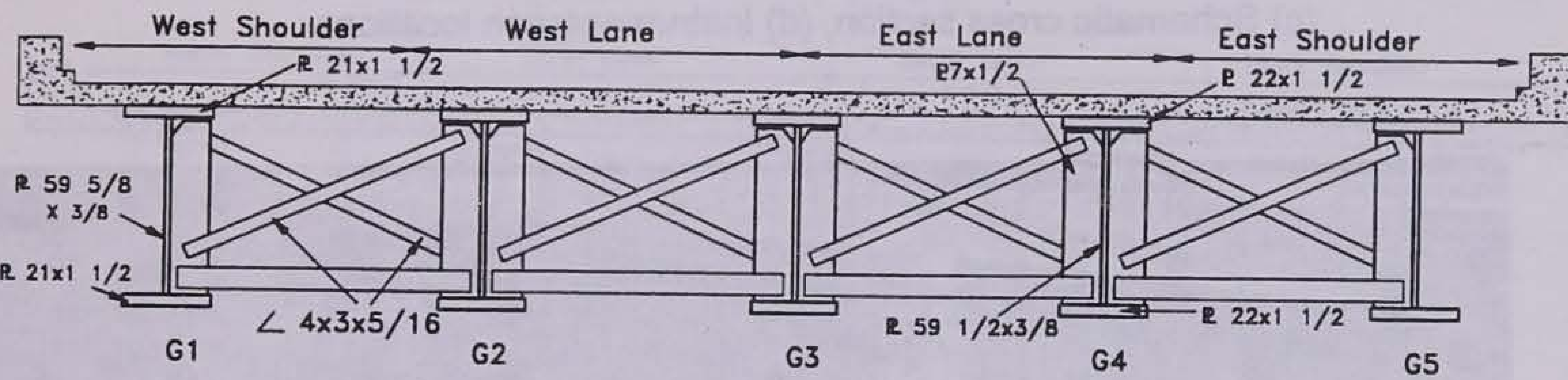
Figure 2 Boone River Bridge: (a) Overall view, (b) Schematic plan view, (c) Schematic cross section, (d) instrumentation locations



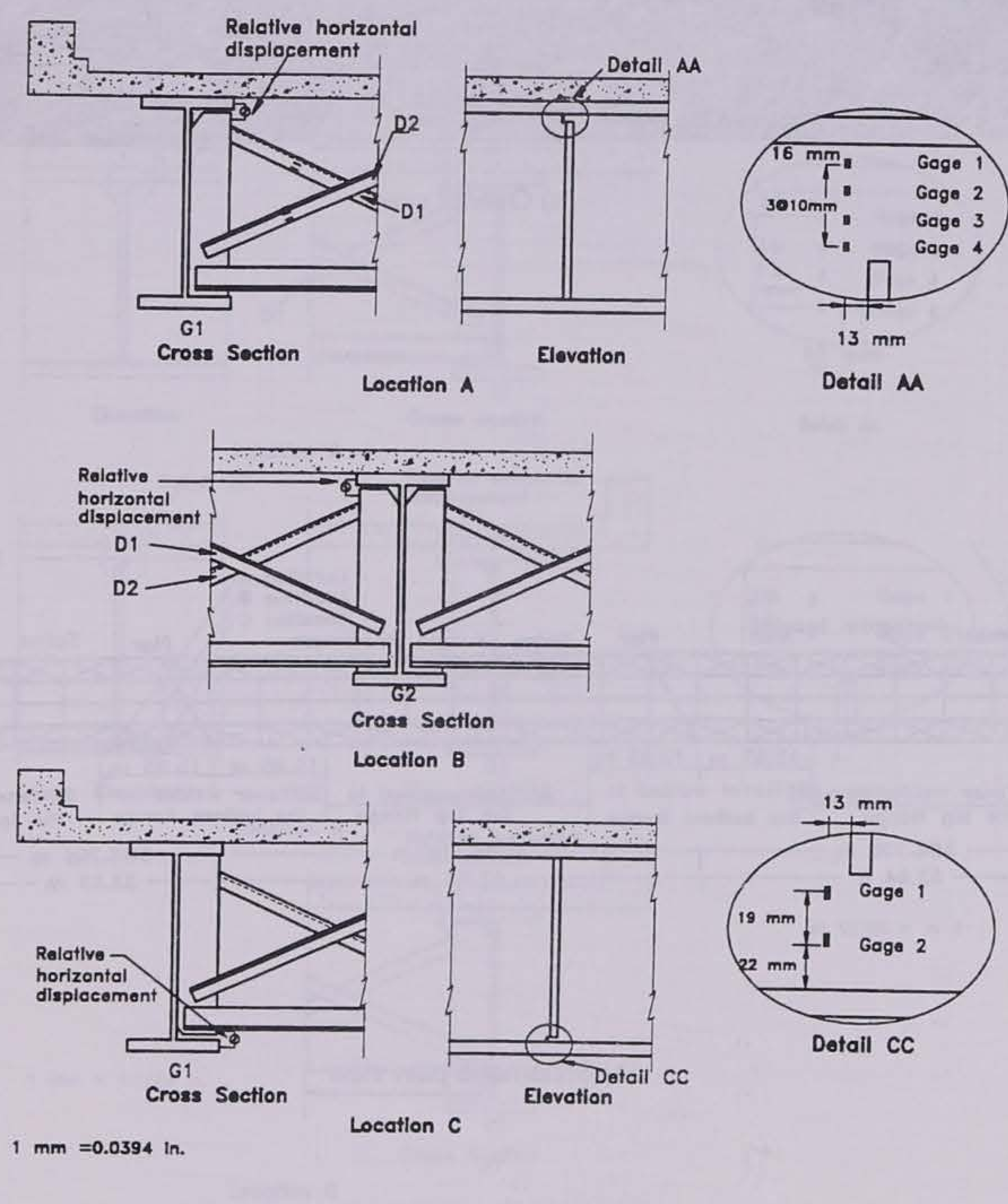
(a) Overall view



(b) Schematic plan view

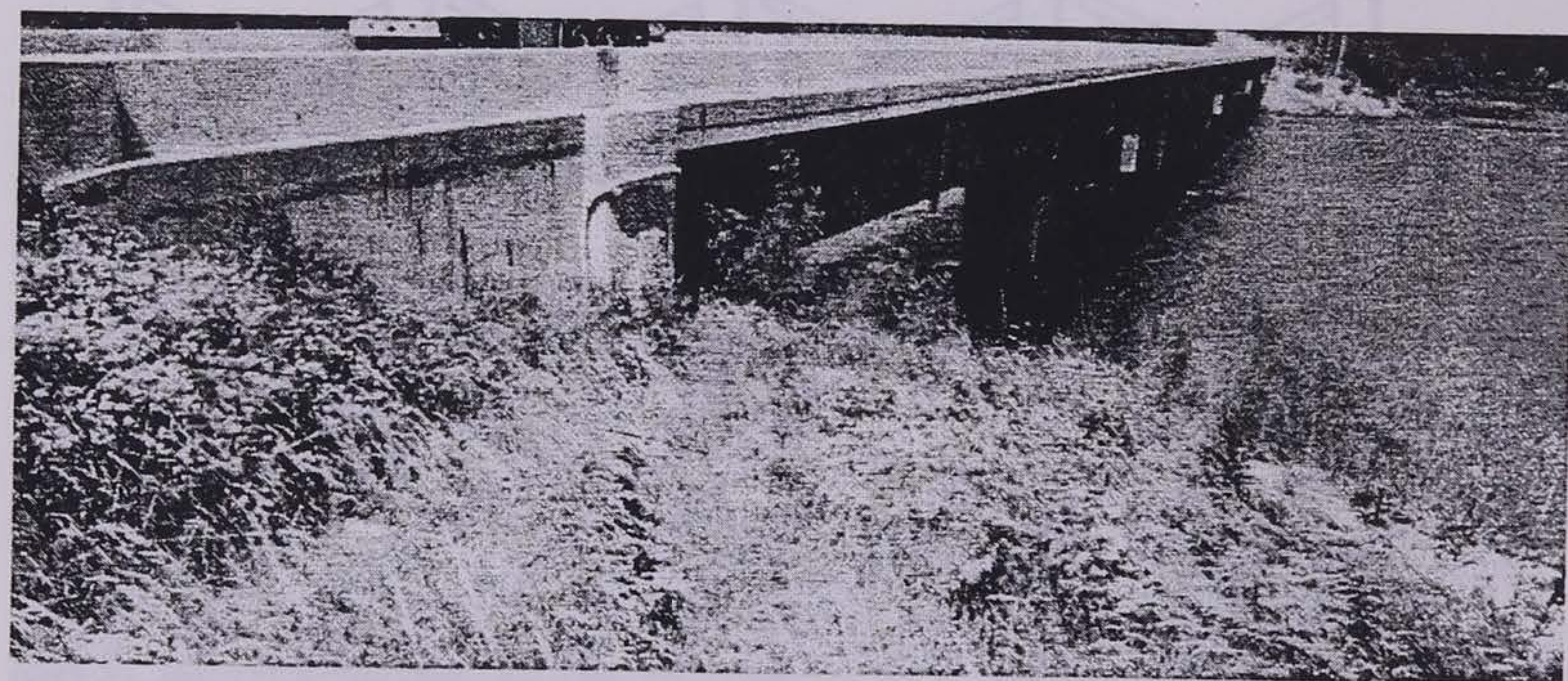


(c) Schematic cross section

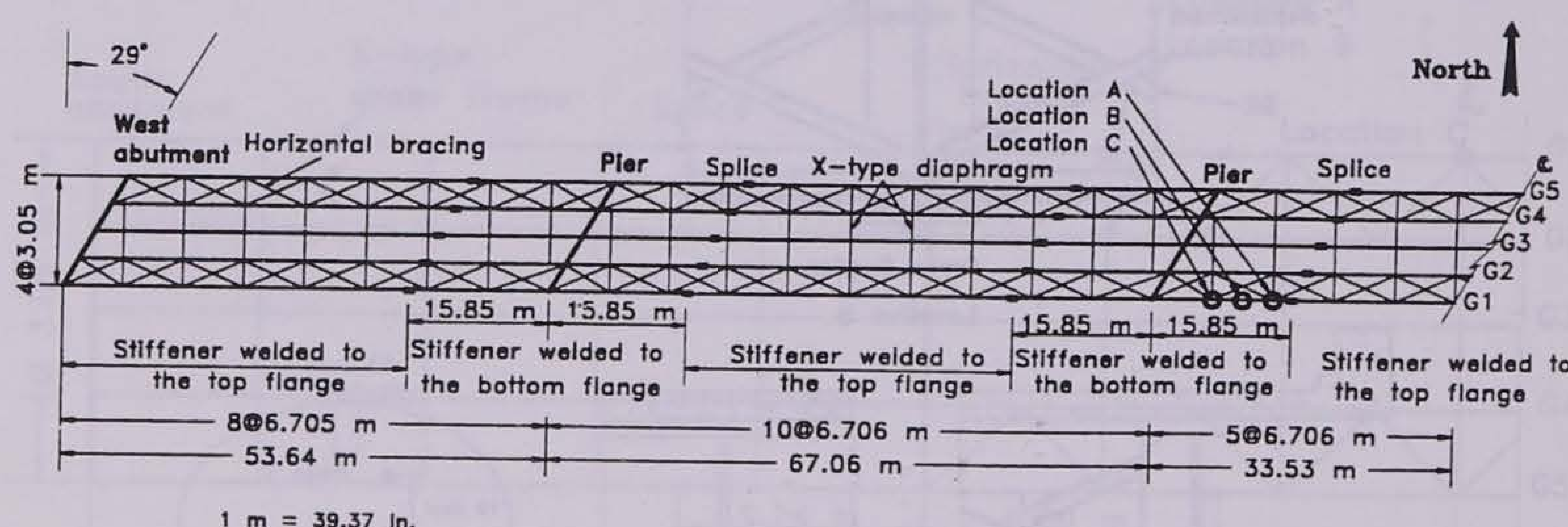


(d) Instrumentation locations

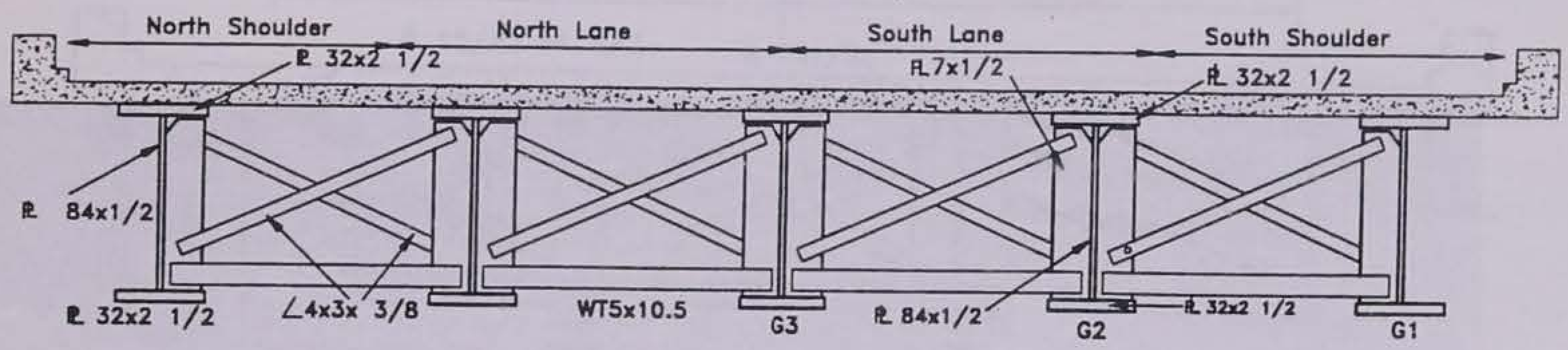
Figure 3 Des Moines River Bridge: (a) Overall view, (b) Schematic plan view, (c) Schematic cross section, (d) instrumentation locations



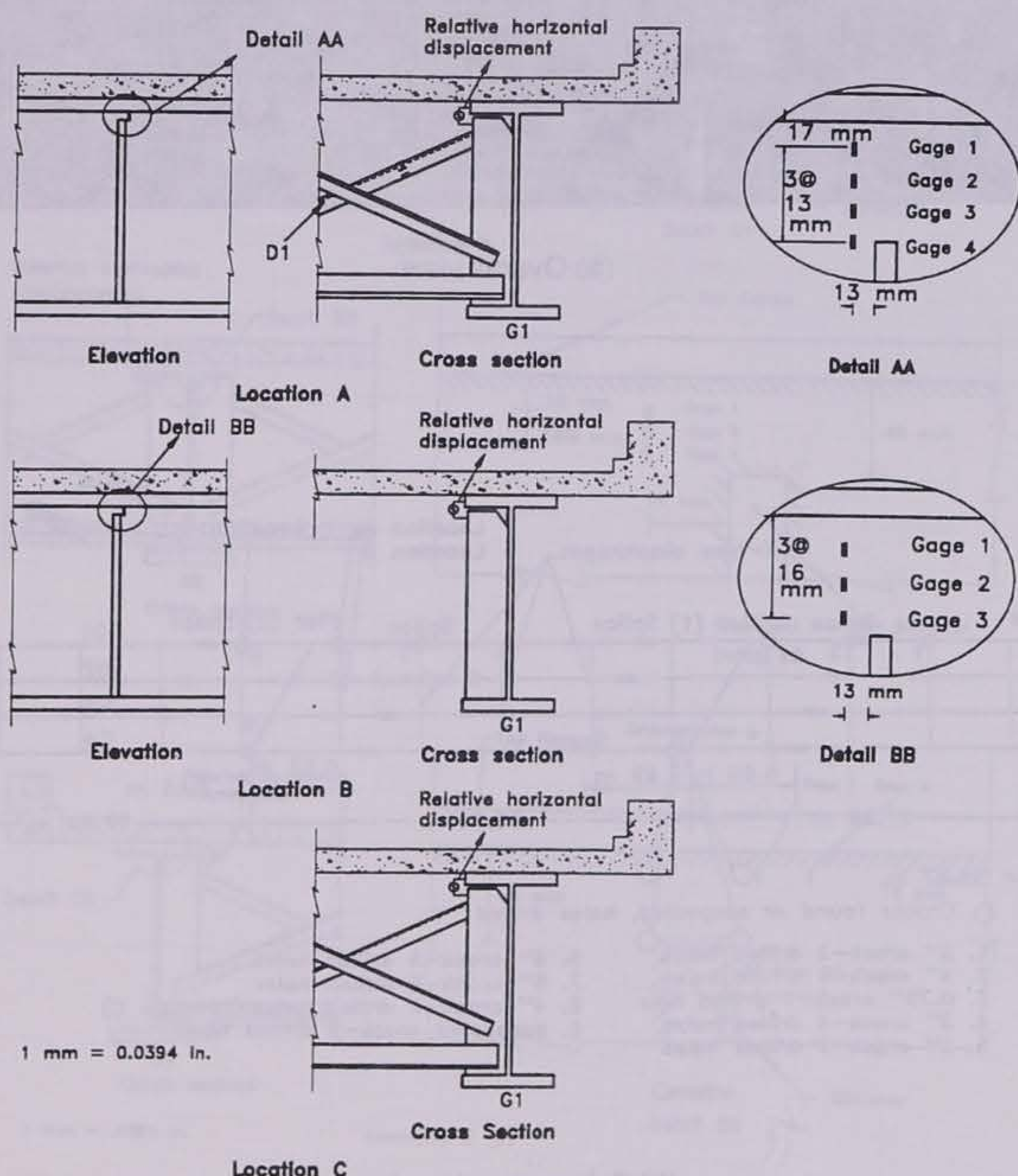
(a) Overall view



(b) Schematic plan view

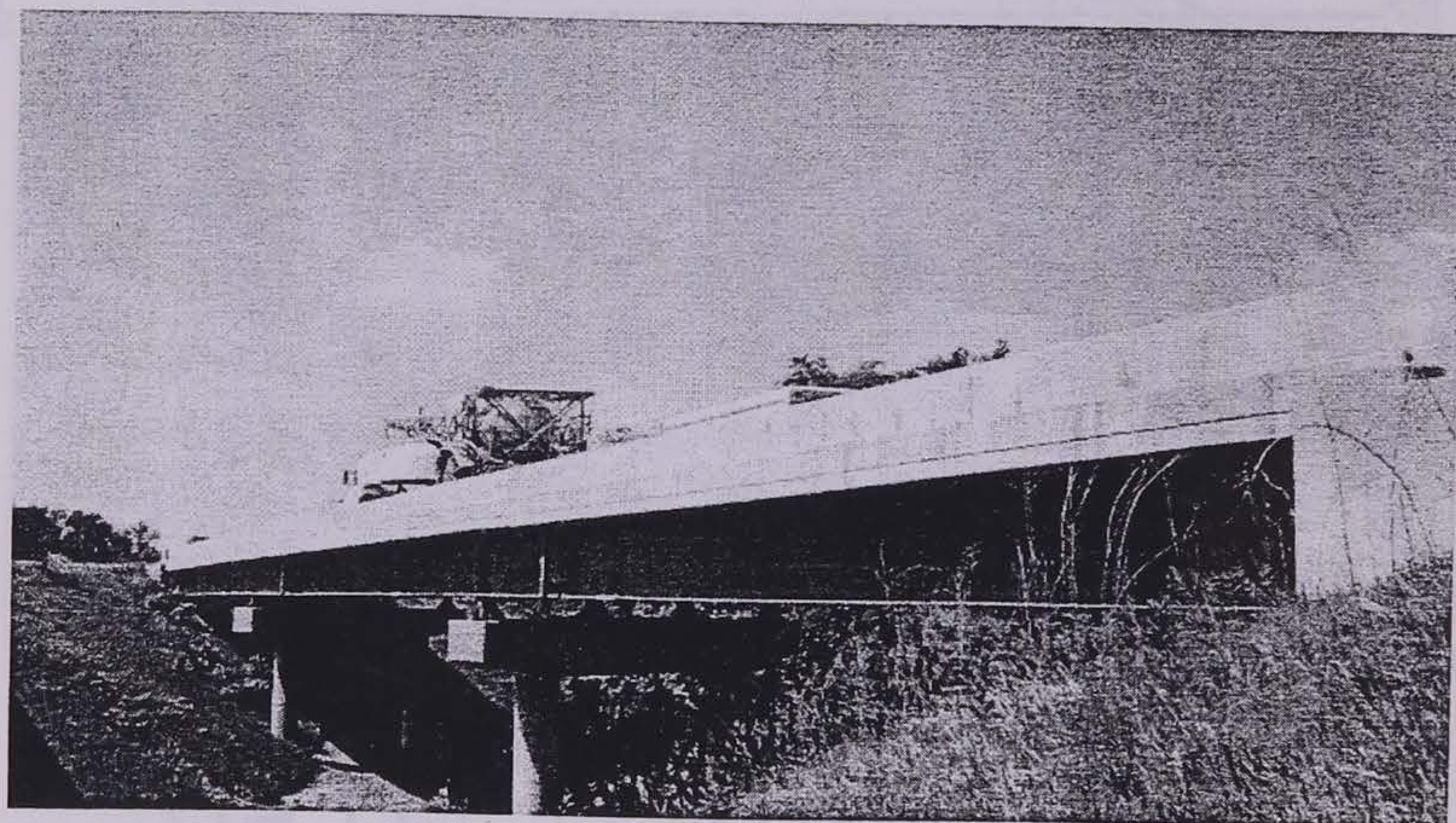


(c) Schematic cross section

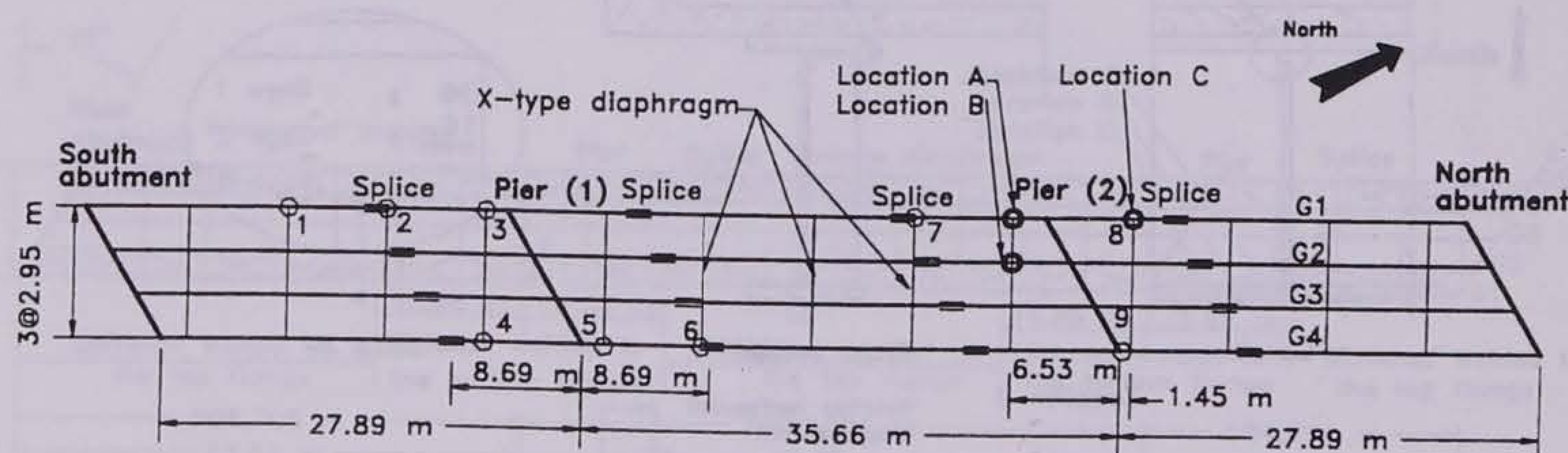


(d) Instrumentation locations

Figure 4 I-80 Bridge no. 7804.8L080: (a) Overall view, (b) Schematic plan view, (c) Schematic cross section, (d) instrumentation locations



(a) Overall view

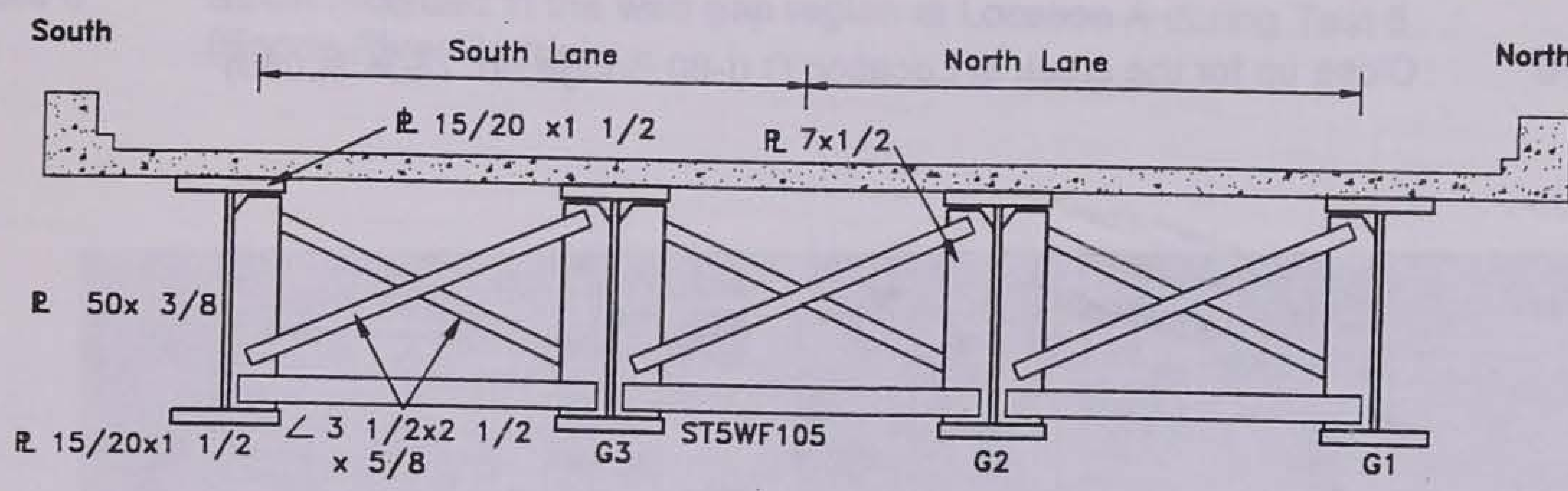


1 m = 39.37 in.

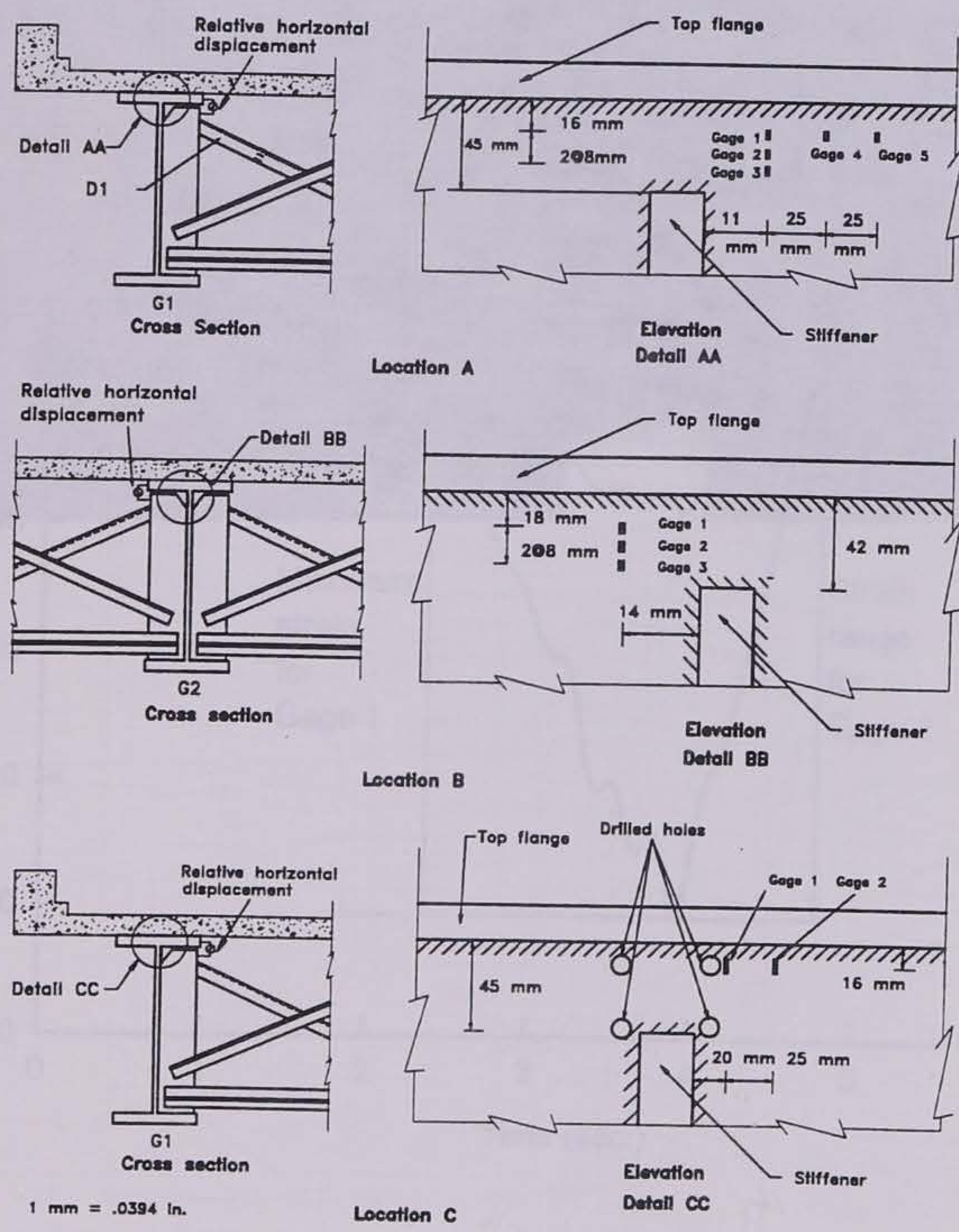
○ Cracks found or suspected, holes drilled

1. 5" crack–2 drilled holes
2. 4" crack–6 drilled holes
3. 0.75" crack–1 drilled hole
4. 3" crack–4 drilled holes
5. 2" crack–2 drilled holes
6. 6" crack–5 drilled holes
7. 5" crack–6 drilled holes
8. 4" crack–4 drilled holes (Location C)
9. suspected crack–2 drilled holes

(b) Schematic plan view



(c) Schematic cross section



(d) Instrumentation locations

Figure 5 Close up for the crack at Location C (I-80 Bridge no. 7804.8L080)

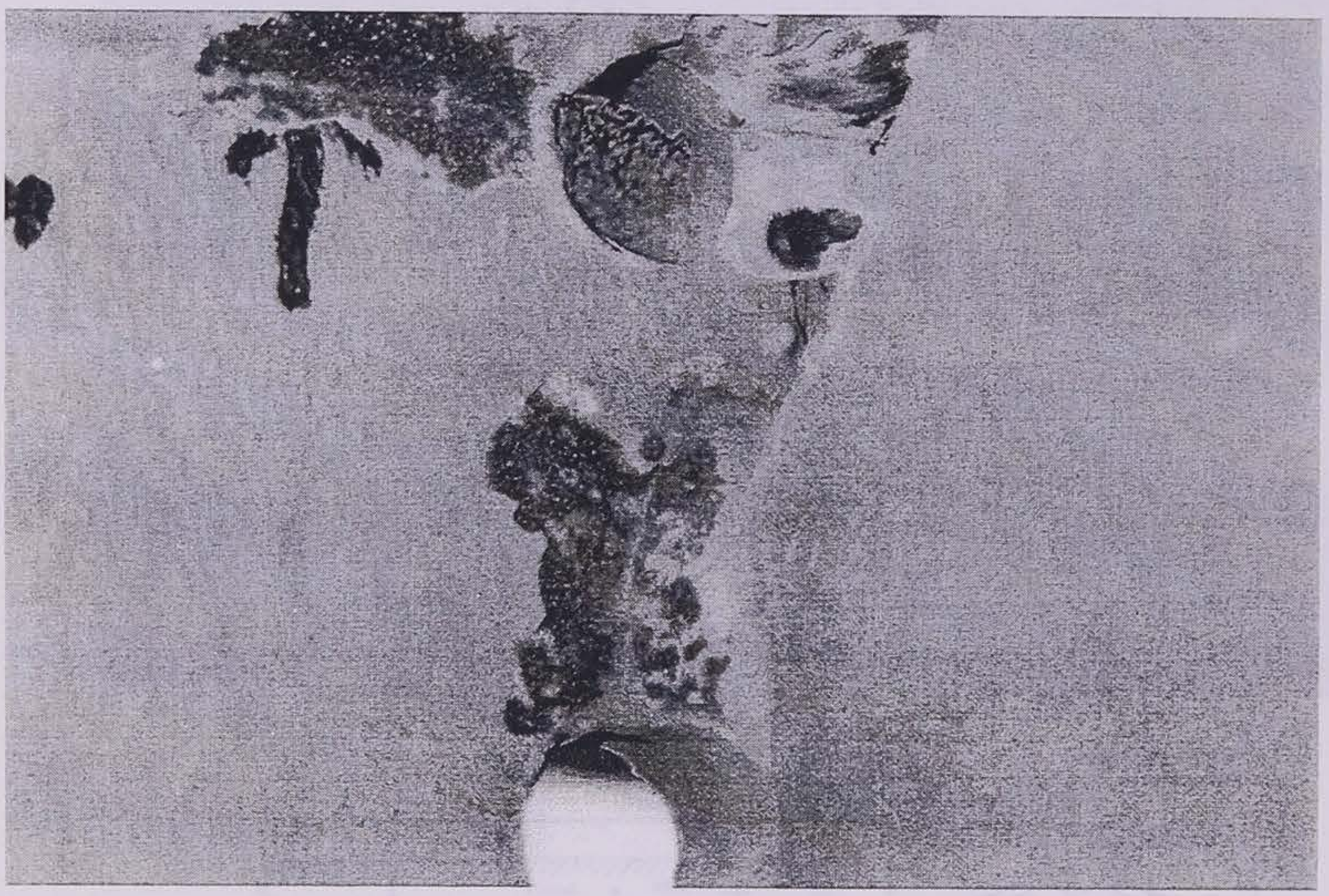


Figure 6 Strain recorded in the web gap region at Location A during Test 5 (Boone River Bridge)

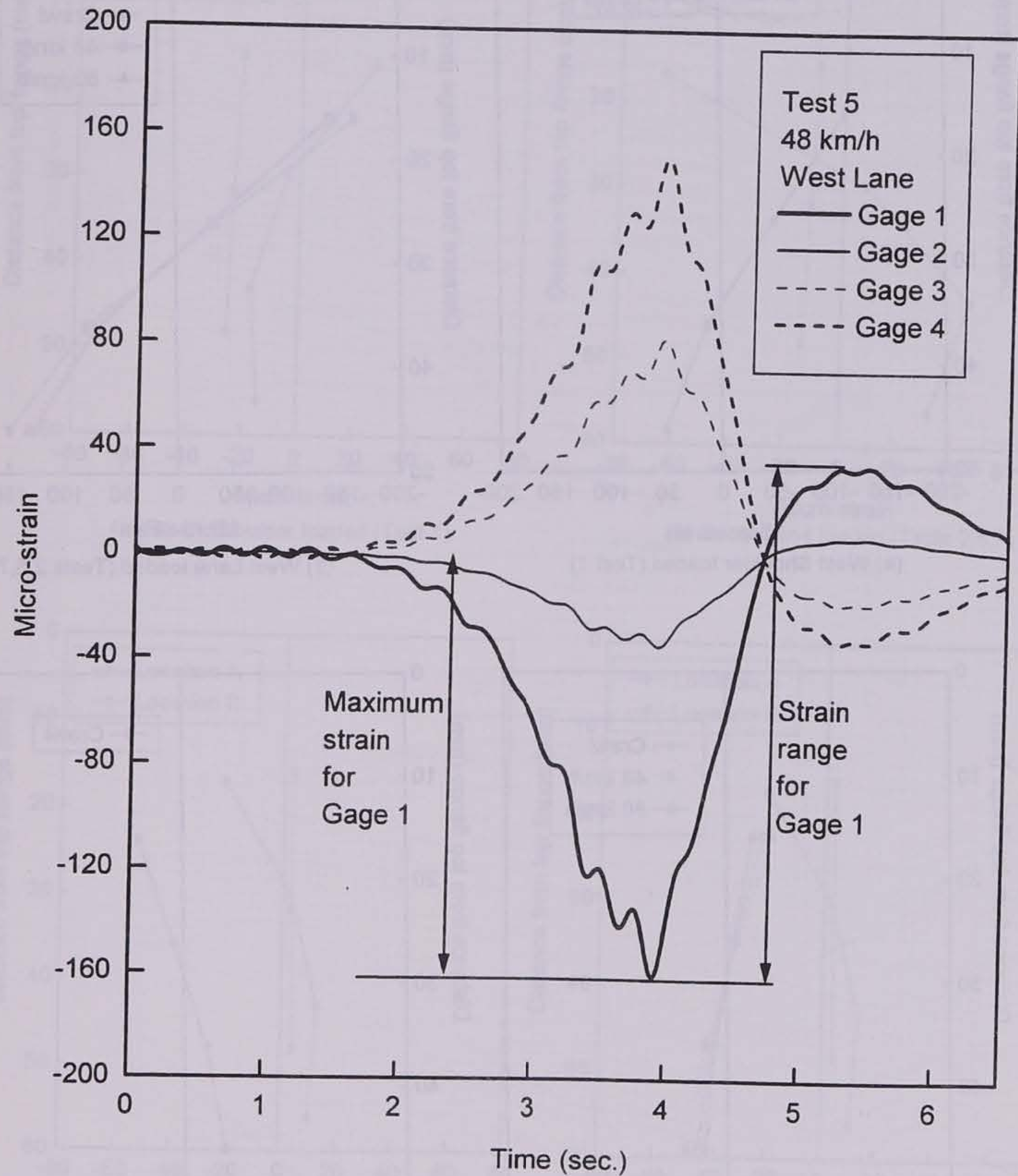
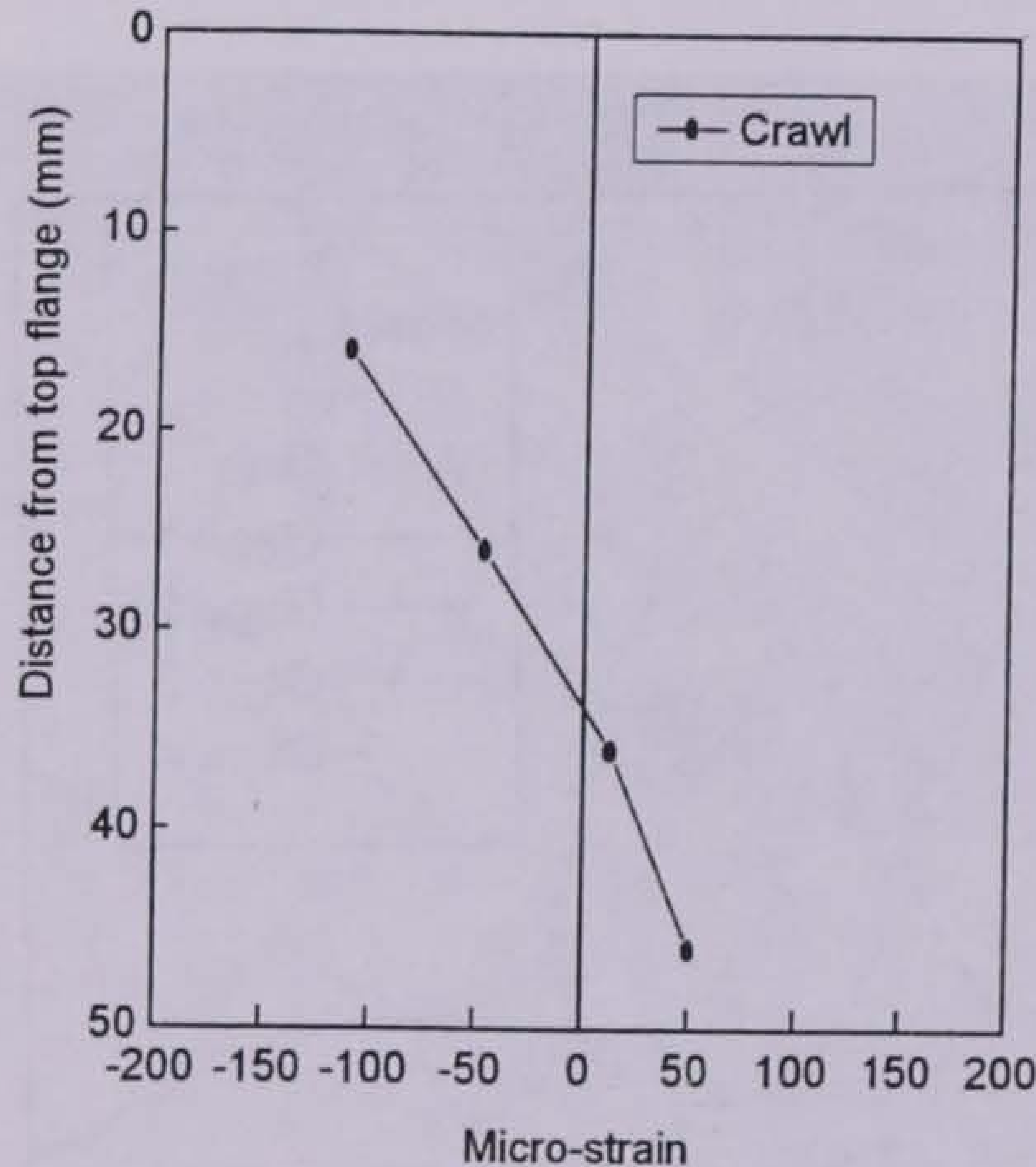
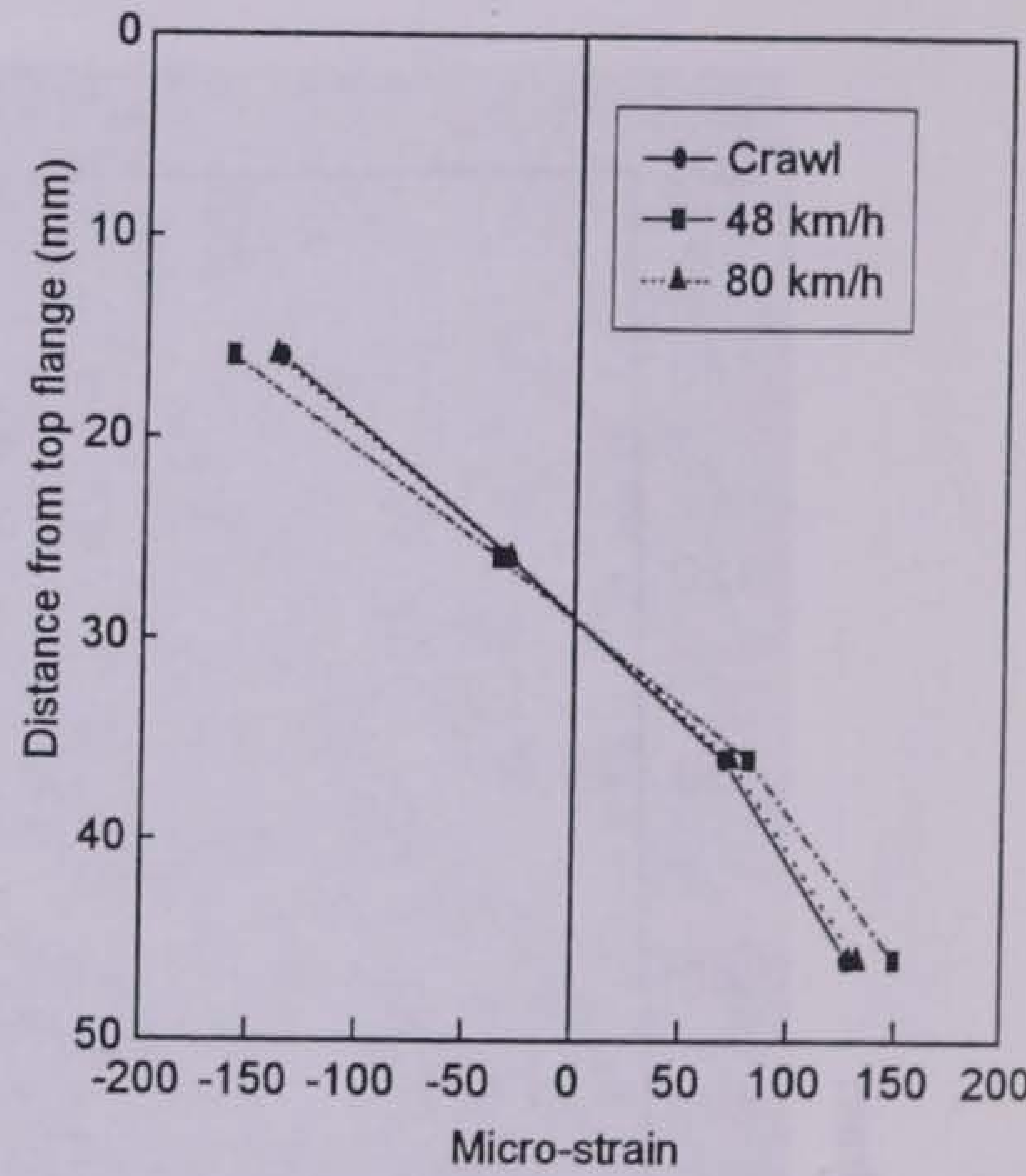


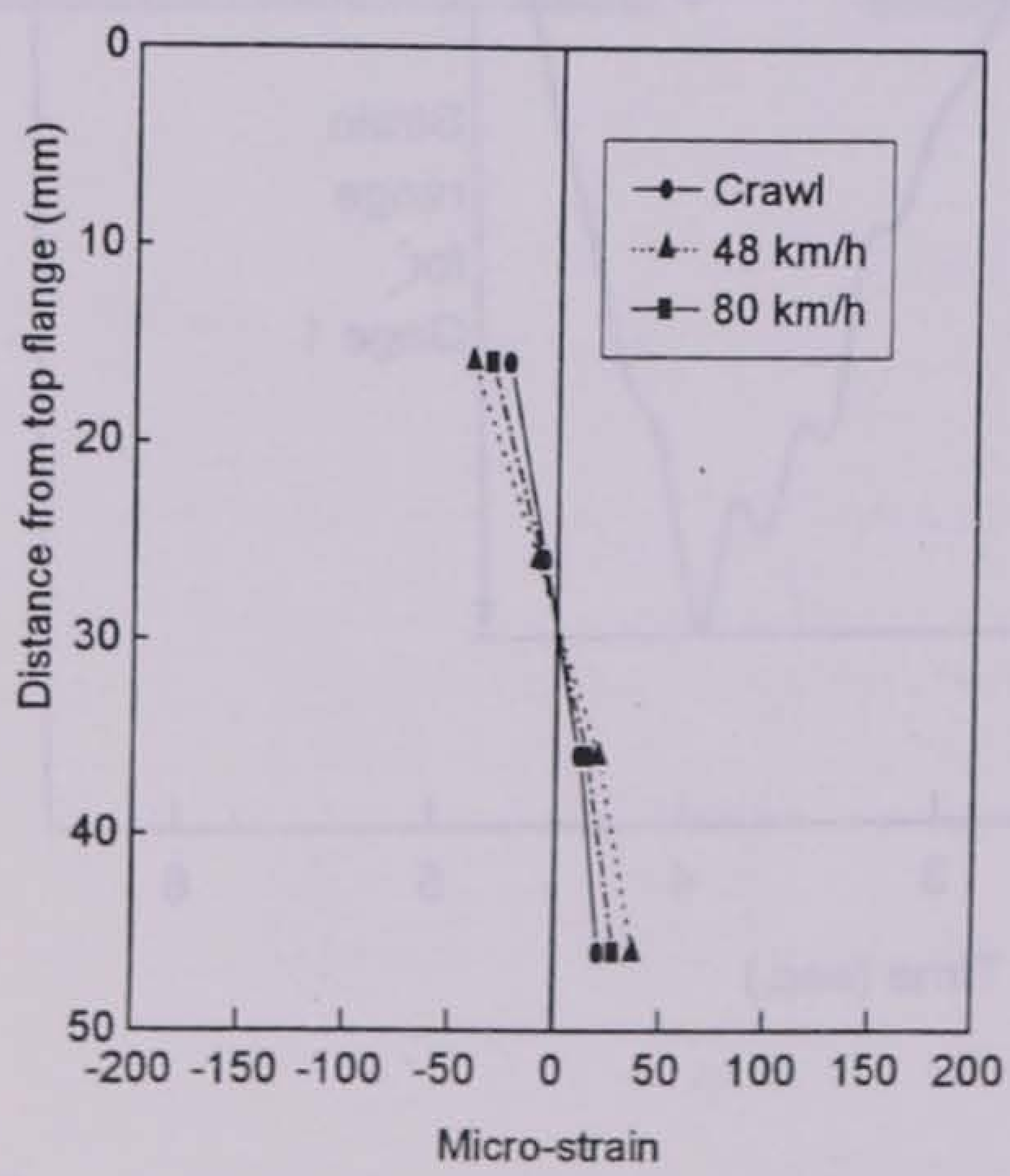
Figure 7 Vertical profile of the maximum strains in the web gap at Location A due to a single truck (Boone River Bridge): (a) West Shoulder loaded, (b) West Shoulder loaded, (c) East Lane loaded, (d) East shoulder loaded



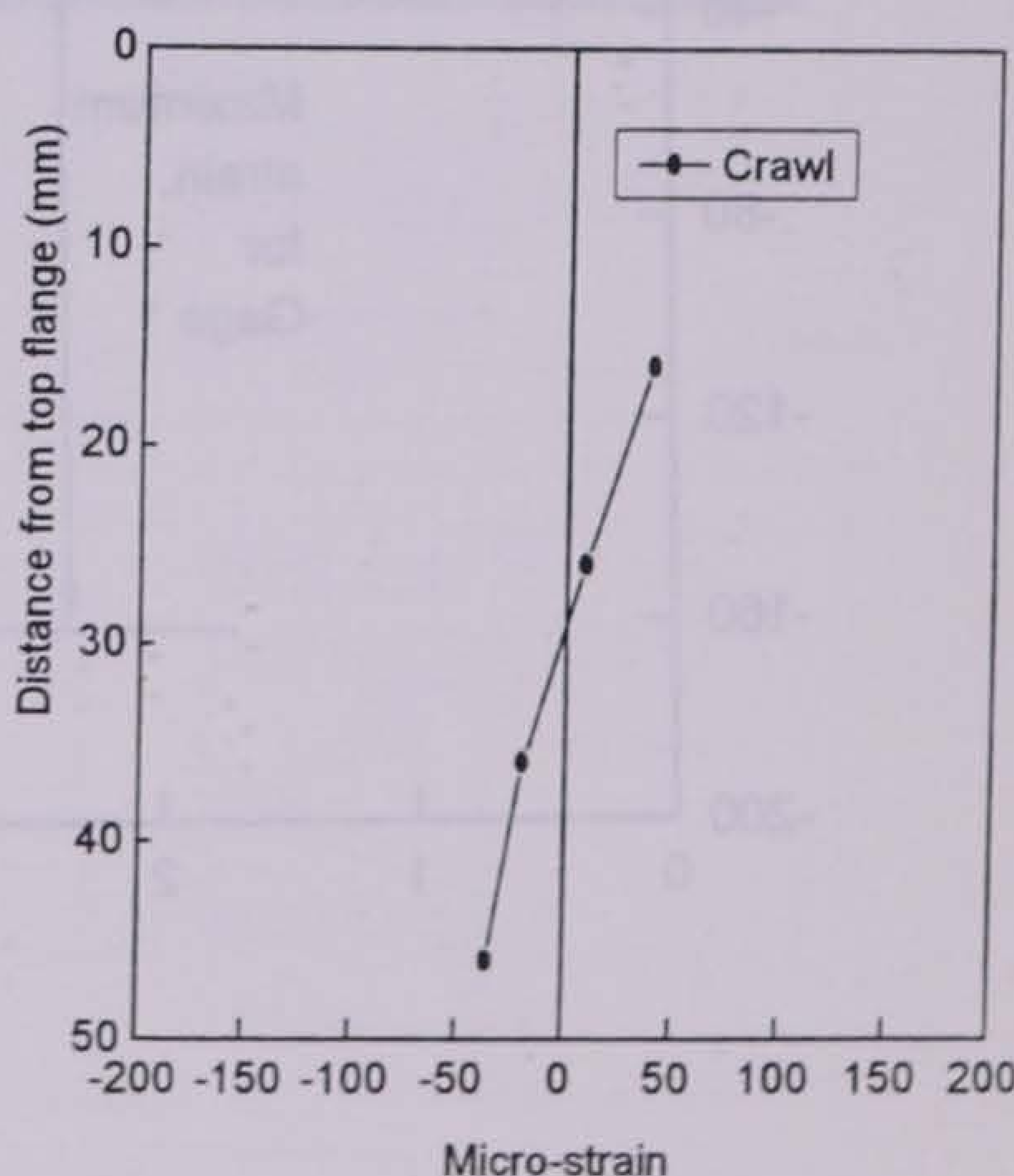
(a) West Shoulder loaded (Test 1)



(b) West Lane loaded (Tests 2,5,7)



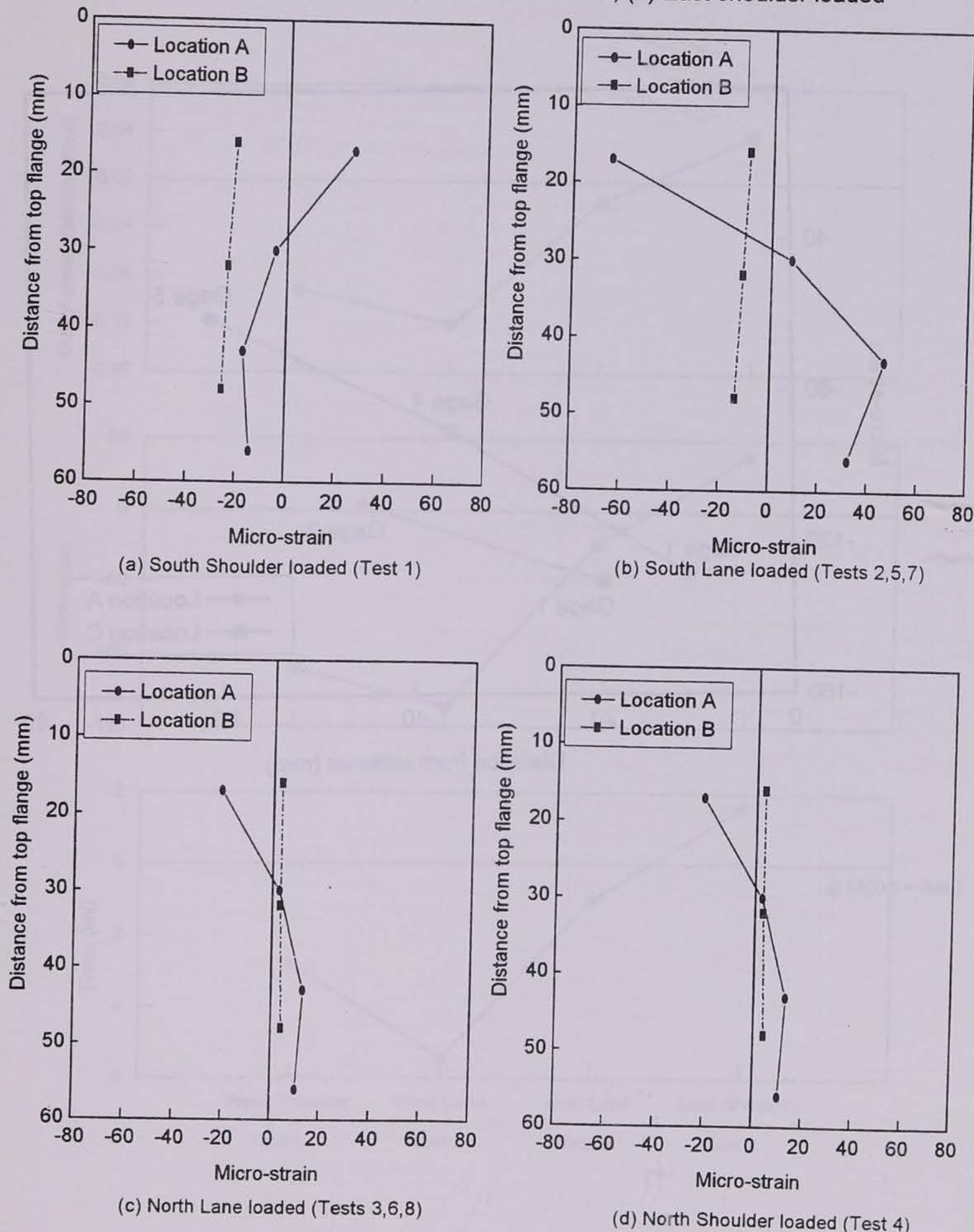
(c) East Lane loaded (Tests 3,6,8)



(d) East Shoulder loaded (Test 4)

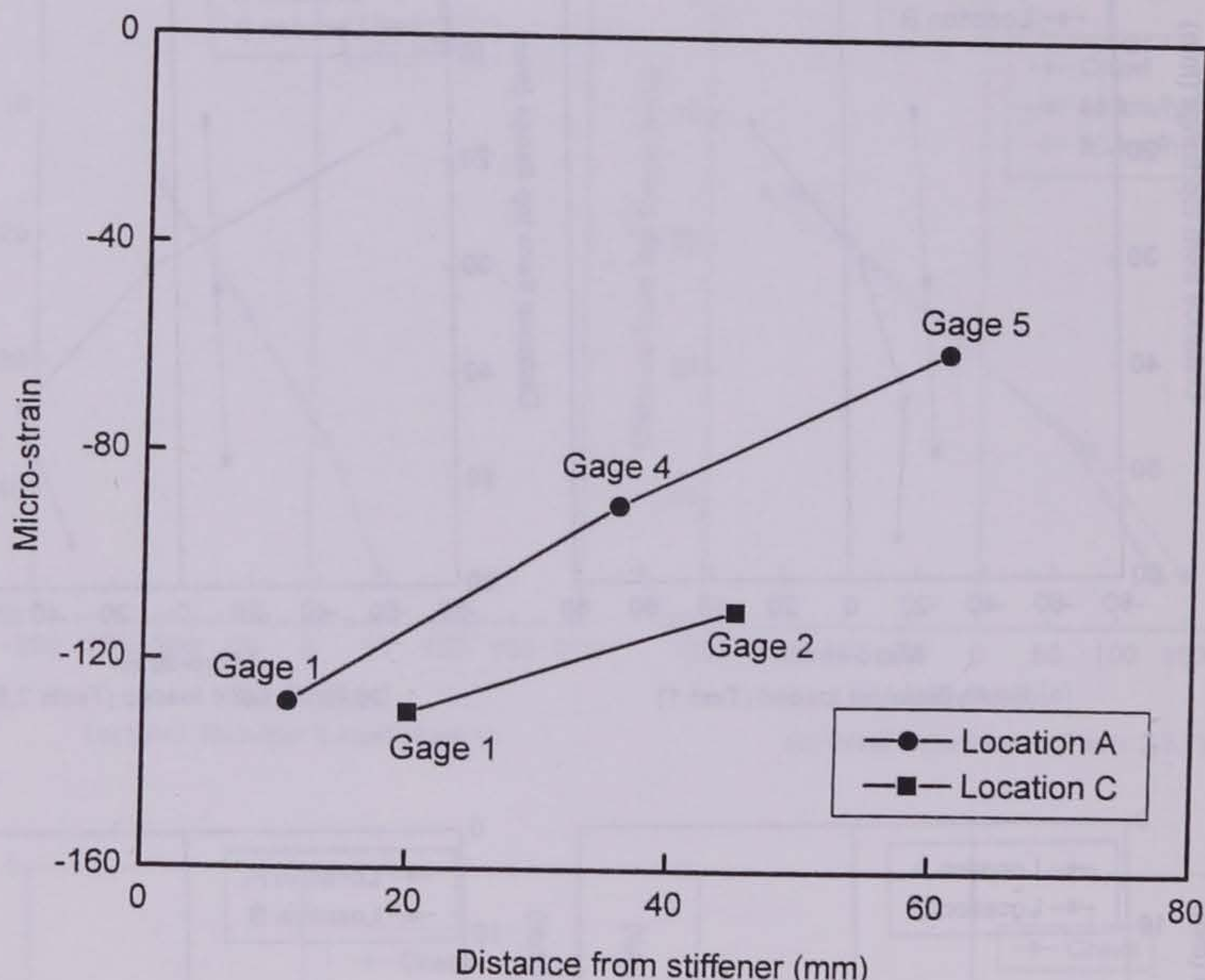
1 mm = 0.0394 in.

Figure 8 Vertical profile of the maximum strains in the web gap at Locations A and B due to a single truck (Des Moines River Bridge): (a) West Shoulder loaded, (b) West Shoulder loaded, (c) East Lane loaded, (d) East shoulder loaded



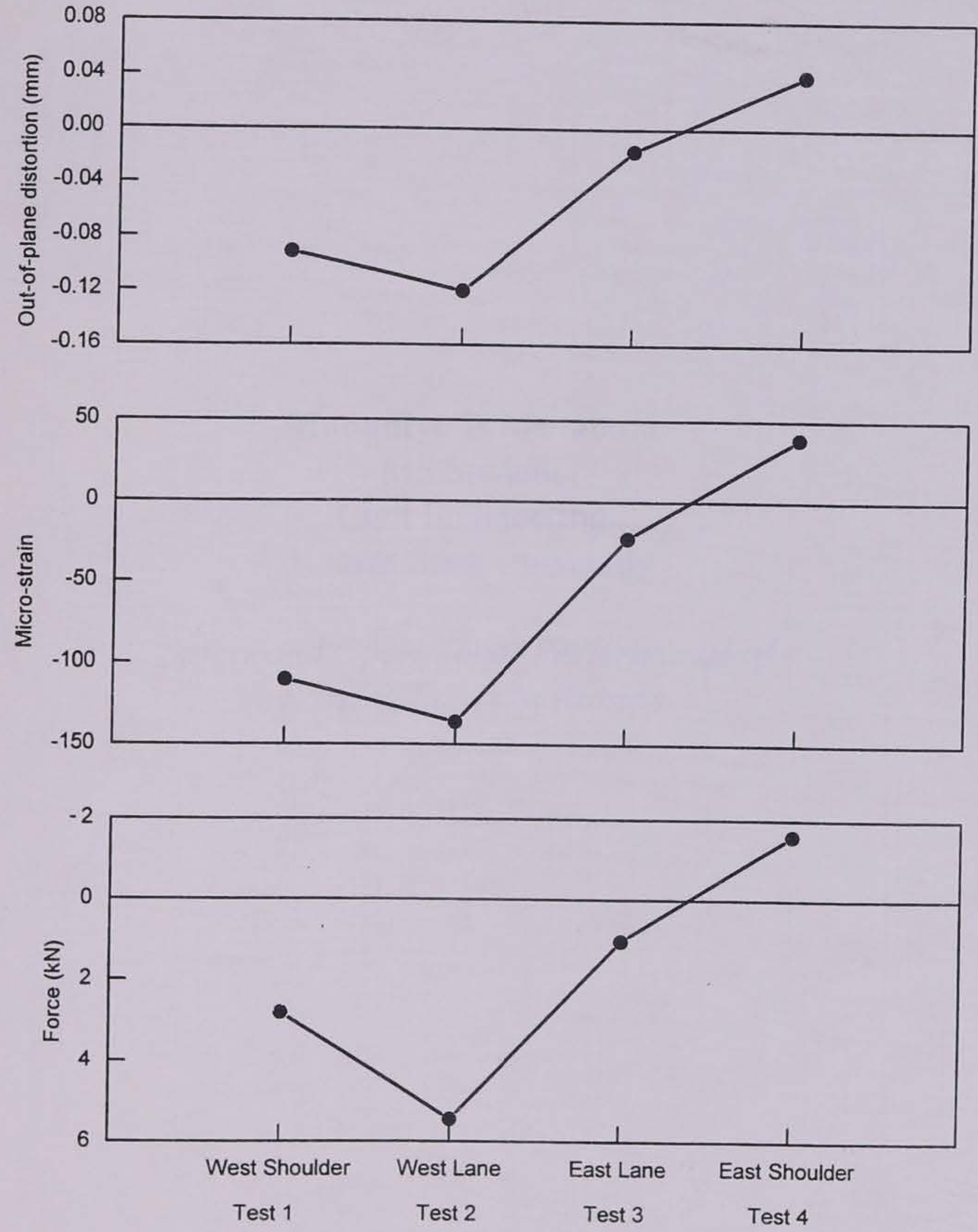
1 mm = 0.0394 in.

Figure 9 Horizontal profile of maximum strains in the web gap of Locations A and C during Test 2 (I-80 Bridge no. 7804.8L080)



1 mm = 0.0394 in.

Figure 10 Out-of-plane distortion, Gage 1 readings, and diaphragm diagonal (D1) force at Location A during Tests 1-4 (Boone River Bridge)



1 mPa=0.145 ksi, 1 mm = 0.0394 in., 1 k N= 0.2247 kips.

Madaniyo Is Mutabazi
MS Student
Civil Engineering
Kansas State University

Safety and Operational Performance of Passing Lanes in Kansas

ABSTRACT

A program of providing passing lanes on places other than unsustainable grades along rural two-lane highways is still at the infant stage in the state of Kansas. The state highway agency has an interest to know how the existing passing lanes are being used by drivers with an objective of making improvements in their planning, design and operation. This limited study has revealed that heavy vehicles are often passed than they do; left turn vehicles from a main highway into side roads constitute a major potion (one-third) of conflicts to the through traffic on the main highway; Location of side road intersection has no impact from a safety point of view; And that drivers see the biggest advantage of passing lanes is to increase safety rather than reducing travel time.

Key words: Rural two-lane highway, Passing lane, Rural intersection, Traffic conflicts.

ACKNOWLEDGMENT: This research is sponsored by Kansas Department of Transportation (KDOT) through its the design bureau. The contents of this paper reflect only the views of the author, who are solely responsible for the facts and accuracy of the information presented herein.

Introduction

Passing maneuver on rural two-lane highways is the most difficult and risk maneuver for a driver, but yet it is the major element influencing efficiency of these highways. One of the most effective ways in increasing the passing opportunities, hence the operational performance is the provision of section(s) with two lanes in one/both direction of travel. The added lane is called "a passing lane." The old concept of passing lane is the "climbing lane" provided on unsustainable grades where some vehicles experiences the problem of maintaining the desired speed. Nowadays, passing lanes are becoming more common at locations other than on unsustainable grades, i.e., in level or rolling terrain where maintaining speed is not a problem. In this paper the term "passing lane" will refer to added lanes on sections other than unsustainable grades.

Problem Statement

Because of side-by-side passing lane configuration (figure 1) used in the state, Kansas Department of Transportation (KDOT) is concerned with safety at intersections where side roads intersects a main highway within a passing lane section. In particular, the through traffic from the side road needed to cross all four lanes at once was thought to be dangerous to the through traffic on the main line. Locating passing lanes while trying to avoid intersecting is a very difficult exercise when working with a network with high cross road density like in Kansas. The density of side road intersections along the highways studied averages at one intersection every 1.12 miles.

Although added lanes increase passing opportunity, it is also true that the added lane-drop and lane-addition sections of the passing/climbing lane may have a negative safety impact due to merging and diverging operations respectively. The comparison of accident rates between lane-addition, lane-drop, and middle sections of passing lanes came up with interesting results *(1)*: lane-drop and lane-addition had the same accidents /mile, although both have higher accident per mile compared with the middle of passing lane. In another study, Homburger *(2)* investigated merging-related accidents for a five-year period on 21 locations of climbing lanes in California. His conclusion was that merging does not seem to cause a grave safety concern after he found only 7 percent of the accidents were related to merging maneuvers.

Previous studies *(1, 3, 4, 5, 6)* have shown that, passing lanes are more effective than other possible treatments in improving the Level-of-Service (LOS) and safety of two-lane highways. Several studies that have tried to evaluate the effectiveness of passing lanes have used percent time delay, speed, and passing rates as major measure of effectiveness *(1, 3, 4, 5)*. Percent time delay, speed and capacity utilization are used by Highway Capacity Manual (HCM) *(7)* to define Level-of-Service (LOS) for a two-lane highway. Table 1 summarizes some major studies, and their respective performance measures *(1, 3, 4, 5)*. KDOT feels that previous studies may not be direct applicable to Kansas because of two reasons: 1) they did not differentiate between passing and climbing lanes, and 2) high density of intersecting roads in Kansas.

Objectives

The objectives of this paper are: 1) to determine whether location of intersections within the passing lane cause great safety concern, 2) comparison of different lane-drop taper lengths from a safety point of view, 3) evaluation of operational benefits of passing lanes, and assess public opinion on safety and performance of passing lanes.

Passing Lane Program in Kansas

While some states in the United States (USA) and countries like Canada, Australia, etc. have been using passing lanes since late 1970's, KDOT started constructing passing lanes in 1994. The network contains nine sites with passing lanes and three more are under construction. Each site has a passing lane in each direction of travel. These sections are found along US50 and US54 highways. Both highways have a posted speed limit of 65 MPH.

Literature suggests locating passing lanes on places which 1) are logical to drivers, 2) will minimize construction costs, and 3) will not degrade safety of the highway section on which they are provided. Passing lanes in Kansas were located on rehabilitated projects while trying to avoid side roads' intersections possible. Despite such a strategy, within the nine sites there are seven cross road intersections.

There are nine possible arrangements (configurations) of passing lanes when used as single lane or a combination of more than one passing lanes as shown in figure 1. Configuration c or e (figure 1) known as tail-to-tail is more effective than head-to-head configuration d or f (figure 1) because by the time vehicles are leaving the passing lanes section, they are not in a platoon as opposed to head-to-head configuration. Existing passing lanes in Kansas have a side-by-side configuration.

Federal Highway Administration (FHWA) suggests an optimum length (excluding tapers) for a passing lane of 0.5 to 1.0 miles (0.8 to 1.6 Km) *(8)*. Passing lane lengths in Kansas seems to be within the suggested range spanning from 0.6 to 1.1 miles (0.96 - 1.76 Km). The Manual on Uniform Traffic Control Devices (MUTCD) *(9)* recommends a minimum desirable merging taper length (L) of 780 ft(238 m) for passing lanes on the highway sections in this study. This length results from the MUTCD formula: $L = S \times W = 65 \times 12 = 780 ft$

Where: L = Minimum length of the taper in feet

W = Width of the lane to be dropped in feet, and

S = Posted speed or 85^{th} percentile speed during the off peak period in miles per hour.

Merging taper lengths for Kansas passing lanes range from 518 ft (158 m) to 840 ft (256 m).

Passing lanes on US 50 have two advance signs, the first at two miles (3.2 Km), and the second at ¼ miles (0.4 Km) before reaching the passing lane. At the beginning of the lane-drop section of passing lane they are signed "**KEEP RIGHT EXCEPT TO PASS**." Passing lanes on US 54 have only one advance sign, at ¼ miles (0.4 Km) before reaching the passing lane, and at the beginning of the lane-drop section of passing lane they are signed "**SLOWER TRAFFIC KEEP RIGHT**"defined as R4-3 by MUTCD *(9)*. Passing lanes on both highways have a symbolic lane reduction transition sign near the beginning of the lane-drop taper and are marked with double yellow lines restricting passing in the opposite direction. The lane reduction transition sign is defined as W4-2 by the MUTCD.

Data Collection

Traffic Filming

Two sites on US50 (Peabody and Burton) were filmed using time lapse video cameras in observing traffic pattern and how drivers are using passing lanes. For each site the camera was placed at 300 feet (90 m) before reaching the lane-drop section (after the end of lane-addition section of the opposing direction). Filming was done continuously day and night for four and three days at Peabody and Burton sites.

Merging Conflicts

Traffic conflicts in merging sections were observed for four hours at each of 16 passing lane sections studied. Eight passing lanes are on US50 and the other eight are on US54. One-way traffic volume in the direction of merging was counted at the same time of conflicts observations.

Intersection Conflicts

Traffic conflicts on three intersections form each highway was observed. Each of the three intersections was chosen at random at the following locations: 1) within the full passing lane section(four lanes), 2) immediately after the lane-drop of the passing lane (2-lane), and 3) isolated section free from the influence of the passing lane(2-lane). Like the merging conflict experiment, turning volumes though the intersections were counted at the same time.

Drivers' Survey

Drivers using the highway sections under study were surveyed to collect users' view on how they perceive existing passing lanes in the state from an operational and safety points of view. One thousand mail-in postcards survey were handled to the drivers for them to fill and mail back.

Results and Discussion

Traffic Filming

Although the camera could view the traffic in both directions of travel, opposing traffic, and night time data was not easy to analyze. This paper presents data 11 and four hours from Peabody and Burton sites respectively. The data extracted from the video tapes includes vehicle mix, percent of vehicles performing passing maneuvers, type of vehicles being passed, vehicles using the right (shoulder) lane. Vehicles were classified into three classes: 1) Passenger cars, 2) Medium size vehicles, and Heavy vehicles. Passenger cars include all 4-tired vehicles, medium vehicles include recreation vehicles and light trucks (6-tired pickups), while heavy vehicles include all single unit trucks, trailers, semi-trailers and farm equipment.

Traffic at Peabody Site has a higher percentage of heavy vehicles of 29% compared with Burton that have 13% (table 2). The percentage of heavy vehicles at Peabody is very close to the value of 24% derived from continuous counting all year round by KDOT. However, the value for Burton was much lower than KDOT value of 20% probably due to smaller sample size of four hours compared with 11 hours for the Peabody site.

From table 2 the proportion of passes in each vehicle class are apparently proportional to the proportion of that class. It can also be seen that heavy vehicles are often passed more than themselves passes. While at Peabody sites only 5% of all passes made were executed using the right lane, at Burton sites as high as 19% of total passes were made in the right lane.

The state of Kansas prohibits passing to the right. At the studied sites, passing to the right is restricted through the "**KEEP RIGHT EXCEPT TO PASS** " sign at the beginning of the lane-drop section. Passing to the right reflects the level of intolerance for drivers traveling behind slower vehicles. At a passing lane, this intolerance will mainly depend on the number of slow vehicles keeping right, and the level of platooning. The fact that the "keep right" compliance for both site is the same (51% for Burton and 52% for Peabody refer table 3) then it can be suggested that other factors such as platooning level, sample size, etc. might be responsible for the difference in proportions of passing to the right at the two sites. For both sites, heavy vehicles and medium vehicles comply equally in keeping right at a level of about 70%, while the compliance rate of passenger cars is about 45% as shown on table 3.

Channeling traffic to the outer lane is highly recommended because it discourages slow vehicles from occupying the passing lane (an inner lane). Staba et al. *(5)* conducted a before-and-after experiment in California to assess the effect of marking the lane-addition. In the before study (no channelization) it was found that 80 percent of entering traffic moved directly into the passing lane. In the after study (channelization) 80 percent of entering traffic moved directly into the outer lane. Kansas passing lanes are marked similar to the before condition (no channelization) of the California study. The proportion of vehicles entering the right lane (20%) at the beginning of the passing lane at Burton sites is similar to that observed in California. At the Peabody site the proportion is somewhat less than that at Burton sites. The proportion of vehicles entering the right lane at the beginning of the passing lane are reduced from column four and column five of table 3. Column 4 gives the percentage of all vehicles keeping right, while column 5 gives the percentage of vehicles keeping right somewhere after beginning the passing lane section, i.e., the number for Burton sites would be 51%-31% = 20%.

Figure 2 shows the relationship between the passing rate and one-way volume. The hourly volumes on Peabody sites are far less than those on Burton sites and therefore have a lesser passing rate. However, trend lines fitted by the best linear fit suggests that at comparable hourly volumes, Burton Site will have higher passing rate than Peabody Site. This could be due to the following reasons: 1) Peabody Site has higher proportion of heavy vehicles compared with Burton Site at the expense of passenger cars that have a higher passing rate as was shown on table 2, 2) Burton Sites is relatively shorter than Peabody Site which is likely to produce higher pass rates (Peabody Site is 1.321 Km (0.826 miles) while Burton Site is 1.212 Km (0.758 miles)), 3) Peabody Site begins on a 1.17% upgrade while Burton Site is on a flat grade. Interesting to note is the parallelism of the trend lines suggesting similar relationship between volume and pass rate for both sites. This could be supported by the fact that traffic at both sites behave the same when it comes to factors affecting passing rate such as keeping right.

Merging Conflicts

The objective of this experiment was to determined if there is any difference from between two merging taper lengths from safety point of view. The first level for the factor length was the length less than the recommended minimum length of 780 ft, the second level was length greater or equal to 780 ft. Highway section was used as blocking factor with two levels (US50 and US54). For the range of merging taper lengths studied, i.e. 512 - 840 ft.(155 - 255 m), the analysis of variance on hourly number of conflicts per 100 vehicles on the main line didn't detect any difference between the two levels of taper lengths (p-value of 0.506). The average number of conflict rate for shorter taper length was 2.5, while for longer taper length was 2.9. Also the analysis didn't show benefits of blocking the experiment on highway sections of US50 and US54 (p-value of 0.161).

Intersection Conflicts

The objective of this experiment was to determine whether the location of a side road intersection within the passing lane degrade safety of the through traffic on the main highway. This design was constructed to see if locations other than within passing lane degrade safety than the within location. Classical safety assessment use accident data to assess the safety of the highway facility. In this study it was difficult to use accident data because the passing lanes have been in operation for a short period to produce meaningful data for statistical analysis. Traffic conflicts analysis was used in this experiment instead of accident data.

At a four-leg intersection there are five turning movements which can cause conflicts to the main line thru movements: 1) left-turn from the main line, 2) left-turn from the side road, 3) Right-turn from the main line, 4) right-turn from the side road, and 5) through from the side road. Comparison of intersections using all conflicts caused by all five movements is difficult. The analysis on number of conflicts for all six intersection studied suggests that highest percentage (33%) of left-turn vehicles from the main line causes conflicts. For this reason, conflicts by left-turn vehicles were used to make intersection location comparison. Table 4 shows the percentage of vehicles for each movement causing conflicts.

The analysis of variance was performed considering three levels of location (within, after, and isolated) with highway section as blocks of two levels (US50 and US54).The number of conflicts per 100 left turning vehicles was used as response variable. Analysis of variance couldn't detect differences between the three intersection locations. The p-values for pair comparisons are: 1) Within Vs Immediate = 0.76, 2) Within Vs Isolated = 0.35, and Immediate Vs Isolated = 0.26. The mean for within, immediate and isolated are 45.5, 52.6, and 21.6 respectively. Also the advantage of blocking was not realized (p-value of 0.15).

Drivers' Survey

Of the 1000 distributed survey cards, 406 cards were mailed back, which represent the response rate of 40.6 percent. The items note worth to report here is the response of drivers on operation performance (travel time saving) and safety. Safety received the highest rating, with 93 percent of drivers thinking that passing lanes improve safety. About 53 percent of respondents think that passing lanes save time. Although engineers provide passing lanes with the primary objective of dispersing platoons and hence saving time, drivers in Kansas consider safety as great a benefit of passing lanes than time savings.

Conclusion

Keep right compliance at the beginning of the passing lane is about 20 percent with an overall compliance of about 50%. Heavy vehicles and medium size vehicle have the highest compliance rate of about 70 percent while passenger cars have the smallest compliance rate of about 45%. This compliance rate can be increased by channelizing traffic to the outer lane by the means of pavement marking.

Most people think that heavy vehicles reduce the capacity of highways at unsustainable grades alone, this study shows that even at level grade heavy vehicles are often passed than they pass. The correlation between passing rates and traffic volume seems to be constant, however, there are other factors which affect passing rates not measured in this study.

The sample sizes for intersection location and merging taper length experiments were not big enough to detect significant differences between these factors. Side road through and left turning movements do not pose a biggest safety threat to the main highway traffic as it was thought initially, instead the left turning vehicles from the main highway do. Although engineers provide passing lanes with the primary objective of dispersing platoons and hence saving time, drivers in Kansas consider safety as great a benefit of passing lanes than time savings.

References

1. Harwood, D.W., and A.D. St. John. Passing lanes and Other Operational improvements on Two-lane Highways. Report No. FHWA/RD-85/028, Federal Highway Administration. Washington, D.C., December 1985.
2. Homburger, W.S. An Analysis of Safety at Upgrade Terminals of Climbing Lanes on Two-Lane Highways. Transportation Research Record 1122, Transportation Research Board, National Research Council, Washington, D.C. 1987, pp 27-36.
3. Emoto, T.C., and A.D. May. Operational Evaluation of Passing Lanes in Level Terrain. Final Report. Report UCB-RR-88-13. Institute of Transportation Studies, University of California at Berkeley, July 1988.
4. Morrall, J.F., and L. Blight. Evaluation of Test Passing Lanes on the Trans-Canada Highway in Banff National Park, Proceedings of International transport congress, Roads and Transportation Association of Canada. Vol. 5, Montreal, September 23-27 1984, pp B63-B93.
5. Staba, G.R., H.O. Phung, and A.D. May (1991). Development of Comprehensive Passing Lane guidelines, vol.1: Final Report. Report UCB-ITS-RR-91-1, Institute of Transportation Studies, University of California at Berkeley, January 1991.
6. Taylor W.C. and M.K. Jain. Warrants for Passing Lanes. Transportation Research Record 1303, Transportation Research Board, National Research Council, Washington, D.C. 1991, pp 83-91

7. Highway Capacity Manual. Special report 209, Third edition, Transportation Research Board, Washington, D.C. 1994.

8. Harwood, D.W., and C.J. Hoban (1987). Low - Cost Methods for Improving Traffic Operations on Two-Lane Roads: Information Guide. Report No. FHWA-IP-87-2. Federal Highway Administration, Washington, D.C.

9. Federal Highway Administration. Manual on Uniform Traffic Control Devices: Foe streets and Highways, Report No. FHWA-RD-89-226, 1988, pp 72-90.

Table 1: Operational Performance Measures for Evaluating Passing Lanes. Source: ***(1, 3, 4, 5)***

Study	**Measures of Effectiveness (MoE)**	**Suggested Major MoE**
Passing Lane Research Study for the Trans-Canada Highway in Banff National Park. ***(4).***	• Percent vehicle in platoon • Passing rate • User opinion	———
Passing Lanes and other Operational Improvements on Two-lane Highways. ***(1)***	• Speed • Percent vehicle in platoon[b] • Passing rate	Passing rate
Operational Evaluation of Passing lanes. ***(3)***	• Speed • Percent time delay • Passing rate[a] • Lane utilization	Percent time delay
Development of Comprehensive Passing Lane Guidelines. ***(5)***	• Speed • Percent vehicle in platoon • Passing rate • Lane utilization • Platoon structure	Passing rate

[a] Results were inconclusive because of limited data
[b] Surrogate measure of percent time delay *(7)*

Table 2: Traffic Pattern at Passing Lanes

Site	Vehicle Class	% Volume	% Passing	% Passed	Passing to the right	
					% of Right Passes	% of Total Passes
Burton	Heavy	13	10	21	5	19
	Others	87	90	79	95	
Peabody	Heavy	29	23	43	26	5
	Others	71	77	57	74	

Table 3: Percent of Vehicles Keeping Right

Site	Class	Total, Within Vehicle Class	Total, All Vehicles	After Lane Begins, All Vehicles
Burton	Passenger cars	46	51	31
	Medium vehicles	73		
	Heavy vehicles	74		
Peabody	Passenger cars	43	52	38
	Medium vehicles	70		
	Heavy vehicles	69		

Table 4: Intersection Conflict Distribution by Type of Turning Movement

	Turning Movement[a]				
	LT from main line	LT from side road	RT from main line	RT from side road	TH from side road
Movement Volume	139	108	132	185	81
Number of Conflicts	46	6	10	7	4
Percentage Conflicts	33.1	5.6	7.6	3.8	4.9

[a] LT = Left Turn, RT = Right Turn, TH = Through

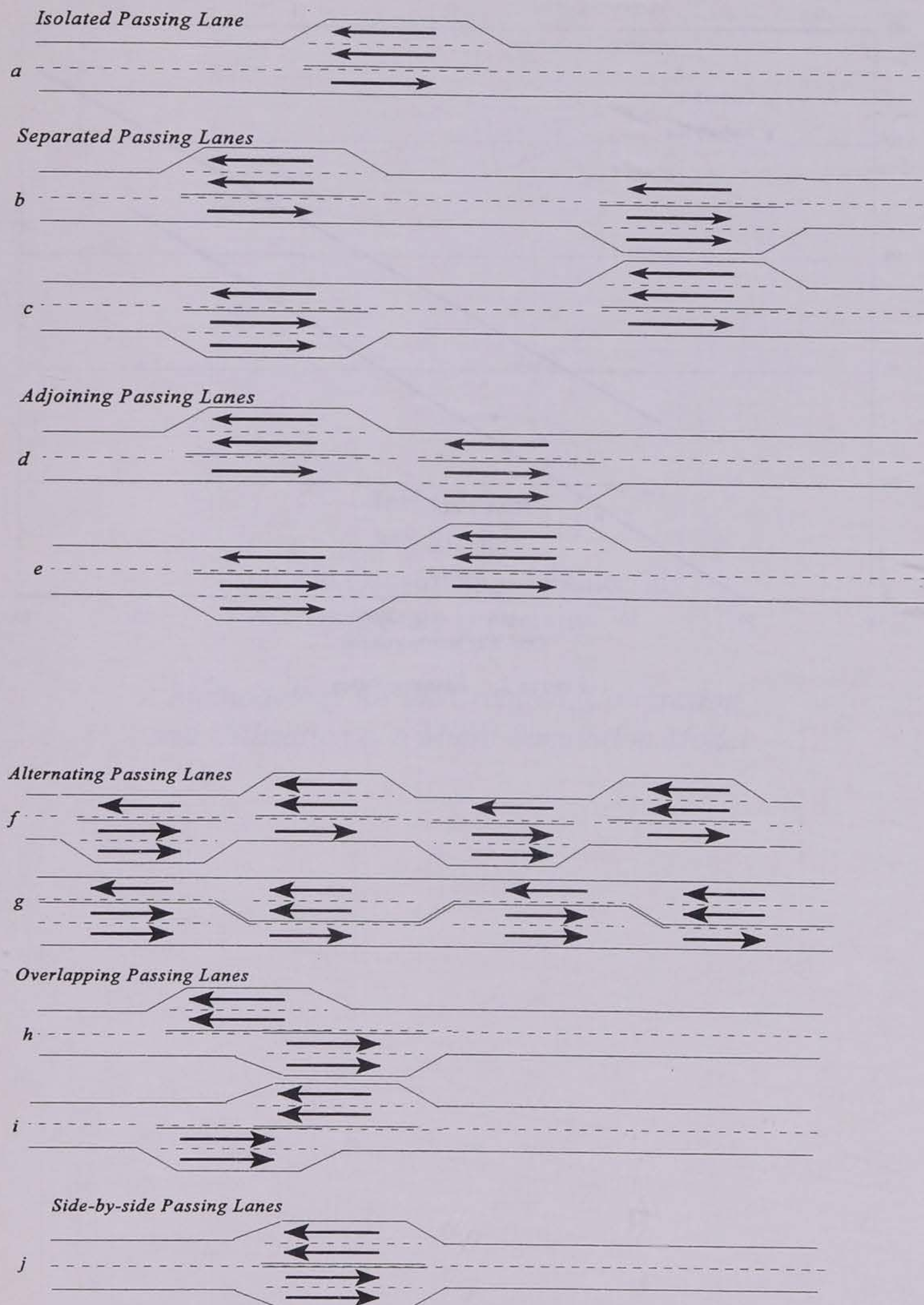


Figure 1: Passing Lane Configurations. Source: ***(8)***

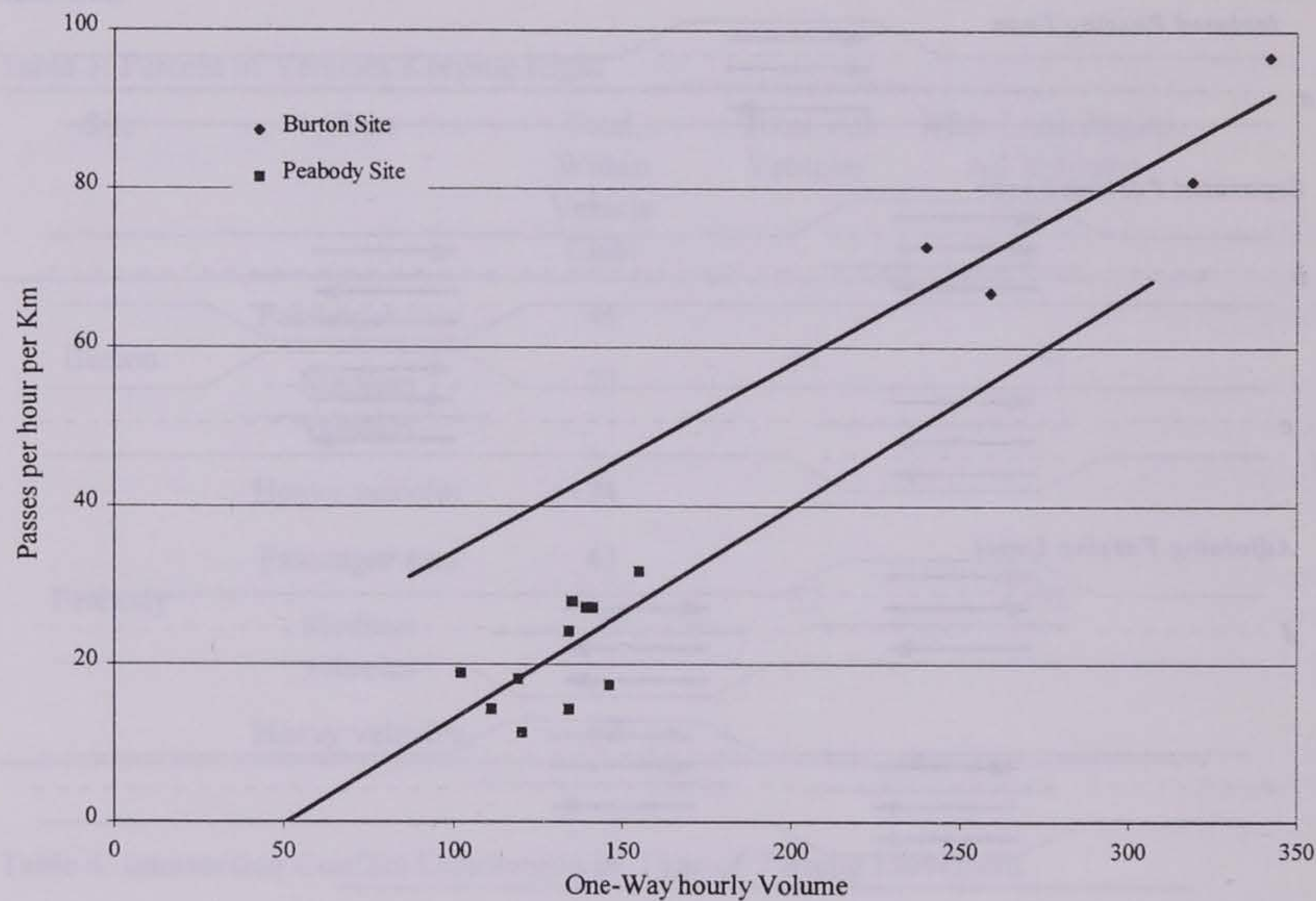


Figure 2: Passing Rates

Jeff Gerken
MS Student
Civil and Construction Engineering
Iowa State University

A Methodology for the Creation, Calibration, and Utilization of a Micro-Simulation Model

INTRODUCTION

The advent of microcomputers has created a multitude of traffic engineering tools, one such tool is the computer micro-simulation model. This paper presents the methodology required of a traffic engineer in the creation and use of a micro-simulation model. This paper explains the background and reason for choosing a micro-simulation model and uses the example of an interstate weigh station to further develop the concepts of model generation, verification, validation, and finally model output.

BACKGROUND INFORMATION

Reasons for Using Micro-simulation Models

The traffic engineering field is continually being asked to do more with less. This includes better initial designs, improved interim measures, and more thorough reconstruction and maintenance procedures. These improvements could lead to reduced additional costs during construction and maintenance periods and increased safety in work zones. One useful tool to aid in these processes is the computer micro-simulation model. These models provide a means to alter design strategies in an effort to generate the best alternative for the task at hand. Traffic simulation models are more practical than field experiments for the following reasons:

- less costly
- results are obtained quickly
- data generated includes several measures of effectiveness (MOEs) that cannot be easily obtained from field studies
- traffic operations are not disrupted, as is the case with field experiments

- physical changes to the facility under consideration are not required for study purposes
- prospective design configurations can be subjected to future traffic demands
- numerous variables can be altered or held constant as desired (1)

Basically, micro-simulation models allow the traffic engineer to test alternatives in an office environment where the measures of effectiveness can be analyzed to prove or disprove a concept's worth without negatively impacting the operational and safety aspects of the existing infrastructure.

Measures of Effectiveness

According to the *Highway Capacity Manual*, measures of effectiveness are defined as the parameters selected to define levels of service for each type of facility. Further, measures of effectiveness represent available measures that best describe the quality of operation on the subject facility type. Table 1 lists the measure of effectiveness with various facility types.

TABLE 1 Measures of Effectiveness by Type of Facility

Type of Facility	Measure of Effectiveness
Freeways	
Basic freeway segments	Density (pc/mi/ln)
Weaving areas	Avg travel speed (mph)
Ramp junctions	Flow rates (pcph)
Multilane highways	Density (pc/mi/ln) Free-flow speed (mph)
Two-lane highways	Time delay (%)
Signalized intersections	Avg stopped delay (sec/veh)
Unsignalized intersections	Avg total delay (sec/veh)
Arterials	Avg travel speed (mph)
Transit	Load factor (pers/seat, veh/hr, people/hr)
Pedestrians	Space (sq ft/ped)

(2)

Micro-simulation models can quickly generate output files that contain the measures of effectiveness resulting from input parameter variations. This gives the traffic engineer the ability to make quantifiable comparisons between alternatives.

Micro-simulation model output files can be tailored to display the desired measures of effectiveness. Two common measures of effectiveness for traffic engineering are average network speed (measured in miles per hour) and total delay time for the network (measured in vehicle-hours).

CREATION OF A MICRO-SIMULATION MODEL

Selecting a Micro-Simulation Model

Undertaking a project that utilizes simulation technology can be a difficult task. First, the type and specific computer model must be selected. This is commonly based on the traffic engineer's experience, knowledge of the program, and the intent of the project. There are two basic types of computer simulation models, macro and micro. Macro computer simulation models can be used for general corridor analysis and are sometimes used to identify initial strategies (followed by more in-depth analysis with micro-simulation models). Macro-simulation models aggregate the vehicles within the model as compared to micro-simulation models that retail individual vehicle identity. This paper focuses on micro-simulation models.

Micro-simulation models generate and retain specific entities (i.e. vehicles) and model the behavior of those entities based on performance characteristics (acceleration, deceleration) and network design (geometrics, signal timing, link attributes, etc.). Micro-simulation models yield output information that can help the traffic engineer develop strategies based on vehicle specific information.

The author chose CORSIM (CORridor SIMulation) as the micro-simulation program. CORSIM evolved from previous versions of both micro and macro simulation models. CORSIM is comprised of two programs, FRESIM (FREeway SIMulation) and NETSIM (NETwork SIMulation), and several associated support modules. As their names imply FRESIM is used to simulate freeway systems and NETSIM is used to simulate network level systems such as arterial and collector streets and intersections. The use of both of these modules will be discussed later in this paper. CORSIM is a Windows™ based program that utilizes graphical input and output programs. However, at this time the current graphical input editor requires frequent correction due to errors in the program. This problem can be alleviated though, through the use of input text editor.

Case Study Specific Information

The case study used for this project was a typical interstate weigh station and the goal of the case study was to determine the delay within the weigh station network. This presents an interesting problem, the mainline links must be modeled in FRESIM, whereas the ramps and weigh scale links must be modeled in NETSIM. The reason for using both components of CORSIM is the type of delay that must be assigned to the NETSIM network to mimic the real work conditions. Weigh stations typically consist of a mainline section, off-ramp section (deceleration area), scale area (potential stopped delay), on-ramp section (acceleration area), and merge area with the mainline traffic. The case study network could be modeled in FRESIM with the exception of the weigh scale area. Stopped delay must be assigned to the weigh scale area to account for the potential stopped delay that occurs if a truck is actually ordered to weigh and FRESIM can not accomplish this modeling task. The stopped delay can be modeled in NETSIM through the use of pre-timed traffic signal node control. The delay that accumulates on the ramps and scale links due to the trucks slowing down and preparing to stop is modeled by altering the speed limit attributes.

BUILDING A CORSIM MICRO-SIMULATION MODEL

The CORSIM manual offers suggestions as to the procedural steps to generate a NETSIM and/or FRESIM model. These procedures are rather intuitive and require minimal computer programming experience. However, some programming knowledge is required, since errors will occur in the modeling process and programming knowledge will prove beneficial once debugging commences. It would be incorrect to state that no knowledge in the area of traffic engineering is required. Creating and operating micro-simulation models such as CORSIM requires more than mere cursory knowledge in the area of traffic engineering.

A link/node network structure is used within micro-simulation models to simulate streets (links) and intersections (nodes). Coding a link/node system requires the traffic engineer to anticipate the interaction of link/node relationships and has the ability to recognize and understand when those relationships adversely interfere with each other.

Model Input Parameters

Basic procedural steps require placing nodes (intersections) at the desired x,y coordinates and connecting links (roads) between the proper nodes. Geometric design plans can prove to be a helpful information source at this point. Figure 1 below shows the link/node structure of the mainline exit ramp into the weigh station. Node 101 is the point at which the off-ramp begins and node 7000 is the point at which the FRESIM model and the NETSIM model interact. Once the basic link/node network exists, the next step is to assign attributes to both the links and the nodes. Node attributes consist primarily of the traffic control type. These include sign (stop/yield), pretimed-signal, or actuated-signal. Link attributes consist of lane geometry (number of lanes, acceleration/deceleration lanes, right/left turn lanes, lane alignment), free-flow speed, grade, super-elevation, surface type, traffic volumes, and turning movements.

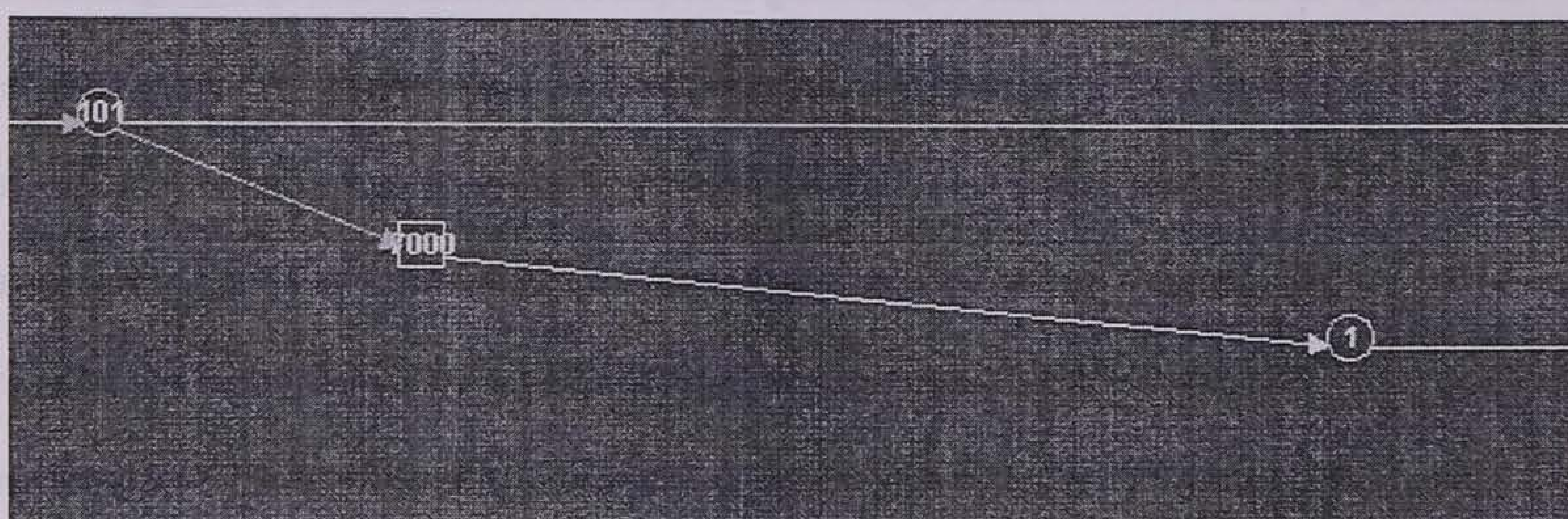


FIGURE 1 Links and Nodes in CORSIM Input Editor

Once all information is attributed, the CORSIM run procedure can begin. This procedure checks for required information and transforms the input information into a useable programming format. Any errors in the attribute information, such as incorrect lane alignment or missing turn movements, will generate a program termination error.

The error will then have to be corrected before any further processing can occur. The process of finding and correcting errors in the program is known as troubleshooting and debugging. Error messages are fairly descriptive and can assist greatly in the debugging and troubleshooting phase. When all errors are corrected, the model will run through the programmed simulation and generate a tabular output file. The processed output file can also be viewed through the use of the traffic viewer module. This module generates visual graphics and offers a dynamic display of the model conditions and results. Figure 2 below shows a still image of the output viewer module. It is worth noting that both Figures 1 and 2 display relatively the same location, just in different program modules.

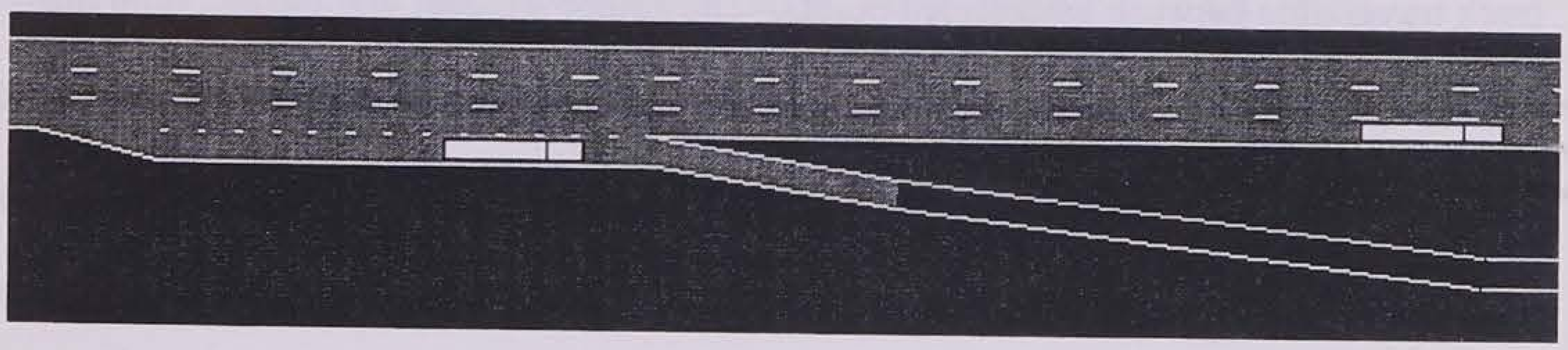


FIGURE 2 CORSIM Output Viewer

After creating a working model, there are two steps that must be taken before any conclusions can be drawn from the model. The first step is model verification.

CALIBRATING THE MODEL

Model Verification

Model verification seeks to ask the question: does this model do what it is supposed to do? Model verification begins with the debugging and troubleshooting phase. To complete the task of model verification, the traffic engineer simply needs to examine the model and see if it is performing the way it was designed. The graphical output module is an excellent tool for this task, because it allows the traffic engineer to observe the model in operation with traffic.

Model Validation

Model validation is a much more daunting task than verification. Where verification asks the question: does it work, validation asks the question: how much confidence do I have in the model and its output? (3) Validation is the process of comparing the model to collected field data and is often thought of as a calibration procedure. For the weigh station simulation field data was collected at an actual weigh station. These data were collected over a one day period and were mainly comprised of truck travel time between established points. The author's model was created with the established points geometrically coded so that no confusion would exist between the field data and the simulation model output. The data links of concern were: off-ramp node (1) to the diverge point (2), diverge point (2) to the weight scales (3), weight scales (3) to the on-ramp point (4), and finally the off-ramp node (1) to the on-ramp (4). Figure 3 shows graphically the links of interest for the model validation.

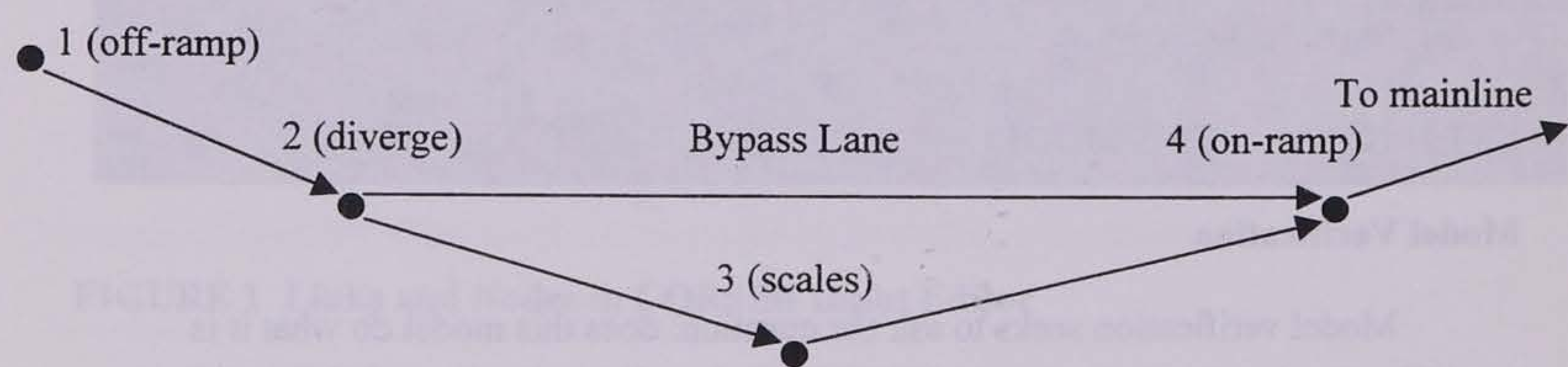


FIGURE 3 Validation Links of Interest

Micro-simulation model validation is an iterative process where model outputs are compared to collected field data. The variation between model output and field data is analyzed and alterations are made in the model code. In the weigh station model, the field data indicated that the time between points 1 and 2 was 28.5 seconds. Model run #1 resulted in a time between points 1 and 2 to be 14.6 seconds. The discrepancy was caused because the off-ramp link attributes had too high of a free-flow speed. The free flow speed was then lowered, which caused the travel time between points 1 and 2 to rise near acceptable levels. The process of changing model attributes to calibrate the model was repeated until acceptable variations were reached. It is worth noting that the model is a dynamic system, therefore once an attribute is altered in one portion of the model, the rest of the model reacts to that change. This is why some knowledge of traffic engineering is required. Model validation can take considerable time and effort, especially if the procedure mentioned above is required for a large network.

Acceptable levels of calibration is fairly subjective to the traffic engineer's experience and knowledge of the calibration data and model purpose. For this case study a more refined method of verifying the confidence was established. Once the model was perceived to be reasonably close to field data values, 10 model simulation runs were completed. A spreadsheet program was used to keep track of the output which consisted of the time , in seconds, between the nodes. Table 2 shows a portion of the spreadsheet used to validate the model.

TABLE 2 Spreadsheet of Validation Process

Validation Time	run 1	run 2	run 3	run 4	run 5	run 6	run 7	run 8	run 9	run 10
1-2 (28.5)	27.3	27.5	27.7	27.4	27.4	27.6	26.9	27.3	27.5	26.8
2-3 (48.8)	51.3	50.7	53.0	50.6	48.0	52.6	48.9	50.1	52.5	48.1
3-4 (55.4)	56.9	56.1	57.8	55.9	54.8	57.3	55.3	56.9	57.4	55.6
1-4 (66.7)	74.6	74.3	75.1	72.8	74.5	74.9	74.3	75.4	74.2	73.4
errors	0.04	0.04	0.03	0.04	0.04	0.03	0.06	0.04	0.04	0.06
from	0.05	0.04	0.08	0.04	0.02	0.07	0.00	0.03	0.07	0.01
standard	0.04	0.01	0.05	0.01	0.01	0.03	0.02	0.01	0.07	0.05
	0.03	0.01	0.04	0.01	0.01	0.03	0.00	0.03	0.03	0.00
	0.06	0.05	0.06	0.06	0.08	0.07	0.05	0.06	0.04	0.04
	0.11	0.10	0.11	0.08	0.10	0.11	0.10	0.12	0.10	0.09
sum of errors	**0.16**	**0.16**	**0.32**	**0.16**	**0.13**	**0.28**	**0.08**	**0.18**	**0.14**	**0.01**

As shown in Table 2, the validation data were summarized and the simulation program ARENA was used to compute confidence levels for the specific links of interest. A calculation was then performed to compare the confidence level to the mean. The results were the percent variation from the mean. Figure 4 shows the percent deviation from the mean time that the model computed for all calibration links.

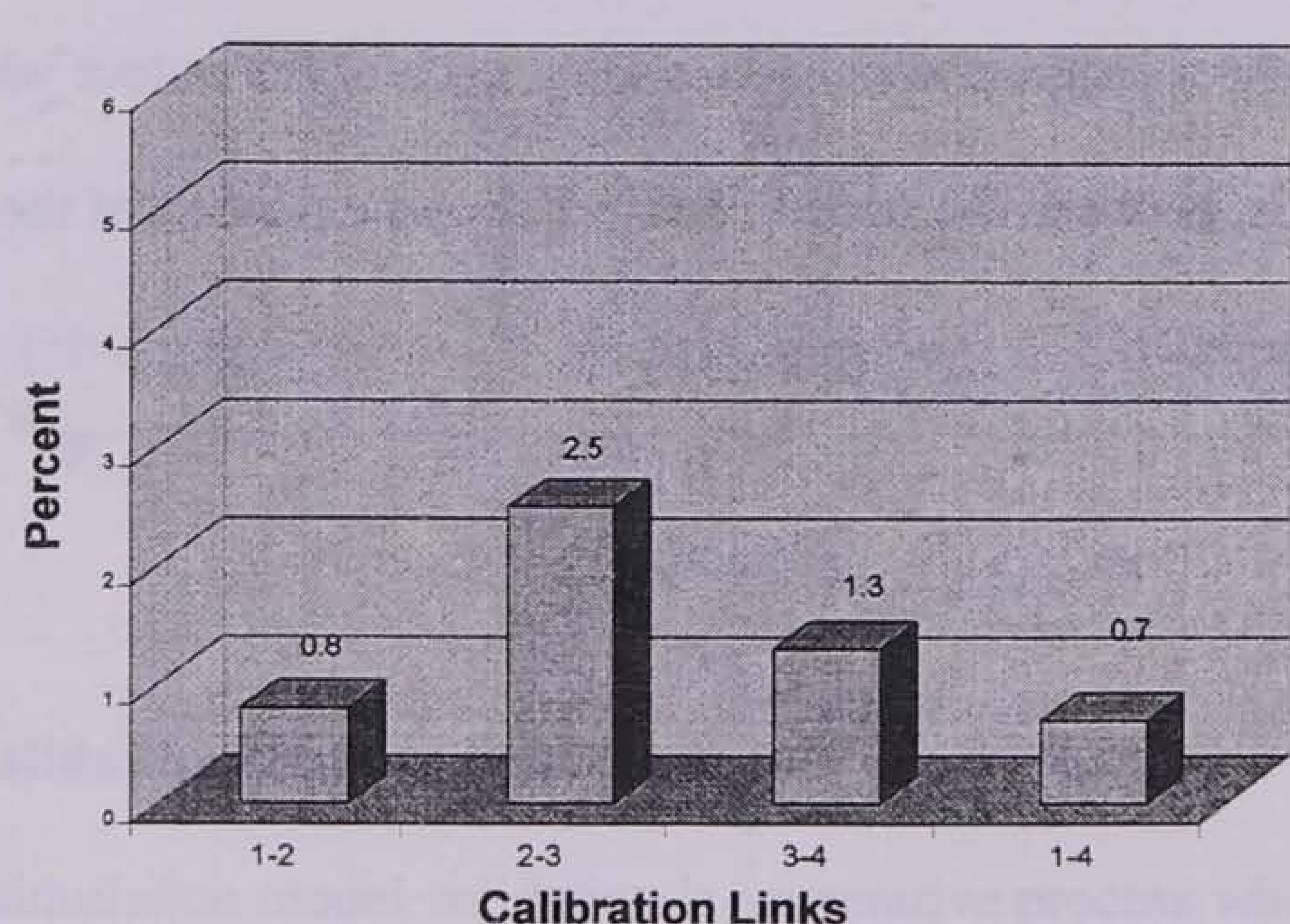


FIGURE 4 Percent Deviation from Mean for Calibration Points

It could be concluded from Figure 4 that the model calibration is complete and satisfactory. This is a valid statement since model has repeatedly produced results that are within 2.5 percent of the mean, at a 95 percent confidence interval. For other applications a wider error percentage may be acceptable. The level of acceptable error is up to the traffic engineer and is completely subjective.

MODEL OUTPUT

Model Results

After the model has been validated, it is ready for use. Probably the most interesting capability of a simulation model is the ability to alter the input parameters and compare various output measures of effectiveness. The main parameters varied were truck volumes and the percentage of trucks turning into the weigh station. The percentage of trucks turning into the weigh station from the mainline varied based upon the queue buildup near the mainline exit ramp. As far as truck volumes, it is anticipated that by the year 2004 the number of truck on U. S. highways will increase by 13.4 percent (4). The current truck volume of 270 vehicles per hour was determined from the field data mentioned previously. A future truck volume of 500 vehicles per hour was assumed for demonstration purposes. Two measures of effectiveness were used to discuss the model results, they were average speed through the model in miles per hour and total delay time through the model in vehicle-hours. As an added parameter, the percentage of trucks turning into the weigh station was varied.

Figure 5 shows the comparison of average speed through the network varied by truck volume and percentage of trucks turning into the weigh station.

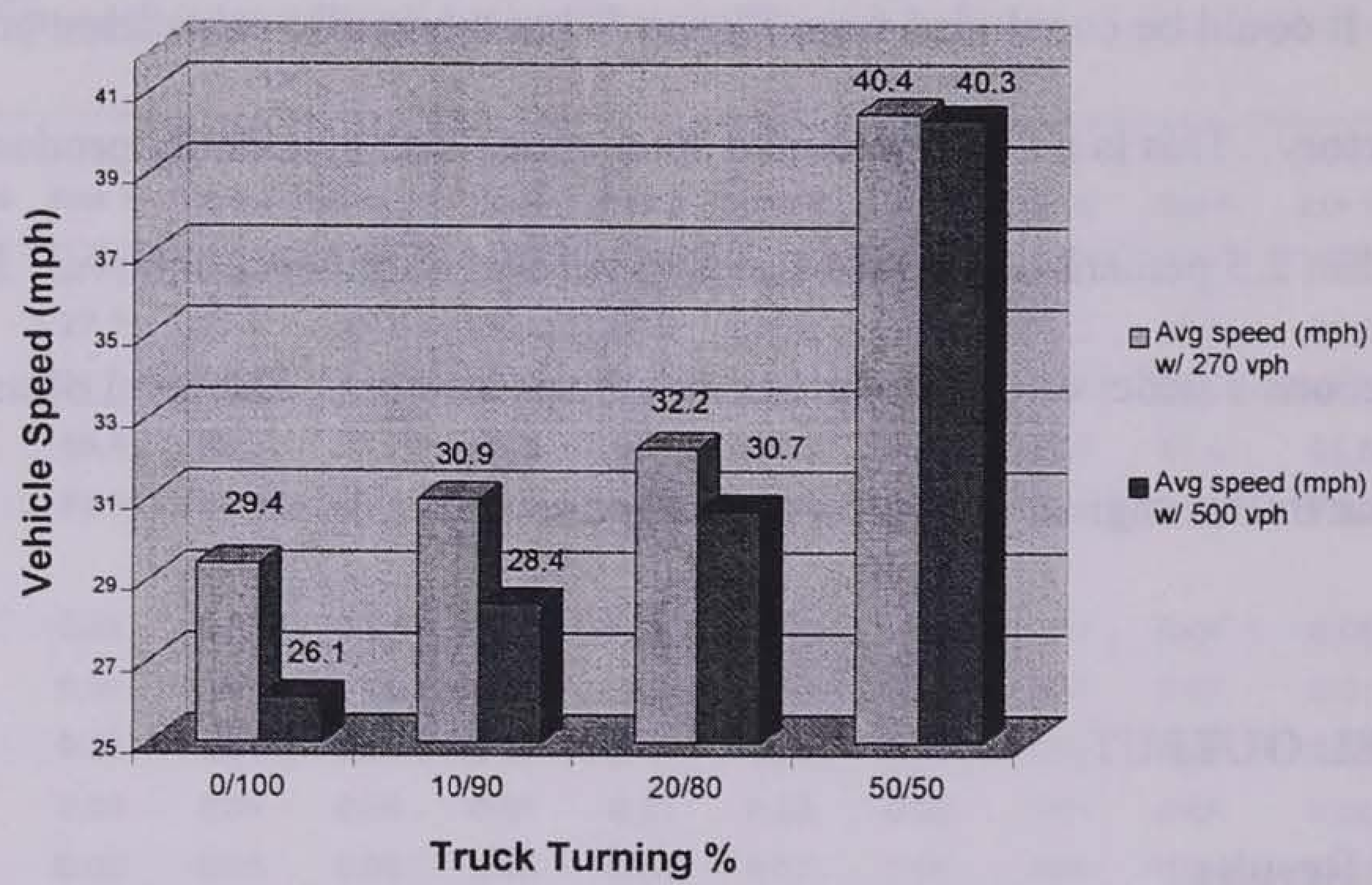


FIGURE 5 Comparison of Average Speed

From Figure 5, it can be concluded that as the percentage of trucks turning into the weigh station decreases, the average vehicle speed through the network, both mainline and weigh station, increases regardless of the increase in truck traffic volumes.

Figure 6 below shows the comparison of delay time through the network varied by truck volume and percentage of trucks turning into the weigh station.

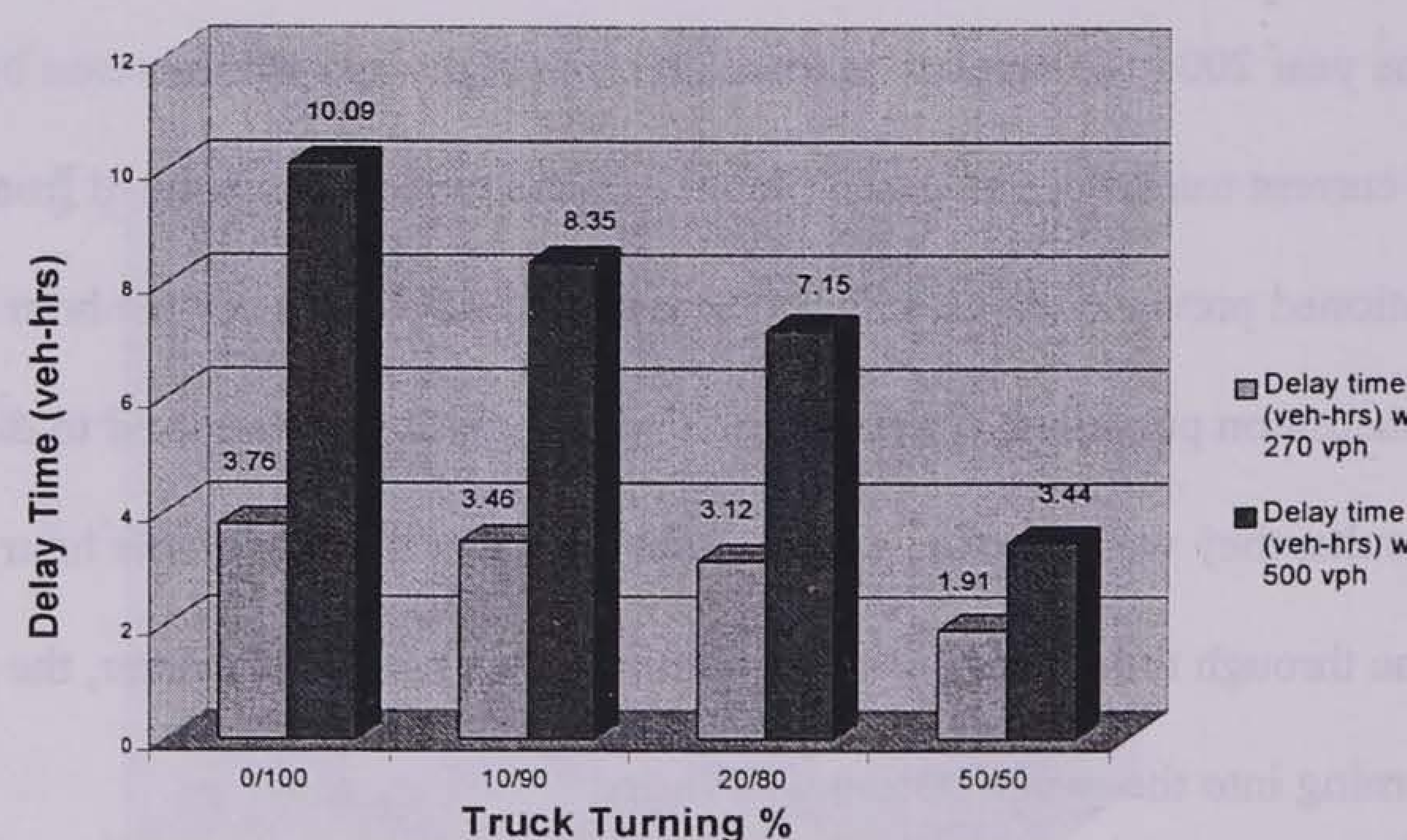


FIGURE 6 Comparison of Delay Time

From Figure 6, it can be concluded that as the percentage of trucks turning into the weigh station decreases, for all volumes, the delay time through the network, both mainline and weigh station, decreases.

Conclusion

The benefits of using a micro-simulation model compared to field testing are clear. Micro-simulation models cost less, obtain quicker results, include several measures of effectiveness, do not disrupt traffic operations, do not require physical changes to the infrastructure, allow the prospective design configurations to be subjected to various traffic demands, and allow numerous variables to be altered or held constant as desired.

There are numerous tasks that need to be completed prior to using the model. They include model coding, model verification and validation, and finally model output generation. The author has presented some output from a weigh station model. Although the output presented does not indicate any profound information, the methodology described does present the concepts needed to generate more advanced output and thus more meaningful conclusions.

REFERENCES

(1) *TSIS User's Guide*, Version 4.01 Beta, November 1996, Kaman Sciences Corporation.

(2) *Highway Capacity Manual*, Third Edition, 1994, Transportation Research Board.

(3) C. Pegden, R. Shannon, R. Sadowski, *Introduction to Simulation Using SIMAN*, McGraw-Hill, Inc, 1995.

(4) *U.S. Freight Transportation Forecast to 2004*, DRI/McGraw-Hill, Inc, Submitted to the American Trucking Association Foundation, Second Annual Report, February, 1996. P. 15.