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# EFFECTIVE SCHEDULING OF ROAD AND BRIDGE CLOSURES: PHASE II

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PURDUE UNIVERSITY

FINAL REPORT

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# EFFECTIVE SCHEDULING OF ROAD AND BRIDGE CLOSURES: PHASE II

by

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**16. Abstract**

This research provides a study on work zone impact analysis. In case of multiple road closures, the network approach is used to find an effective scheduling such that the total user delay is reduced. A dynamic model for analyzing the work zone impact during the period when network is in transition state is also developed. A salient feature of the dynamic model is drivers' perception updating model which incorporates availability and the quality of information as perceived by drivers.

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# Implementation Report

The objectives of this study were to review the procedures used in work zone traffic plans and to develop static and dynamic models for work zone impact analysis. A review of the current practice for work zone traffic control was done, which can help work zone planners in designing an effective traffic control (TCP). An effective TCP should address the work zone problems from drivers' as well contractors' perspectives. This can assure a safe and smooth traffic flow around work zones. Also, an understanding of the effectiveness of various control strategies under a wide range of scenarios can help field engineers in selecting appropriate strategies for a given work zone scenario. The current practice of work zone impact analysis (using such procedures as QUEWZ) assumes a fixed fraction for traffic diversion and ignores the impact on adjacent roads. The case study with the I-70 re-construction project in Indianapolis demonstrated that QUEWZ can give a gross underestimation of the total user delay. Also, the prediction of diverted fraction of traffic was found to be far from trivial; it depends on the network configuration and the existing traffic volume on the network. Therefore, it is suggested that a network approach be used for a realistic work zone impact evaluation. A user friendly software was written for an easy use of the network equilibrium model. The software requires an input file, the format of which is described in detail in the appendix of this report. The input required to create the file includes: O-D matrix and the graph representation of the road network. A step-wise procedure has been provided in the appendix for developing the input file. The computer program has been written in C language and is highly portable which makes it compatible with workstations as well as PC's. The software can be used for the following purposes:

1. **Predicting change in traffic pattern:** First the software provides traffic volume on each link of the affected network in the absence of work zones. Work zone descriptions are entered interactively and then the software again calculates traffic on various links in the

presence of work zones. Thus, the network traffic patterns corresponding to two scenarios can be compared. This will also assist work zone traffic planners in predicting the resulting traffic pattern due to work zones in future (by specifying a suitable growth factor).

2. **Identifying congestion spots:** Any possible congestion spot caused by network disruptions can be identified from the predicted link flows in the presence of work zones. This will help work zone planners in designing effective network level work zone traffic control strategies.

3. **Estimation of network level delay:** The software provides the total travel time in the network corresponding to both situations of with and without work zones. Thus, the total user delay caused by work zones can be estimated by this computer program.

4. **Scheduling work zones:** It was shown in Chapter 4 that the impact due to more than one work zones, in terms of user delay, is not additive. For a given set of work zones the software generates a number of possible combinations of work zones and provides user delay for each combination. This will assist planners in scheduling work zones in a way that will reduce the total user delay.

A dynamic model was developed to predict day-to-day variations in traffic pattern due to work zones. This model is applicable during the period when drivers are looking for alternate routes, in other words, when network is in transition from one equilibrium (before the work zone) to the other (some time after the work zone is initiated). Depending on the network configuration and the locations of work zones, the transition period can be sufficiently long. Therefore, the adverse impact during the transition period may be far more than that associated with the situation when the network reaches a state of equilibrium. This makes it important to study the nature of changes in the traffic pattern from one day to the next. The model for capturing day-to-day dynamics also incorporates the provision of information to travelers. Thus, the model can be used to evaluate the impact of information provision on the network performance. This is particularly desirable in the context of emerging ITS technologies. Based on the dynamic model, a software was also developed. However, the applicability of this software may be restricted by the availability of a dynamic traffic simulator. The study used DYNASMART, which was developed at the University of Texas at Austin under the sponsorship of FHWA.

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# 1. INTRODUCTION

## 1.1 Introduction

In recent years, the emphasis has shifted from the construction of new highway facilities to the maintenance and rehabilitation of existing ones. As a result of this shift, the problem associated with the safe and efficient conduct of traffic in and around work zones has been receiving considerable attention. Also, highway work zones constitute a major source of delay for road users and therefore cost effective strategies are needed to mitigate the adverse impact of work zones. In addition to causing a reduction in the capacity of roads, construction zones pose a serious safety problem. Crash rates on highways with work zones are often much higher than those on highways without work zones. The task of traffic planners, thus, is to ensure an efficient as well as safe traffic flow in and around work zones. A significant effort has been made in recent years to help planners select appropriate traffic control strategies. Much research has been carried out to develop effective traffic control devices and plans. The objectives of the present study were:
(a) review of guidelines for the selection of appropriate work zone traffic control plans,
(b) development of an evaluation tool for predicting the impact of work zones on the road network and,
(c) development of a model for dynamic analysis of traffic due to work zones in the context of ATIS/ATMS.

## 1.2 Organization of the Report

While individual states apply their own specifications for traffic control devices, their procedures are similar to those prescribed in U.S. Department of Transportation's Manual on Uniform Traffic Control Devices (MUTCD). However, not every possible circumstance can be handled with MUTCD. Moreover, it has been found that procedures described in the MUTCD may not always be the best choice [Noel et al. 1988, Benekohal 1992]. Therefore, researchers have suggested various innovative traffic control plans for work zones. These are summarized in Chapter 2. A set of general guidelines is also provided in Chapter 2 for selecting appropriate traffic control strategies. Also, various existing work zone traffic flow models have been reviewed, which can help planners understand the complex traffic behavior in work zones.

The scope of current practices for work zone planning is restricted to those roads where work zones are located. In other words, the impact of work zones on adjacent roads are generally ignored. The applicability of a network equilibrium model to predict the change in traffic pattern over the network as well as to evaluate the impact of work zones on the entire affected network has been demonstrated through a case study in Chapter 3. The case study was made for I-70 reconstruction near Indianapolis Airport. The purpose of using a network model was to (a) predict the change in traffic pattern on the network because of work zones, which would help work zone planners determining traffic control strategies on other roads; (b) estimate out the overall adverse impact of work zone on the affected road network; and (c) if more than one project are to be completed in a construction season then, suggest an effective scheduling such that the impact on the network during the construction period can be minimized.

The analysis approach suggested in Chapter 3 is applicable only after the network reaches an equilibrium state. However, it should be noted that after the beginning of a work zone, the network would take some time to stabilize. In other words, the network will be in a transient state for some time after the work zone starts. A dynamic model is developed in Chapter 4 to model the variation in the traffic pattern from one day to the next. The model explicitly accounts for the information availability to drivers, which makes it a helpful tool to evaluate various information strategies. This is particularly useful in the context of emerging ITS technologies. An empirical study of the model is also provided. Finally, a summary and conclusions of this study are provided in Chapter 5. A users' manual is provided in Appendix A of the report to assist INDOT personnel in using the work zone impact evaluation software. The manual describes a step-wise use of the software. It also explains the required data and input format for the software. A sample run of the software is also provided which describes various components of the software from users' point of view. One of the key inputs to the software for evaluating work zone impact is OD matrices. A step wise procedure is provided in Appendix B for preparing OD tables in a format which is compatible with requirements of the software.

# 2. REVIEW OF CURRENT PRACTICES

## 2.1 Introduction

The purpose of this chapter is to summarize the findings of past studies on work zone traffic control. This information can help traffic planners in selecting effective traffic control strategies. Most of the terminologies that are used in this report are self explanatory. However, an excellent introduction to the concept, definition and standard terminologies in work zones is presented by Lewis (1989).

Selecting an appropriate traffic control strategy is a trade-off between drivers' needs and work requirements. Ideally, a driver would never like to have lane(s) closed; whereas closing lane(s), would almost always make it convenient for workers as well as contractors. Therefore, an attempt is made in this chapter to study the work zone problem from drivers' as well from work perspective.

## 2.2 Work Zone Problem from the Perspective of Contractor and Agency

Various measures which are taken in the work zone to ensure smooth (and safe) progress of work are discussed in this section. Emphasis in this section is not on how to minimize the project duration or to expedite the work but on how to provide a safe and adequate environment for carrying out work. For example, approach for finding out an optimal work zone configuration is not a part of the discussion here. Issues like selecting appropriate speed control devices, appropriate management techniques are described. Several control devices are used in work zones for different purposes but speed controlling devices and techniques are the only one that is studied in detail in this report. This is because of two reasons. First, speeding is a very common phenomenon in the work zone and secondly, speeding contributes to a larger number of crashes than any other single factor. Therefore, an extensive literature review was done in order to understand the violation of speed control signs and devices in the work zone. Effectiveness of speed control devices and techniques is reviewed in Section 2.2.1. Work zone crashes are studied in Section 2.1.2. Some innovative methods for handling traffic around work zones are discussed in Section 2.1.3. Subsections are concluded with recommendations and suggestions which may serve as general guidelines for selecting appropriate traffic control strategies. The recommendations are based on the literature cited in this report.

### 2.2.1 Speed Control in the Construction Zone

Speed control in and around the work zone has been a matter of concern for several years [Graham et al. 1977, Humphreys et al. 1979]. Studies have indicated [Nemeth and Migletz 1978, Richards and Faulkner 1981, Humphreys 1979, Nemeth and Rouphail 1983] that excessive speed contributes to more work zone crashes than other violations. Highway agencies have developed several techniques for enforcing speed limit through construction zones. Some of the innovative techniques that have been evaluated for their effectiveness are summarized in this section. However, [Richards et al. 1985] overall and relative effectiveness of many of these techniques have not been well established.

A study on evaluating speed reduction effect of using a Changeable Message Sign (CMS) in advance of the work zone and/or inside the work activity area indicated that the message on the CMS affected the speed of cars at a location close to the device. The impact on the trucks took place further from CMS. The result suggests the necessity of a study to determine the optimal location for CMS. CMS located near the advance signing of the work zone [Richards et al. 1985] were found to have little or no effect on speed. However, CMS was more effective in causing a speed

reduction when it was located closer to the actual work area. Also, Richards et al. found that CMS are effective in slowing drivers at the urban freeways. A number of other studies [Hanscom 1982, Richards and Dudek 1986] have indicated that CMS is usually effective in reducing speed.
A large percentage of the crashes resulting in injury or death of highway workers were found to involve drunken drivers and nearly all of them involved over-speeding within the work zone [Levine and Kabat 1984]. The study revealed that active presence of law enforcement officers in urban highway work zones can minimize motorists' erratic behavior. Stationary police officers were found more effective in increasing the level of compliance compared to patrolling officers. Several other studies [Richards et al. 1985] support the observation that the law enforcement has substantial effect on the level of compliance.

Speed reduction effect of radar activated audible message has recently been evaluated [Benekohal 1992]. Audible message was provided to the speeding motorists. The system was found to have some speed reduction effect but further empirical evidence is needed to substantiate the findings.

A common problem associated with the speeding these days is that drivers carry radar detector and they reduce their speed only when they get signal from the detector. To overcome this difficulty, drone radar, which is a passive radar, has been tested for its speed reduction effect on such fast moving vehicles [Benekohal 1992]. The drone radar, however, loses its effect, once it is known to the driver that it is drone and not real. Therefore, it is suggested that drone radar should be used at a place where chances of being caught by an officer is maximum. Flagging procedures are described in Manual on Uniform Traffic Control Devices [MUTCD 1984]. Researchers have also proposed and evaluated [Noelet al. 1988, Benekohal et al. 1992] other flagging procedures. A flagger with one hand pointing to a nearby speed limit and other motioning motorists to slow down was used in conjunction with MUTCD procedures [Noel et al. 1988]. The procedure was found more effective in reducing the speed. Also speed reduction effect of trained flaggers was compared to that of contractors' flagger [Benekohal 1992]. It was found that trained flaggers were more effective than usual contractor's flaggers, albeit with a higher cost.

#### 2.2.1.1 Recommendations for Implementation of Speed Control :

Due to the misuse (and sometimes abuse) of work zone speed control measures, drivers have little respect left for the work zone speed control devices. So, as far as possible, attempt should be made to use these measures strictly on the basis of requirement. However, for the work zone speed control measures to be effective, following two considerations should be taken into account (a) Effectiveness of the device under given scenario and (b) Proper implementation of the techniques. The purpose of writing this section is to provide a general guideline for the selection of speed control technique.

Law enforcement is the most effective method for large speed reduction for any kind of work zone. The method is highly recommended during night time. The law enforcement method has demonstrated such a strong speed reduction capability that special contractual provisions for implementation of law enforcement treatment into the traffic control plans is recommended. The implementability of law enforcement is totally dependent in institutional constraint. The other method to achieve large speed reduction is through flagging. However, flagging is particularly effective in reducing speed in the work area of two lane, two way highway and urban arterial. They are not equally effective at urban freeway sites. Two factors need to be considered regarding the implementability of flagging (a) Drivers should not have problem seeing the flaggers and (b) Flagger safety. The later factor may preclude the use of flagger for some work zone sites. For a short duration project where portability of device is a concern, CMS is a useful speed control device. They are effective (and easily implementable) in inclement weather too. CMS should not be used in isolation. Rather, it should be treated as a supplement to other conventional speed control devices. CMS is suitable for all kind of work zones but its effectiveness may decrease if it is used for a long time with the same message. For a long duration project, where safety had not been a big problem, lane width reduction may prove to be a good speed control technique. However, it should not be desirable for multilane highways. Capacity reduction and increase of crash potential are the two factors which should be thoroughly reviewed before using lane width reduction technique.

The study on speed reduction techniques is summarized in Table 2.1. The ranks in the table indicate the overall relative effectiveness in reducing speed within work zone area and are based on studies cited in this report.

### 2.2.2 Work Zone Crashes

Many studies [Nemeth and Miglitz 1978, Wang and Abrams 1981, Hargroves and Martin, 1980, Hall and Lorentz, 1989] in the past have shown that number of crashes during the construction period is more than that before the construction. National statistics [Engineering News Record 1987] also confirm this finding. The difference is even higher for urban work zone where congestion is more. These statistics show the need for a careful study towards the development and implementation of effective safety measures in work zones. This section is presented to review the characteristics as well as reasons for the higher number of crashes in work zones. Most studies in this area indicate that site specific factors such as traffic, geometry etc. play an important role in contributing to the crashes in work zones. Speeding, which has been a major reason for work zone crashes has been discussed in Section 2.2.1.

Crashes in entrance ramp areas on two long-term freeway reconstruction projects were compared [Casteel and Ullman 1992] with non entrance ramp areas to study the impact of entrance ramp on the number of crashes in long-term construction zones. Although the increase in the frequency of crashes in the entrance ramp area was

| Techniques | Uses | Rank | Comments |
|---|---|---|---|
| Flagger | For all kinds of lane closures; effective for multilane highways | 1 | Effective when used with hand signals;<br>flaggers' safety is a concern |
| CMS | Short duration projects | 4 | Can be used in inclement weather: versatile equipment; performance may depend on its location. |
| Law Enforcement | All kinds of work zones | 1 | Very costly; availability is an issue<br>long lasting impact |
| Lane Width Reduction | For long term projects where capacity is not a big problem | 3 | May disrupt traffic flow; may increase accidents |
| Rumble Stripes | All kinds of work zones | 5 | Effective in alerting drivers |

Table 2.1 Summary of the Performance of Various Speed Control Techniques

found more than that in non ramp area, the difference was not significant for the case where crashes before the construction was very less. Thus, the study suggests that entrance ramps having higher crashes rates before the construction are more prone to adverse effect during construction. Kentucky Transportation Research Program identified crashes [Agent and Pigman 1987] in which road construction was listed as a contributing factor. The crash data before construction was compared [Pigman and Agent 1990] with those during construction. Findings of this study were based on a large empirical data set from the field (for a period of three years). Factors contributing to work zone crashes were identified. Severity and the number of crashes with respect to the locations in the work zone were also studied. Advance warning sign and work activity area corresponded to most severe and maximum number of crashes respectively. Side swipes and rear end collisions were found to be the most frequently occurring crash types. The findings were in agreement with most of the other studies. Reliability and accuracy of crash records were investigated by Hall and Lorent(1989). They studied construction zone crashes in New Mexico for a period of three years and found that frequency of crashes in construction zones was substantially greater than that indicated by crash record system. Effectiveness of traffic control devices with respect to crash reduction capability has not been studied in detail. A regression model was developed [Garber and Wo 1991] relating work zone crash rate with crash rate prior to the construction period and types of control devices. The most effective combination (of traffic control devices) for work zones on multi- lane highways was found to be cones,flashing arrows and flagman. Federal Highway Administration (FHWA) issued a rule that required the use of concrete barriers at transition zones where four-lane (divided) operations change to two lane and vice versa. This was probably done because of the high expectancy of head-on collisions under this type of work zone configuration. However, a study, whose primary objective was to verify the need for concrete barriers [Pang and Yu 1982], suggested that barrier requirement is not justifiable for low volume roads.

### 2.2.2.1 Recommendations for safety measures

The number of crashes was found to increase at work zones but the increase was uniform over crash characteristics. This makes it difficult to recommend safety measures for those crash types which increase unproportionally at work zones. Nevertheless, some opportunities still exist for remedial actions, which are listed here:

- Proper application of traffic control devices and enhancement in the visibility of work zones may be helpful in reducing the number of rear end collisions at work zones.

- Some effort is needed to enhance the awareness of transportation agencies as well as contractors regarding the importance of regular inspection and proper use of traffic control devices which include installation and maintenance and record keeping. Crashes due to the lack of maintenance of traffic control signs and devices are common at work zones.

- Crashes during the night are more severe. It is mainly because of the low volume which leads to a higher operating speed. Proper lighting of the work zone traffic control devices may be helpful in reducing the number of crashes during the night.

- Extra traffic control measures should be taken for entrance ramps at long term work zones on high volume roads.

- Since most of the severe crashes were found to have taken place in the advance warning area, early merges should be encouraged. Early merge also has a favorable impact on traffic behavior. This is discussed in Section 2.4 of this report.

### 2.2.3 Traffic Management

Maintenance and rehabilitation activities of existing highway networks have been increasing at such a high rate that the traditional techniques of work zone traffic control may not be sufficient to maintain an acceptable level of service around work zones. Researchers are now looking for some innovative traffic control strategies which would better utilize the available network capacity. Several studies have been conducted (Richards and Dudek 1981, Dudek and Richards 1982) on capacity improvement for work zone operations. Some of the capacity improvement techniques that can be implemented are: temporary use of the shoulder lane, closing entrance ramp within the work zone, providing information through the Highway Advisory Radio (HAR), etc. These techniques have already been used successfully in Chicago, Houston, Indianapolis and many other places in the United States. However, they have been used on a limited basis and hence more empirical evidence is needed to evaluate their role improving system performance. Some of the innovative control measures that have been used in the field or that have been proposed are summarized in this section. In order to enhance the rate of maintenance activity, a specially trained crew was formed (Levine 1989) and was specifically designed the task of handling traffic techniques, consistent with MUTCD. This led to an increase in the number of hours available for maintenance activity. The increase could be gained because of the ability to change the traffic control plan as the traffic condition changed. Thus traffic management was done in close to real time. Also, real time traffic management is a key factor in re-establishing drivers' faith in work zone traffic control devices. This is discussed in the next section. In another research, Denny and Levine (1979) developed tolls for scheduling crews employing innovative traffic management strategies. A study has been conducted (Faulkner and Richards 1982) to evaluate the effectiveness of HAR. About half of the drivers surveyed in this study indicated that they noticed the HAR advance sign and it was concluded that HAR was successful. It should be noted that the HAR is invariably used in conjunction with a number of other devices and therefore, it is difficult to study the effectiveness of the HAR in isolation. Artificial Intelligence techniques have also been used in work zone traffic control. A prototype expert system, TRANZ, was developed [Faghri and Demetsky 1990] for selecting appropriate traffic control strategies and management techniques at work zones. Initially, we also thought that the expert system might be a good tool for developing effective traffic control plans at work zones. But based on the interview of experts and the literature review, we concluded that the expert system may not be the appropriate tool for addressing this problem. We reached this conclusion primarily because selection of appropriate traffic control strategies was found to be very much site specific. This was also realized by the developers of TRANZ. During the validation of TRANZ [Demetsky 1992], it was concluded that "it is difficult to develop a system that will accurately handle all the possible permutations of a problem". Thus, site specific nature of the problem makes the number of such permutations so large that it seems difficult to develop a general knowledge-base for solving this problem. We do not completely rule out the possibility of such an expert system. Rather, we believe that any such attempt may require a long time and may have to go through a cycle of validation and correction before it can be used in the field.

#### 2.2.3.1 Recommendations for Traffic Management

Several observations can be made related to efficient traffic managment at work zones. These are summarized in Table 2.2 and discussed below.

- Number of hours available for maintenance activity can be increased, even for high volume roads, with the use of innovative traffic management strategies.
- An attempt should be made to use the available network capacity to the fullest extent. Some of the techniques that can be used for this purpose are : diversion,

controlling traffic at entrance ramps to the work zone, providing information to the user regarding alternate routes, use of the shoulder lane and so on.

- Stage construction should be investigated. A common practice in work zone traffic control is to close a longer section of the road while maintenance work is performed in a small part of it. In order to establish drivers' faith in work zone traffic control devices, this should be avoided as far as possible.
- HAR is particularly recommended for work zones where delay is excessive and reasonable alternate routes exist. Travelers should be informed about the availability of HAR well in advance of the work zone.

## 2.3 Work Zone Problem from Drivers' Perspective

The focus of this section is on studying drivers' needs in terms of work zone information. Drivers' requirement of minimizing delay is not considered. The issues like what kind of information is effective and how the information should be provided to the drivers in order to help them negotiate through work zone with less discomfort are discussed. Here, work zone information implies the signage and control devices and hence should not be viewed in the context of Advance Traveler Information System (ATIS). A number of driver surveys were carried out in the past to capture drivers' opinion about work zone traffic controls. Important features of these surveys have also been described in this section. Wherever possible, an attempt is made to draw implications from drivers' responses. Finally, some recommendations are made. These recommendations may help planners in developing a Traffic Control Plan (TCP) which would properly address drivers' problems in work zones.

### 2.3.1 Drivers' Need, Understanding and Behavior

From the drivers' point of view, a work zone is simply a hazard on their way to the destination. The relatively high rate of crash rates associated with work zones implies

| Traffic Management Strategy | Advantages | Disadvantages/Problems |
|---|---|---|
| Use of shoulder lane | More capacity | No place for emergency stopping: may not be available |
| Closing entrance ramps in work zones | Lesser demand | Reasonable alternate route may not exist |
| Special management crew | Real time traffic management; more work hours available | High cost; may be feasible for high congestion areas |
| Stage construction | More capacity; enhances drivers' respect for traffic control in work zones | May delay the project |

Table 2.2 Examples of Innovative Traffic Management Strategies in Work Zones

drivers' difficulty in negotiating through work zones. Problems encountered by drivers may not have been properly addressed in the MUTCD. A model for determining drivers' information need and presentation of that information was suggested by Pain and Knapp (1979). According to them, the decision sight distance plays an important role in determining drivers' needs. In order to provide sufficient time to driver to maneuver, the model suggested that placement of various control devices should be decided on the basis of decision sight distance. Decision sight distance was defined as "the distance at which a driver can detect a signal in an environment of visual noise or cluster, recognize it, select appropriate speed or path and perform the required action safely and efficiently" (Hilgard 1953). An assessment from human factor point of view is needed to understand drivers' concerns and needs in work zones. A number of drivers' surveys have been carried out (Ogden 1990, Benekohal 1993) for this purpose. A comprehensive study on drivers' understanding of work zone is so vast (because the restricted version of this problem, e.g., "how the drivers behave when they see a regulatory sign." These individual surveys are reviewed here and some conclusions drawn based on drivers' opinions.

### 2.3.2. Drivers' Opinions About Work Zones

A survey was conducted (Ogden 1990) to investigate motorists' comprehension of construction signing, and it showed that not all aspects of signing are fully understood by the drivers. "Low Shoulder" was the most poorly understood sign. "No Center Lane" was another confusing sign; they found that drivers understood the meaning of this sign but failed to act accordingly, i.e., difficulty making decisions regarding lane change. Another survey (Benekohal 1993) indicated that messages given by flaggers are some of the most correctly understood messages and are usually followed by most drivers. The study further confirmed drivers' non-compliance for lane change. An interesting observation of this study was that an appreciable percentage of drivers did not find work zone driving more hazardous than no-work-zone driving. This may be partly because of recent improvement made in work zone traffic flow and partly because drivers have now started appreciating the need for the reconstruction and hence are ready to tolerate inconvenience. In an earlier survey carried out by Nemeth and Rouphail (1983), the lane changing behavior at work zones was studied. Majority of the drivers in that survey indicated that they changed lane at the earliest possible time. However, the results of the recent survey by Benekohal (1993) contradicted the earlier findings.

#### 2.3.2.1 Recommendations and Suggestions for Addressing Drivers' Needs in Work Zones

This section is written to help work zone traffic planners in understanding the work zone problem from drivers' perspective. This is an important factor in enhancing the effectiveness of a Traffic Control Plan (TCP) , because the effectiveness of a TCP eventually depends on drivers' performance in the work zone. From the TCP point of view, there are three aspects of driver related problems (a) their need, (b) their understanding of signs and devices and (c) their compliance. Some of the more important needs of drivers in work zones are : adequate and advance information, use of control measures which are consistent with drivers' expectations and credible work zone information. Previous research indicated that the second aspect of the problem (understanding) is more crucial and needs more careful investigation. Often, drivers' misunderstanding of the construction signs leads to their non-compliance. It was observed by several researchers that those signs which are understood more correctly receive higher degree of compliance from drivers. Another cause of non-compliance is the non-reliability of the traffic control devices in the work zone. After seeing the construction signs, if a driver complies with that but does not find any work zone activity, then either he looses his respect for the signs or he is confused. Both the cases lead to his/her non compliance. Therefore, an attempt should be made to design understandable as well as reliable traffic control measures. Ideally, reliability implies that traffic control signs should reflect the current status of maintenance activity in the work zone. This can be achieved by developing a condition responsive TCP.

Recommendations for addressing drivers' needs:

Workers should wear bright clothing, particularly if they are adjacent to the open lane, to be clearly visible to the drivers. Flaggers should use their hand in conjunction with the flag to provide more understandable signal to the drivers. National MUTCD suggests flagging motion alone for alerting traffic but it has been found that it is not clearly understood by all the drivers. In addition, a reasonably high speed limit should be allowed, whenever the situation permits it. This will enhance the credibility of the work zone signs and devices.

## 2.4 Work Zone Traffic Flow Models

The complexity of the traffic flow in and around work zones has attracted the attention of many researchers. As mentioned earlier, the possible number of work zone scenarios is so large that it is almost impossible to develop one comprehensive model to accommodate all kinds of work zones. Therefore, researchers have proposed models for individual circumstances. In this section, the features and limitations of these models are also summarized. This will help in comparing the traffic behavior under different work zone scenarios. The section is concluded with suggestions for improvements that can be made in these models.

Considering the number of signs and control devices and the complex decision making process of drivers, it is easy to foresee that the development of an analytical model for the work zone traffic flow is difficult. Researchers, therefore, have used computer simulation technique for this purpose. Most of the available simulation models are concerned with lane closures. A model, based on rational description of drivers in a freeway lane closure situation, was developed [Nemeth and Rathi 1983] to simulate traffic flow at freeway lane closures. Some of the important output from this model are : (a) measures of performance in terms of travel time, delay and speed gradient and (b) lane changing in terms of frequency distribution, statistics of lane change initiation points and gap acceptance. Further work on this model suggests [Rathi and Nemeth 1986] that compliance with the reduced speed limit should not increase the disturbances created in the traffic by the lane closure. The result, thus, was counter-intuitive. The problem associated with freeway lane closures was found to increase [Nemeth and Rathi 1983] as the approach volume to the open lane reached the capacity. Based on this result, it can be suggested that strategies to encourage early lane changes should be incorporated in the TCP. Also, early merges would reduce the number of crashes in the advance warning area, which are more severe (see the section on Work Zone Crashes). Traditional techniques used for lane changes brought about by lane closures were found to be insufficient. Therefore, further study was recommended to find effective methods to encourage early merges. Drivers' lane changing behavior was also studied [Stock and Park 1978] through a stimulus response model. The model assumed that each sign or pavement marking or the view of the work zone itself induces a certain proportion of drivers to change lanes. Following were the two important findings of the stimulus response model : (a) signing had more impact on left-side drop than for the right-side drop; and (b) pavement marking did not have significant impact with comparison to signs. Though observed and modeled lane changing behaviors were shown to match well, more empirical evidence is needed to justify the assumption behind stimulus response lane changing model.

All the traffic control strategies described so far, including those in MUTCD. are empirical guidelines. They were not evaluated in terms of system optimality. The development of a model to optimize the performance of the work zone traffic control is difficult, mainly because of the stochastic nature of traffic flow in the work zone. Furthermore, uncertainty in drivers' behavior and a large number of possible control strategies make the problem very challenging. This problem was addressed by Mausa et al. [Mausa et al. 1990]. They used an existing algorithm [Azadivar and Talavage 1980] to develop an optimization model and integrated the optimization model with a simulation model to evaluate the effectiveness of work zone traffic control strategies in the context of system optimality. Though the applicability of the model was established only in finding an optimal merging strategy, it is reasonable to expect that the model can be extended to include other configurations. It is, however, felt that the optimal traffic operation aspect of the work zone problem has not been addressed well and there is a scope for further study in this area. The study conducted by Mausa et al. (1990) provided a good insight to this aspect and may be useful for future work.

The features of various work zone related traffic flow/control models which were discussed in this section are also summarized in Table 2.3.

## 2.5 Chapter Conclusions

This chapter provided a review of current practices for selecting appropriate traffic control strategies in and around work zones. The work zone traffic problem was looked at both from drivers' point of view as well as from agencies' point of view. Drivers' responses to various work zone traffic control strategies were examined and broad guidelines were given for selecting appropriate control devices in work zones from drivers' point of view. Various factors involved in work zone crashes were studied and possible elements of a work zone planning that can reduce the number of crashes were reviewed. Finally, the state-of-the-art in work zone traffic flow modeling was examined and recommendations were provided for their use and possible improvements.

| Model | Feature/Description | Drawbacks |
|---|---|---|
| QUEWZ | Queue and user cost evaluation of work zones; evaluation of road user cost is based on AASHTO manual; easy to use software is available. | Applicable to freeway work zones only; delay is used to estimate diversion; queue length estimation is based on traditional input-output |
| FREESIM | Microscopic, stochastic simulation model; car-following approach is used; can be used for optimization application, e.g. optimal lane-closure length; easy to use software is available. | FREESIM is primarily a software to evaluate traffic performance and it does not provide any estmatation of road user cost; |
| TRANZ | An expert system for selecting appropriate traffic control strategies in work zones | Does not estimate diversion; not in implementation stage still undergoing through a validation process. |
| MicroBenCost | A general purpose software to estimate user cost; can provide cost in terms of present worth; user friendly software is available. | Traffic in and around work zones is not modelled explicitly. |

Table 2.3 Work Zone Traffic Impact Models

# 3. NETWORK ANALYSIS

## 3.1 Introduction

Current practice of impact evaluation of work zone generally assumes the impact to be limited to roads where work zones are located and hence ignores the impact on adjacent roads. In case of substantial change in traffic pattern due to traffic restrictions imposed by work zones, this assumption may give an underestimate of the overall impact. Therefore, a tool is needed to evaluate the impact of work zones on the entire affected network and not only on roads where work zones are located.

Most of the previous studies on work zones [Dudek and Richards 1986, Wonderlick and Dudek 1985] dealt with operational considerations and safety aspects of various traffic control strategies. Traffic flow problems in and around a work zone was also addressed in the past. Traffic flow models were developed to estimate user delay due to work zones [Rouphail and Tiwari 1982, Rathi and Nemeth 1986]. Most of these models do not incorporate any network approach to capture the change in traffic pattern because of the work zones. A computer model, Queue and User Cost Evaluation of Work Zones (QUEWZ), was developed [Memmott and Dudek 1984] to estimate the additional road user cost resulting from lane closures in one or both direction. This model, based on anticipated delay, assumes a certain percentage of traffic to divert from the roads with work zones. A simple empirical model was also developed on the basis of field data for predicting the percentage of traffic that would divert from an affected road section [Boruff 1993]. Corresponding to a range of values of volume-to- capacity ratio (V/C) on affected roads and length of alternate routes, the model predicts the percentage of vehicles which are likely to divert from affected roads. However, the estimation of percentage of diverted traffic is far from trivial. It depends on network structure as well as existing traffic pattern. Consequently, the amount of diverted traffic, predicted by empirical relations, may not be even close to the actual diverted traffic.

Recently, with the advent of Intelligent Transportation Systems (ITS) there has been a growing interest in dynamic analysis of network. Much research has been been performed [Mahmassani and Jayakrishnan 1988 Jha et al. 1995] to understand drivers behavior during the the construction period when network is in disequilibrium. These studies focus more on time varying nature of traffic pattern and attempt to reduce the impact of work zones during the transition period. It should be noted that this paper focus more on a long term impact and is not concerned with the time period when traffic pattern on the network is changing from one to the next. These are the issues addressed in literatures on *day-to-day* dynamics, dynamic network modeling and related areas. Furthermore, we do not attempt to validate the static equilibrium approach in the context of work zones. The validity of using static network equilibrium approach for predicting the change in traffic pattern due to long term construction zones has been demonstrated [Janson et al. 1986] before.

The case study presented in this report involves an urban highway network in which a stretch of Interstate was to be partially or fully closed for reconstruction. Several reasonable alternate routes exist around the Interstate. Therefore, diversion of Interstate traffic was possible. A complete closure of the Interstate would expedite the reconstruction work but could cause an unacceptable amount of delay on other roads. This report describes the result of applying a network equilibrium approach to evaluate the total delay in the network. Total delay is defined as the difference between total travel time experienced by all road users in the network, before and during the reconstruction. This is expressed in minutes during one peak hour. The primary objectives of this study were to (a) demonstrate that a network approach is needed for realistic evaluation of road user cost due to work zones and (b) to indicate how several work zones on a network can be effectively scheduled by reducing adverse impacts on users.

## 3.2 Network Model and Assignment Algorithm

Networks are typically characterized by a set of nodes and a set of links connecting these nodes. Each link is associated with some cost which affects flow on that link. The road network in an urban area includes various components. e.g. Interstate roads, state roads, city streets, and intersections. These components can be represented in the form of directed links and nodes. The cost of traveling on a road consists of several components like travel time, vehicle operating cost, inconvenience etc. However, travel time constitutes a major part of the link cost and is often used as the sole measure of link cost. Several functions have been proposed in the past to relate link cost to link flow [BPR 1964, Davidson 1966]. These functions are commonly known as Link Performance Functions. Finally, an assumption is made regarding the rule by which travelers choose a route which governs the mathematical formulation of the assignment problem.

Following Janson et al. (1986), the User Equilibrium (UE) approach is used for network assignment. Under the UE condition, no traveler can reduce his or her travel time by unilaterally switching path. In other words, travelers select paths to minimize their travel times and the resulting flow pattern is such that all the used paths between an O-D pair have equal cost. The problem of finding the UE flow pattern can be formulated as a mathematical program [Beckman 1956]. Several algorithms exist for solving this mathematical program. In the present research, the UE flow pattern was calculated using the convex combination algorithm. A comprehensive treatment of the mathematical formulation of UE and the application of the convex combination algorithm to solve the UE problem can be found in Sheffi (1985). The link performance function developed by the U.S. Bureau of Public Roads (BPR) is used for the relationship between link flow and link cost. The BPR link performance function [BPR 1964] is given by:

$$t_a = t_a^0[1 + \alpha(x_a/c_a)^\beta] \qquad [3.1]$$

Where $t_a$ is the travel time on the link, corresponding to a link flow of $x_a$. $t_a^0$ and $c_a$ are the free flow travel time and the capacity of the link respectively. $\alpha$ and $\beta$ are the parameters of the function which capture the congestion effect.

Based on the convex combination algorithm and BPR link performance function, a software was developed to find the UE flow pattern on a network. The values of $\alpha$ and $\beta$ in this study are 0.15 and 4.0 respectively. In addition to calculating equilibrium flows, the software can be used interactively to evaluate the impact of lane closures in terms of delay on the network. The software was also used to demonstrate the importance of a network approach in effective scheduling of work zones.

## 3.3 I-70 Reconstruction Project and Traffic Counts

The south-west part of the Indianapolis area road network, near Indianapolis airport, consists of two Interstate roads, I-70 and I- 465, and several state highways and city streets (Figure 3.1). The reconstruction of I-70 is currently being carried out from Lynhurst Drive to Tibbs Avenue. In an attempt to understand the degree of inconvenience and the cost to the travelers who would use I-70 between I-465 and Tibbs Avenue, Indiana Department of Transportation (INDOT) conducted an extensive field study [INDOT 1994]. Link counts were taken on most of the road sections in the network. Judgments of INDOT personnel were used for the missing link counts. O-D matrix for this study was prepared on the basis of *a priori* O-D and the link counts. Again, *a priori* O-D was selected on the basis of the experience of INDOT personnel. It should be noted that a small error in O-D estimation would in no way restrict the scope of this approach. However, for an accurate impact analysis

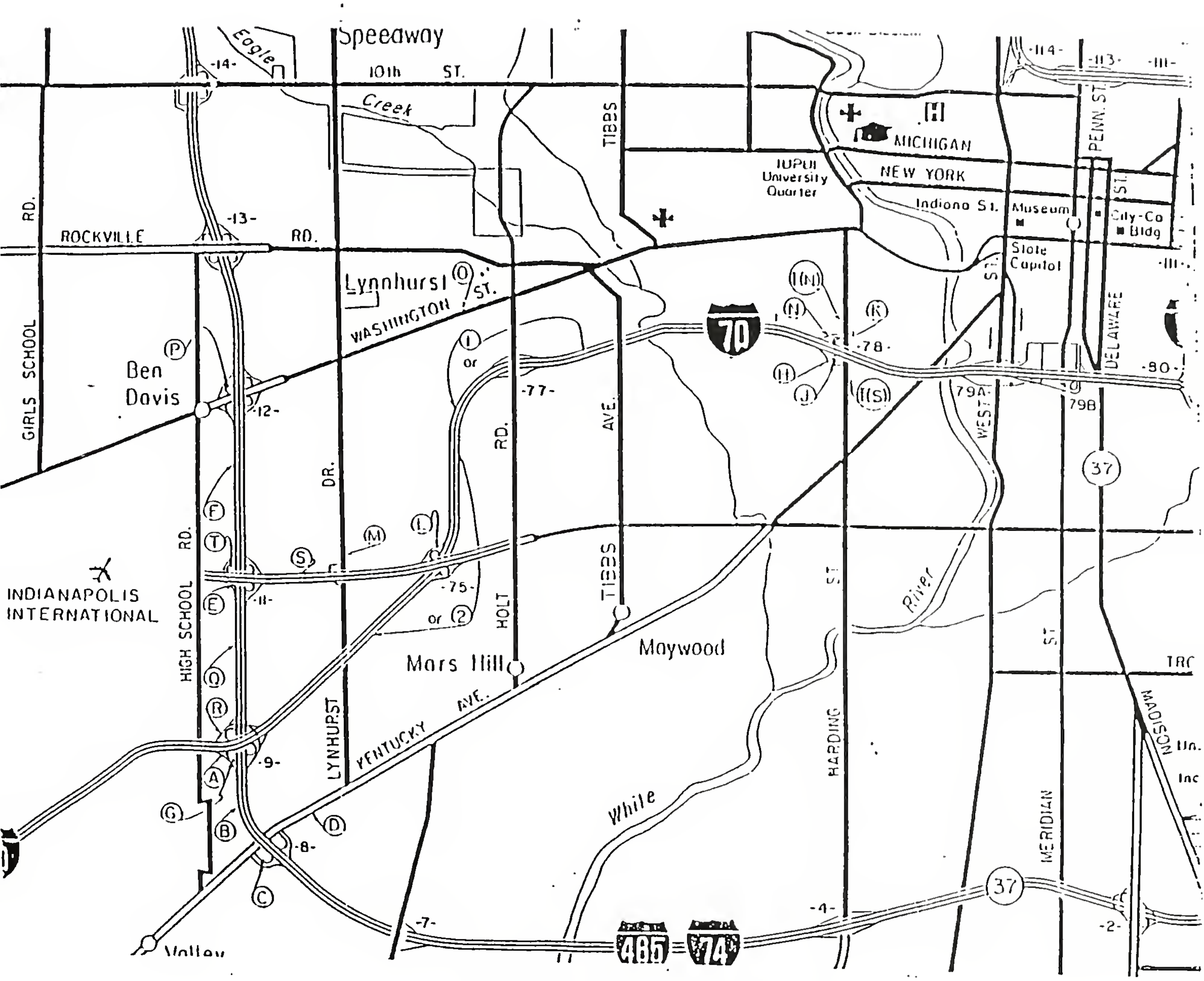

Figure 3.1 Indianapolis Network

of work zones a detailed O-D estimation procedure [Hamerslag 1988] is recommended.

The road system in Figure 3.1 was coded in the form of a directed network. Roads which define the boundary of the network are:

1. I-465, from Washington Street to Kentucky Avenue
2. Kentucky Avenue, from I-465 to I-70
3. I-70, from Kentucky Avenue to Tibbs Avenue
4. Tibbs, from I-70 to Washington Street
5. Washington Street, from Tibbs Avenue to I-465

Thus, it was assumed that the impact of the work zone would not spread beyond the network defined by the above boundaries. The data file consisted of the forward star representation of network configuration, free-flow travel time and capacity for every link in the network. One peak hour traffic was used for trip table. These data were sufficient to find user equilibrium flow pattern on the network using BPR link performance function. One of the difficulties in using a network model is the development of input. Estimating the node-to-node trip table for a large network may not be feasible in most of the cases. Also, the size of network models for large urban areas, incorporating detailed network coding and accurate O-D matrix, can grow beyond practical limit. Clearly, there is a trade-off between the incremental benefit of more accurate prediction and incremental cost of additional data collection and network coding detail.

## 3.4 Results of the Case Study

This section is subdivided into three subsections. The impact of lane closure in both directions on I-70 is evaluated in Section 3.5.1. First, one lane is closed on I-70 in both directions and the impact on the network is summarized. The capacity of I-70 is then further restricted by closing two lanes in both directions. This was done to see if the influence of the work zone would spread any further. In addition, since there is no direct relation between network traffic growth and traffic volume on an individual link, an attempt was made to evaluate the impact of possible reconstruction projects in the future. This is described in Section 3.5.2. In Section 3.5.3 is presented how the timing of a number of work zones can be scheduled in order to reduce the total adverse impact on road users.

In the following discussion, traffic volumes before and during reconstruction are UE flow, corresponding to one peak hour demand. Thus, it is assumed that equilibrium flow is reached in a very short period. This assumption may not be justifiable when the reconstruction period is too short. In that case either equilibrium would never be reached or if it is reached it will be for a very short time. For studying network traffic behavior during the transition period, an appropriate user behavior model is needed to understand the route choice mechanism. An attempt has been made [Jha et al. 1995] to study drivers' behavior regarding their route choice when a network is not in an equilibrium state. These issues are more related with what is termed in the literature as day-to- day dynamics and are not discussed here.

### 3.4.1 Evaluation of Lane Closure on I-70

The impact of closing one lane on I-70 in both directions from Tibbs Avenue to Lynhurst Drive is summarized in Tables 3.1 and 3.2. Table 3.1 shows only a small change in the traffic pattern because of the lane closure. A small fraction of vehicles traveling on I-70 East from Airport Expressway (the section from Holt to I-465 is commonly known as Airport Expressway or AE) to Holt, change their route. Thus, there is no substantial change in traffic pattern on the network. Also, from Table 3.2, it is evident that most part of the delay is caused by traffic on I-70 only. Therefore, evaluating the impact on only I-70 traffic would be a good approximation to total

| | | | Traffic Volume | | |
|---|---|---|---|---|---|
| Road Section | From | To | Before | During | Change |
| I-70 East | Airport ExWay | Holt | 3924 | 3682 | -6.2 |
| Holt | Airport ExWay | I-70 | 1650 | 1892 | +14.7 |
| Airport ExWay | I-70 | Holt | 1100 | 1342 | +22.0 |

Table 3.1 Change in Peak Hour Traffic for One Lane Closure

| | Average Travel Time | | |
|---|---|---|---|
| Road Section | Before | During | % Change |
| I-70 (Lynhurst to Tibs) | 3.28 | 3.70 | 12.8 |
| I-70 (Tibs to Lynhurst) | 3.30 | 3.92 | 18.8 |
| Holt (Airport ExWay to I-70) | 1.60 | 1.68 | 5.0 |
| Airport ExWay (I-70 to Holt) | 0.52 | 0.53 | 1.9 |

Table 3.2 Comparison of Travel Time Before and During One Lane Closure

| | | | Traffic Volume | | |
|---|---|---|---|---|---|
| Road Section | From | To | Before | During | Change |
| I-70 (East) | Airport ExWay | Kentucky | 3924 | 3165 | 19.3 |
| I-70 (West) | Kentucky | Holt | 4529 | 3653 | 19.3 |
| I-70 (West) | Holt | Airport ExWay | 3916 | 3159 | 19.3 |
| I-70 (East) | I-465 | Airport ExWay | 2518 | 2518 | 0.0 |
| I-70 (West) | Airport ExWay | I-465 | 2358 | 2358 | 0.0 |

Table 3.3 Peak Hour Traffic Volume on I-70 Before and During Construction

delay caused by one lane closure on I-70. This is because of the enough unused capacity on I-70. Even after closing one lane most of the drivers find their initial route as the best one.

The above observation does not hold good when (a) there is not enough unused capacity or (b there is a severe reduction in the capacity. Such a situation was studied by evaluating the effect of two lane closures in both directions from Lynhurst Drive to Tibbs Avenue. Traffic volumes on various links on I-70 before and during reconstruction are summarized in Table 3.3. Those links which are not located on I-70 and on which traffic volumes changed as a result of the work zone are shown in Table 3.4. Travel times on corresponding links are compared in Tables 3.5 and 3.6.

Considering the number of adjacent roads that are affected (Table 3.4) and the percentage increase in their travel time (Table 3.6), it is not very hard to foresee that the delay on adjacent roads would become a substantial part of the total delay on the network and hence should not be ignored. For example, while the total delay in the network for one peak hour was calculated to be 43,600 minutes, the delay on adjacent road sections was 12,459 minutes during the same period or about 28.5 percent of the total network delay.

| | | | Traffic Volume | | |
|---|---|---|---|---|---|
| Road Section | From | To | Before | During | Change |
| Kentucky (West) | I-70 | Holt | 1650 | 2526 | 53 |
| Kentucky (East) | Holt | I-70 | 1650 | 2409 | 46 |
| Airport ExWay | I-70 | Holt | 1100 | 1858 | 68.9 |
| Airport ExWay | Holt | I-70 | 950 | 1708 | 79.8 |
| Holt | Kentucky | Airport ExWay | 1650 | 2525 | 53 |
| Holt | Airport ExWay | Kentucky | 1650 | 2408 | 46 |

Table 3.4 Peak Hour Traffic Volume on Adjacent Roads Before and during Construction

| | Average Travel Time | | |
|---|---|---|---|
| Road Section | Before | During | Delay |
| Airport ExWay to Kentucky | 4.60 | 8.59 | 12602 |
| Kentucky to Holt | 2.94 | 4.79 | 6748 |
| Holt to Airport ExWay | 1.78 | 4.68 | 9215 |
| I-465 to Airpoprt ExWay | 1.69 | 2.29 | 1507 |
| Airport ExWay to I-465 | 1.69 | 2.15 | 1077 |

Table 3.5 Calculation Of Delay on Various Links on I-70

| | Average Travel Time | | |
|---|---|---|---|
| Road Section | Before | During | % Change |
| Kentucky (I-70 to Holt) | 5.03 | 6.50 | 29.2 |
| Kentucky (Holt to I-70) | 5.03 | 6.20 | 23.3 |
| Airport ExWay (I-70 to Holt) | 0.52 | 0.57 | 9.6 |
| Airport ExWay (Holt to I-70) | 0.51 | 0.56 | 9.8 |
| Holt (Kentucky to Airport ExWay) | 1.37 | 1.77 | 29.2 |
| Holt (Airport ExWay to Kentucky) | 1.37 | 1.69 | 23.4 |

Table 3.6 Peak Hour Travel Time on Adjacent Roads Before and During Reconstruction

Thus, the conventional method of impact evaluation of work zones would have substantially underestimated the total delay. Moreover, it can be seen from Tables 3.1, 3.3 and 3.4 that the percentage change in network traffic varies from 0% to 25%. This implies that it is not justifiable to assume a fixed fraction for estimating traffic diversion.

### 3.4.2 Impact of Work Zones under Increased Traffic

In the absence of any diversion, the increase in traffic on a link will be equal to the network traffic growth. Due to the complex route diversion, the relation between the two is not straightforward. The increase in traffic volume on a particular link is related to marginal travel time of those paths which include that link. Marginal travel times of the paths, in turn, are dependent on network configuration, travel time functions of the links and O-D matrix. Therefore, there is no direct relation between the growth in the network traffic and the increase in the traffic volume on a particular link. As an example, in Figure 3.2 is shown the increase in traffic on Kentucky Avenue (both directions) as a function of network traffic growth. The work zone consists of two lane closure on I-70 in both directions from Lynhurst Drive to Tibbs Avenue. A hypothetical line for no diversion is also shown. It is clear from the graph that traffic on Kentucky Avenue increases at a faster rate than traffic growth. At 5% growth level, diversion on Kentucky Avenue from other roads would be about 2% whereas at 20% growth level diversion would be about 7%. This indicates that as the traffic on the network increases, the congestion on Kentucky Avenue can be expected to increase at a faster rate. This is because of the closure of two lanes on I-70. The part of the traffic that would have taken I-70 finds Kentucky Avenue as a better alternate route. Thus, understanding the impact of work zones on various links under expected future traffic would help (a) in designing an effective network traffic management plan and in (b) identifying possible congestion spots.

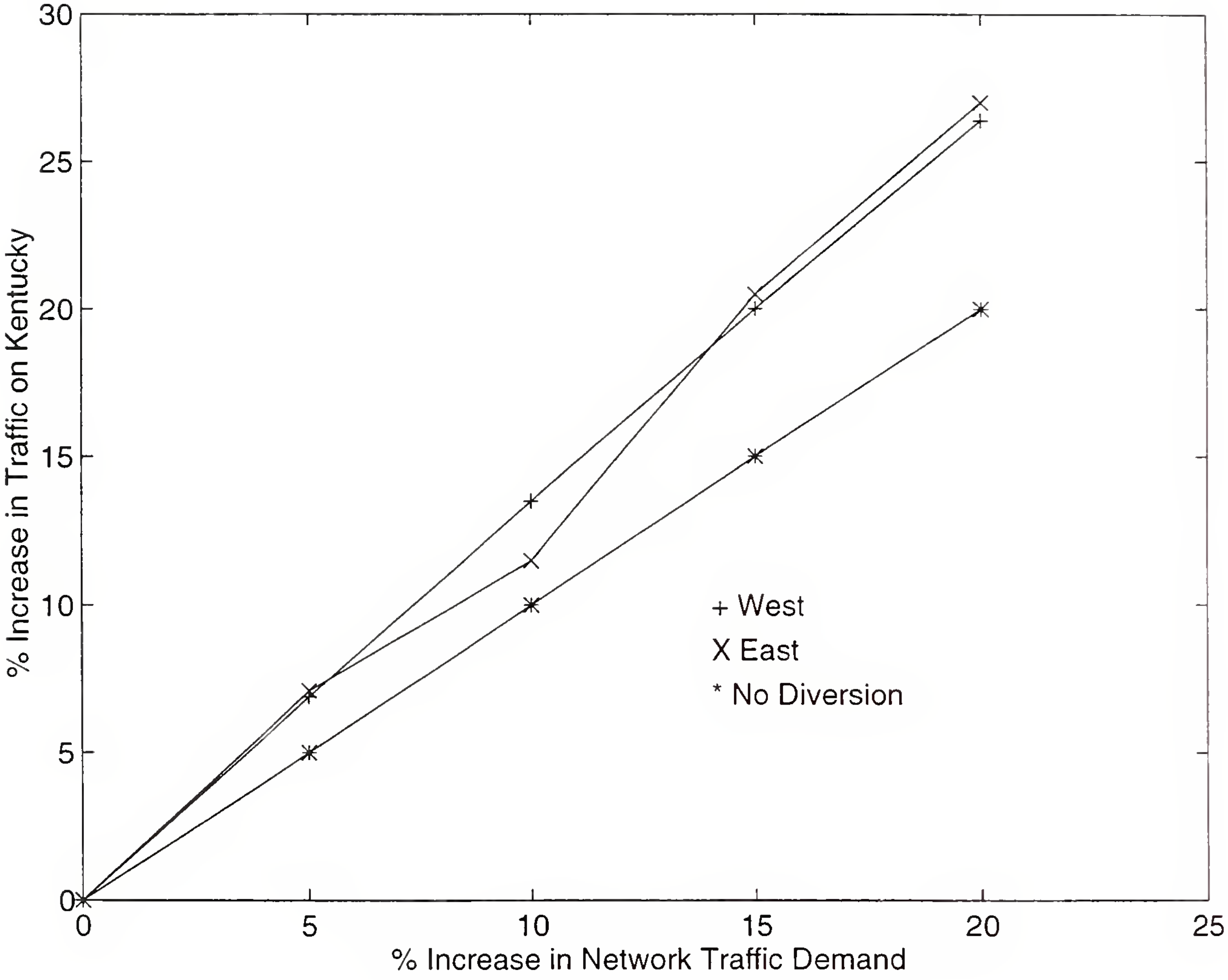

Figure 3.2 Impact of Network Traffic Growth on Kentucky Ave (Work Zone on I-70)

### 3.4.3 Adverse Impact Reduction by Efficient Scheduling

In this section it is shown that if more than one project is to be carried out on a network during a construction season, then a wrong scheduling of the projects may lead to an unacceptable amount of total delay. In the absence of a network model, selection of this kind of undesirable schedule is not very unlikely. Consider for example, a simple network shown in Figure 3.3. Nodes are represented by circles, link numbers are shown in parentheses whereas node numbers are shown within nodes. Assume that (1,2) is the only O-D pair in the network. Free flow travel times on Paths 1-3-2 and 1-4-2 are comparable, implying that these are the two used paths in the network. Free flow travel time on the Link 5 is very high and capacity is low. Therefore Link 5 remains unused. If link 1 is closed, all the traffic goes on Path 1-4-2. As a result no traffic is on Link 2. Therefore, the total delay of closing Link 1 is equal to that for closing Links 1 and 2 together. Next, consider closure of Links 1 and 3. If Links 1 and 3 are closed together all the traffic is forced to use Link 5 causing much more delay. Thus, if Links 1 and 3 are to be closed, it is better to close one at a time. On the other hand, if Links 1 and 2 are to be closed, it is better to close both at the same time. The following conclusion can be drawn from the above example. For a given network configuration, travel time functions for links and associated O-D matrix, if two or more links are to be disturbed for repair then total delay for one schedule may be different from that for other schedule.

The conclusion drawn from the simple network was validated using the same network which was used for lane closure study. The same O-D matrix was considered. For demonstration purpose, a set of three hypothetical reconstruction projects was assumed. Here a reconstruction project is considered as closure of one or more lanes on a section of a road. It was further assumed that one or more projects can start at the same time but no project can start before the previous project(s) is(are) completed. For example, if X and Y are the two projects then our assumption leads to two

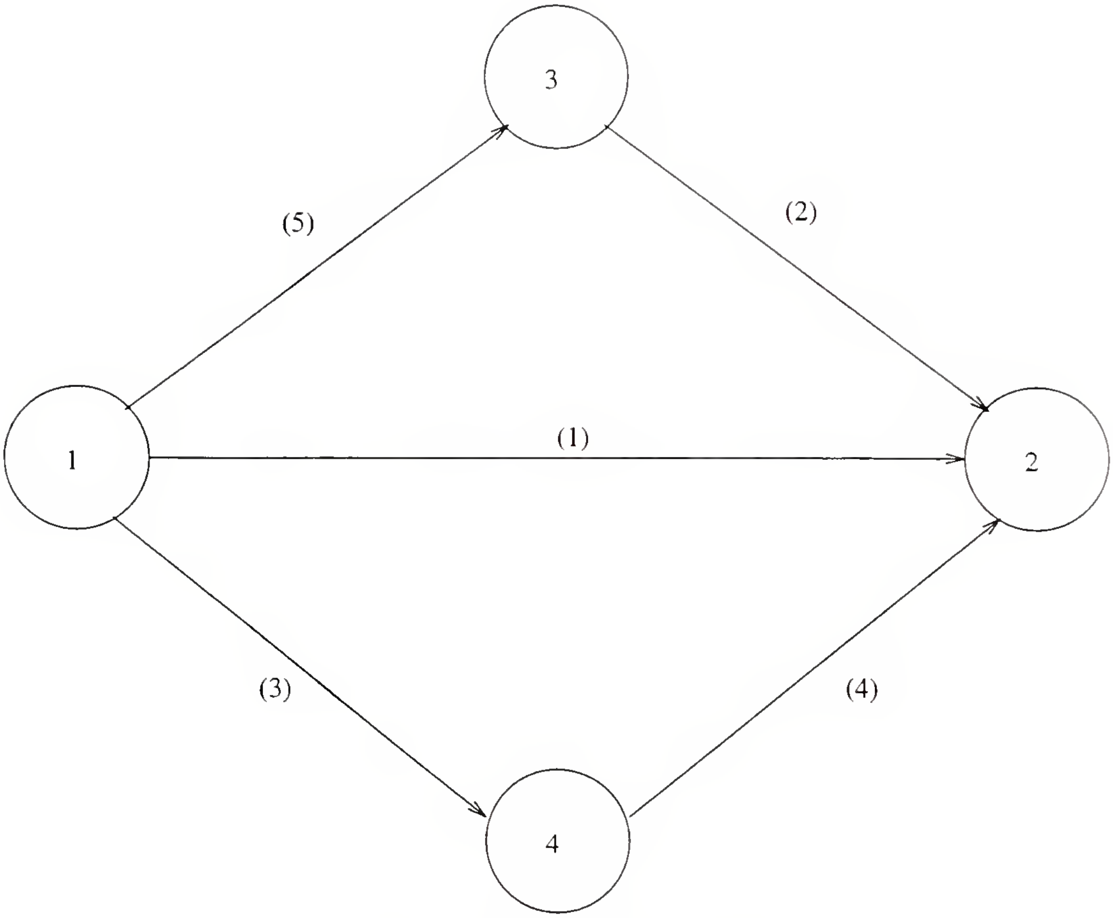

Figure 3.3 A Simple Network

| Road Section(s) | From | To | Total Delay |
|---|---|---|---|
| 1. I-70 | Airport ExWay | Holt | 50,402 |
| 2. I-70 | Airport ExWay | Holt | |
| Holt | Airport ExWay | I-70 | 169,325 |
| 3. I-70 | Airport ExWay | Holt | |
| | Kentucky | Airport ExWay | 80,036 |
| 4. Holt | Airport ExWay | I-70 | 5,044 |
| 5. Holt | Airport ExWay | I-70 | |
| Holt | Kentucky | Airport ExWay | 21,700 |
| 6. Holt | Kentucky | Airport ExWay | 17,116 |

Table 3.7 Total Delay for Various Combinations of Road Closures

possible ways of scheduling them : (a) First X then Y (b) X and Y together. Note that if we reverse the order in (a) it would still give the same total delay. Without any loss of generality this assumption helps in reducing the possible number of feasible schedules. Following are the three hypothetical projects :

1. Road closure on I-70 East, from AE to Holt
2. Road Closure on Holt North, from AE to I-70
3. Road Closure on Holt North, from Kentucky Avenue to AE.

Total delay for all possible combinations of the above projects are tabulated in Table 3.7 . It is obvious from that some of the combinations cause larger delays than others. For example, if Projects 1 and 2 are carried out at the same time the total delay would be more than two times the delay if the projects were carried out one at a time. Since neither a time constraint nor any time value (for early or late completion of projects) is imposed here, it is hard to select the best schedule. Nonetheless, if the projects were to be scheduled on the basis of total delay only, then Projects 2 and 3 should be undertaken simultaneously and 1 should be done alone. This combination gives the minimum delay (Table 3.7). For actual application, the information in Table 3.7 should be combined with project time constraint and user cost values to determine an optimal schedule.

## 3.5 Chapter Conclusions

A simple network equilibrium model was used to demonstrate the need for a network approach for evaluating work zone impact. The applicability of the approach was demonstrated through a case study which involved reconstruction of I-70 near Indianapolis airport. The road system around I-70 was coded in the form of a directed network. Convex combination algorithm was used to calculate the UE flow pattern and the BPR function was used to calculate travel times on links. The Total travel time experienced by all vehicles in the network for various work zone scenarios were calculated and compared against no-work-zone conditions.

It was shown that work zones can have a substantial impact on adjacent roads. Results from the case study indicated that depending on network traffic pattern and extent of capacity reduction imposed by work zone, fraction of vehicles that are likely to divert from affected road section varies appreciably. Thus, any attempt to evaluate the impact of work zones or to estimate diverted traffic should not be restricted to only those roads where work zones are located. Also, for estimating the impact of work zones in the future, traffic assignments should be made with future traffic, because future link volumes may not necessarily be equal to the product of current traffic and growth factor. Finally, it was shown that an understanding of the impact of various combinations of reconstruction projects could help in scheduling multiple projects on a network during a construction season.

The total adverse impact due to work zones consists of two parts : first, when the network is in disequilibrium and the second, after the network reaches an equilibrium. This study focused on impact evaluation corresponding to the second part only. However, for the overall impact evaluation it is also necessary to consider the first part. Therefore, the traffic behavior during the period when network is in disequilibrium needs to be studied for the evaluation of total impact due to work zones. Next chapter describes the *day-to-day* dynamics in a network due to work zones. Also, a model is presented to capture drivers' behavior during the transition period.

# 4. DYNAMIC ANALYSIS OF WORK ZONE TRAFFIC

## 4.1 Introduction

There has been a growing interest in last few years in Dynamic Traffic Assignment (DTA) and dynamic analysis of drivers' behavior. DTA is a temporal extension of conventional static assignment, which was presented in the previous chapter. Dynamics in a transportation network can be of two types : *day-to-day* dynamics and *within day* dynamics. *Day-to-day* dynamics refers to the variation in traffic pattern from one day to the next. Whereas *within day* dynamics is quicker and refers to the time varying nature of traffic within a day. Since the focus of this research is on long term construction zones, only *day-to-day* dynamics is studied within its scope. After disruptions on the network, i.e. after the initiation of the work zones, drivers' previous path no longer remains the best path for them. Therefore, they search for the new path which is the best under disrupted condition. This process of searching the new best path takes some time and during this time period, *day-to-day* dynamics is observed.

The remainder of this chapter is organized as follows. Some related work is summarized in the next section. Next, a model for capturing drivers' learning mechanism through experience and information (if available) is presented. Note that the source of information can be either ATIS or some media like TV, radio or other sources. Next, a model for predicting travelers' route and departure time choice is described. The learning model and the choice model are integrated with a simulator and some results are presented from simulation experiments.

## 4.2 Previous Research

A deterministic equilibrium model for departure time choice [Hendrickson and Kocur 1981] which extends Wardrop's UE condition to time-dependent conditions. was one of the earlier models to describe *day-to-day* dynamics in a transportation network. This model was later extended [Mahmassani and Herman 1984] to incorporate route choice. A stochastic version of the dynamic equilibrium model for departure time dynamics was also developed [Ben-Akiva et al. 1984]. Later the model was extended [Ben-Akiva et al. 1986] to incorporate alternate routes. The scope of the above models is limited to a network with one O-D pair. The model proposed by Ben-Akiva et al. was further extended [Vythoulkas 1990] to the case of general networks. In the models proposed by Ben-Akiva et al. and Vythoulkas, the evolution of traffic pattern on the network from day to day is derived from a Markovian model assuming that the system reaches a steady state. However, the existence and uniqueness of of the steadystate was solely based on simulation results. A stochastic process approach [Cascetta and Cantrella 1991] for modeling *day-to-day* and within day dynamics has also been proposed. Again, the evolution of the traffic pattern from one day to the next is represented by a Markovian model. In this study, it is shown that under a set of assumptions the network reaches a unique steady state. One of the key assumptions for proving the existence and uniqueness of the steady-state is the homogeneity of travel choice probabilities. This assumption implies that users' current route and departure time choices do not affect their future choice probabilities. However, in the context of *day-to-day* adjustment, where users learn from their experience as well as from traffic information, their travel time perceptions are not independent of their previous experiences. Our model, described later, explicitly accounts for the effect of this learning process.

A number of simulation studies were carried out to evaluate the impact of various information strategies on network performance using different user behavioral models.

Most of these studies consider users' accessibility to ATIS as an indicator variable, i.e., either the user is connected or not connected to ATIS. It should be noted that drivers may have different attitudes towards ATIS and the extent of their accessibility to information systems may also vary. By modeling accessibility to ATIS as an indicator variable, the variation across users in terms of how they respond to ATIS is not captured. Some of the studies performed to model the impact of ATIS on network performance are summarized here. Users route choice dynamics in the case of lane closures was studied in a simulation environment [Mahmassani and Jayakrishnan 1988]. It was concluded that providing real time *in-vehicle* information to users can lead the network to a steady state at a faster rate than under the no-information case. In a related simulation study on *day-to-day* dynamics, [Mahmassani 1990] it was found that under different information strategies, the network reached a steady state at different rates. The issue of *day-to-day* dynamics in the presence of ATIS has also been studied [Friesz et al. 1994] analytically where it was shown that under complete or incomplete information, a network would reach a steady state. An important dimension missing in the the study carried out by Friesz et al. is the perceived quality of information. It is assumed that all users connected to ATIS behave in the same way. Little research has been done to capture the dynamics of users' travel time perceptions. A weighted average approach was suggested [Ben-Akiva et al. 1991] to represent driver's perceived travel times as a function of the historic perceptions and the information travel time. This information integration model assumes travel times as deterministic variables and hence does not model the stochasticity in drivers' perceptions of travel times. Drivers' anticipated travel times were also modeled using a bounded rationality approach [Joseph et al. 1992]. Again, the anticipated travel time is modeled as a deterministic variable. Moreover, the model, at the end of each day, generates the departure pattern for the next day based on the experienced travel time without incorporating current travel information. In a recent study [Vaughn et al. 1995], users' responses to information system were studied in a simulation environment. Statistical tests were carried out to empirically describe users' response but no explicit model is suggested to capture the impact of ATIS and experienced time on future choices.

Users' choice of route and departure time is primarily governed by the perceived travel time. Thus, it is important to understand the information processing and perception updating mechanism of users in order to correctly estimate the perceived travel time. Also, the variance of the perceived travel time which represents driver's confidence in the perception is an important factor in the alternative selection. To date, no model is capable of representing driver's confidence and incorporating that in the choice model. We explicitly model driver's confidence in the perceived travel time and use this in our utility function. In the next section, we describe our perception updating model and demonstrate the importance of incorporating drivers' confidence in their perception and the perceived quality (by drivers) of information .

## 4.3 The Perception Updating Model

The proposed framework is based on Bayesian updating. Travel time perception of drivers as well as travel time information provided by ATIS are described by probability distribution functions. Variance of these distribution functions indicate the level of trust on the part of drivers. Thus, drivers can be modeled on the basis of how they perceive the quality of information. It is hypothesized in this model that on any given day drivers have certain level of knowledge about travel time and they update their knowledge in the light of travel time information. The updated perception of travel time is obtained by Bayesian updating where the perception level of driver before receiving information corresponds to the prior and the updated perception level corresponds to posterior. Drivers use their posterior perception to select route and departure time on the given day. After making the trip, drivers update their posterior perception in the light of experienced travel time and come up with the prior perception for the next day. Again, updating is based on Bayesian approach. Thus, updating is done in two stages : once before the trip i.e. *pre-trip* updating and then after trip i.e. *post-trip* updating. The *pre-trip* updating incorporates information availability and quality (as perceived by the user) whereas *post-trip* updating accounts for the experience of individual driver. It is important to note that the no-information case, t.e. if a user does not have access to information or if he/she does not care about information, can be easily modeled. Therefore, the model can also be used to find out the proportion of drivers who should be provided information in order to achieve some system-wide goals e.g. reduction of total travel time in the network. Only *pre-trip* information availability is modeled in the proposed framework. It is easy to see ,however, that the framework can be extended to *en-route* perception updating by using multi-stage Bayesian updating. In case of *en-route* updating, every time a driver will reach a decision node in the network (nodes where the driver can make decision regarding path switching), updating will be done. Next, we describe the mathematical formulation of perception updating model.

### 4.3.1 Model Formulation

We first define some variables which are used in this model:

$T_{k,r}^{1,i,w}$ mean perceived travel time by individual i on day w before reciving information and before the trip for $k^{th}$ path between his/her origin and destination[1] and $r^{th}$ departure interval[2].

$T_{k,r}^{2,i,w}$ same as above but after receiving information and before the trip.

$T_{k,r}^{3,i,w}$ same as above but after undertaking the trip on day w.

$\tau_{k,r}^{j,i,w}$ expected value of $T_{k,r}^{j,i,w}$ where j=1,2,3

$\epsilon$ drivers' perception and measurement errors.

---

[1] Since origin and destination do not vary for a given user, no subscripts or superscripts are used for origins and destinations throughout this paper for clarity of notation.

[2] Departure time is assumed to be discretized into sufficiently small intervals.

$\zeta$ travel time variation (from one day to the next) in the network. These disturbances are essentially caused by the inherent randomness in network performance and fluctuations in demand pattern.

Let the mean perceived travel time for individual i on day w before receiving information and before the trip be expressed by :

$$T_{k,r}^{1,i,w} = \tau_{k,r}^{1,i,w} + \epsilon_{1,k,r}^{i,w} \qquad [4.1]$$

where :

$\tau_{k,r}^{1,i,w}$ is the best estimate of travel time on day w by driver i for $k^{th}$ path and $r^{th}$ departure interval.

$\epsilon_{1,k,r}^{i,w}$ is the perception error of whose distribution is assumed as $N(0,\sigma_{1,k,r}^{i,w})$.

Thus, a driver's mean perceived travel time is modeled as a random variable whose mean is his/her best estimate of travel time. $\tau_{k,r}^{1,i,w}$ is viewed as the best travel time estimate because of the following two reasons :

1. In the context of *day-to-day* dynamics, true travel time can be known only after it is experienced because of the randomness in network performance and fluctuation in the demand pattern from one day to the next; in fact, the travel time experienced by a user can be viewed as the outcome of a random process.

2. Considering the stochasticity and dynamics in the estimation of travel time, it is reasonable to assume that mean perceived travel time for a user will be distributed around his/her best estimate.

### 4.3.2 Pre-Trip Updating

Let the travel time provided by ATIS on day w on $k^{th}$ path for $r^{th}$ departure interval be $ti_{k,r}^{w}$. Without loss of generality, it is assumed that the travel times provided by ATIS do not vary across individuals. It is hypothesized that when users receive traffic information, they modify it based on their perceptions of information. The modified information travel time can be expressed as:

$$tp^{i,w}_{k,r} = ti^{w}_{k,r} + \epsilon^{i,w}_{2,k,r} \qquad [4.2]$$

where :

$tp^{i,w}_{k,r}$ is the perceived value of information travel time by individual i for $k^{th}$ path and $r^{th}$ departure interval on day w.

$\epsilon^{i,w}_{2,k,r}$ is the perception error, which is due to the user's past experience with traffic information, his/her attitude towards the information system etc. The distribution of $\epsilon^{i,w}_{2,k,r}$ is assumed N(0,$\sigma^{i}_{2}$).

If it is assumed that on average, the best estimated travel time is correct[3] then we can express information travel time as :

$$ti^{w}_{k,r} = \tau^{1,i,w}_{k,r} + \zeta^{i,w}_{1,k,r} \qquad [4.3]$$

where :

$\zeta^{i,w}_{1,k,r}$ is the difference between the user's estimation of travel time and the travel time provided by ATIS; this difference is due to the randomness in network performance and fluctuations in the demand pattern and is described by a normal distribution with expected value of zero and standard deviation $\sigma^{i,w}_{3,k,r}$.

The updated best estimate is given by the following Bayesian formula :

$$\tau^{2,i,w}_{k,r} = E[T^{2,i,w}_{k,r}] = \frac{tp^{i,w}_{k,r} * Var(T^{1,i,w}_{k,r}) + T^{1,i,w}_{k,r} * Var(tp^{i,w}_{k,r})}{Var(T^{1,i,w}_{k,r}) + Var(tp^{i,w}_{k,r})} \qquad [4.4]$$

The updated variance of the mean perceived travel time is given by :

$$Var(T^{2,i,w}_{k,r}) = \frac{Var(T^{1,i,w}_{k,r}) * Var(tp^{i,w}_{k,r})}{Var(T^{1,i,w}_{k,r}) + Var(tp^{i,w}_{k,r})} \qquad [4.5]$$

---

[3] we assume that the travel time information is accurate.

traffic information, they modify it based on their perceptions of information. The modified information travel time can be expressed as:

$$tp_{k,r}^{i,w} = ti_{k,r}^{w} + \epsilon_{2,k,r}^{i,w} \qquad [4.2]$$

where :

$tp_{k,r}^{i,w}$ is the perceived value of information travel time by individual i for $k^{th}$ path and $r^{th}$ departure interval on day w.

$\epsilon_{2,k,r}^{i,w}$ is the perception error, which is due to the user's past experience with traffic information, his/her attitude towards the information system etc. The distribution of $\epsilon_{2,k,r}^{i,w}$ is assumed N(0,$\sigma_2^i$).

If it is assumed that on average, the best estimated travel time is correct[3] then we can express information travel time as :

$$ti_{k,r}^{w} = \tau_{k,r}^{1,i,w} + \zeta_{1,k,r}^{i,w} \qquad [4.3]$$

where :

$\zeta_{1,k,r}^{i,w}$ is the difference between the user's estimation of travel time and the travel time provided by ATIS; this difference is due to the randomness in network performance and fluctuations in the demand pattern and is described by a normal distribution with expected value of zero and standard deviation $\sigma_{3,k,r}^{i,w}$.

The updated best estimate is given by the following Bayesian formula :

$$\tau_{k,r}^{2,i,w} = E[T_{k,r}^{2,i,w}] = \frac{tp_{k,r}^{i,w} * Var(T_{k,r}^{1,i,w}) + T_{k,r}^{1,i,w} * Var(tp_{k,r}^{i,w})}{Var(T_{k,r}^{1,i,w}) + Var(tp_{k,r}^{i,w})} \qquad [4.4]$$

The updated variance of the mean perceived travel time is given by :

$$Var(T_{k,r}^{2,i,w}) = \frac{Var(T_{k,r}^{1,i,w}) * Var(tp_{k,r}^{i,w})}{Var(T_{k,r}^{1,i,w}) + Var(tp_{k,r}^{i,w})} \qquad [4.5]$$

---

[3] we assume that the travel time information is accurate.

The updated mean perceived travel time is given by :

$$T^{2,i,w}_{k,r} = \tau^{2,i,w}_{k,r} + \epsilon^{i,w}_{3,k,r} \qquad [4.6]$$

In Equation 4.6, $\tau^{2,i,w}_{k,r}$ is given by Equation 4.4, whereas the variance of $\epsilon^{i,w}_{3,k,r}$ is given by Equation 4.5. The *pre-trip* updating described above is done for all the paths and departure times for which information is available. Note that the variance of $tp^{i,w}_{k,r}$ in Equation 4.4 determines the relative importance in the estimation of the updated mean perceived travel time. Thus, the variance of $tp^{i,w}_{k,r}$ indicates driver's confidence in ATIS. We assume that the error terms in Equations 4.2 and Equation 4.3 are independent. The variance of $tp^{i,w}_{k,r}$ is then given by $(\sigma^{i,w}_{2,k,r})^2 + (\sigma^{i,w}_{3,k,r})^2$. Since $\sigma^{i,w}_{3,k,r}$ is inherent to the system, we model driver's confidence in ATIS through $\sigma^{i,w}_{2,k,r}$. Another important characteristic of our model which is directly implied by the Bayesian updating approach is that the variance of $T^{2,i,w}_{k,r}$ will always be less than $T^{1,i,w}_{k,r}$ indicating that the variance of the mean perceived travel time decreases as users receive more information.

### 4.3.3 Post-Trip Updating

The following updating is done in light of the travel time experienced by individual users. Therefore, *post-trip* updating takes place only for that route and departure time combination which a user selects for the trip. Since experience for a particular departure interval may have some effect on the perceptions for neighbouring departure intervals, an extension is to include updating of travel time perceptions for neighbouring departure intervals. If an individual i selects path k and departure time r then we denote the travel time experienced by individual i by $te^{i,w}_{k,r}$. As in Equation 4.2, the experienced travel time as perceived by individual i, can be written as :

$$tx^{i,w}_{k,r} = te^{i,w}_{k,r} + \epsilon^{i,w}_{4,k,r} \qquad [4.7]$$

where :

$\epsilon_{4,k,r}^{i,w}$ is due to perception and measurement error, whose variance determines the relative importance of experienced travel time in perception updating. The distribution is assumed Normal with mean 0 and standard deviation $\sigma_{4,k,r}^{i,w}$.

As mentioned earlier, the experienced travel time can be viewed as the outcome of a random process. The randomness comes from the network performance as well as the travel choice dynamics. If there is no drastic change in the flow pattern on the network, it can be assumed that the experienced travel time by an individual would have a distribution whose mean is the updated best estimate of travel time and can be expressed as :

$$te_{k,r}^{i,w} = \tau_{k,r}^{2,i,w} + \zeta_{2,k,r}^{i,w} \qquad [4.8]$$

where :

$\zeta_{2,k,r}^{i,w}$ is an error term which represents randomness in network performance and fluctuation in demand pattern; we assume that $\zeta_{2,k,r}^{i,w}$ is N(0,$\sigma_{5,k,r}^{i,w}$).

The best travel time estimate is further updated and is given by :

$$\tau_{k,r}^{3,i,w} = \frac{T_{k,r}^{2,i,w} * Var(tx_{k,r}^{i,w}) + tx_{k,r}^{i,w} * Var(T_{k,r}^{2,i,w})}{Var(tx_{k,r}^{i,w}) * Var(T_{k,r}^{2,i,w})} \qquad [4.9]$$

The updated variance of the mean perceived travel time is given by

$$Var(T_{k,r}^{3,i,w}) = \frac{Var(T_{k,r}^{2,i,w}) * Var(tx_{k,r}^{i,w})}{Var(T_{k,r}^{2,i,w}) + Var(tx_{k,r}^{i,w})} \qquad [4.10]$$

As in Equation 4.5, the posterior mean perceived travel time is given by:

$$T_{k,r}^{3,i,w} = \tau_{k,r}^{3,i,w} + \epsilon_{5,k,r}^{i,w} \qquad [4.11]$$

Note that Equation 4.11 describes the distribution of mean perceived travel time of user i on day w+1. Thus, on day w+1, the parameters of Equation 4.1 are obtained by :

$$\tau_{k,r}^{1,i,w+1} = \tau_{k,r}^{3,i,w}$$
$$Var(T_{k,r}^{1,i,w+1}) = Var(T_{k,r}^{3,i,w})$$

On day w+1, updating is done in a similar way. Updating is repeated for a desired number of days. The variance of the mean perceived travel time for that combination of departure time and route which was selected on day w decreases further.

## 4.4 Route and Departure Time Choice Model

In this section, we present a modified form of existing models for route and departure time choice. Our demand model is a random utility based model and we follow the hypothesis proposed by Ben-Akiva et al. [Ben-Akiva et al. 1986] which suggests that travelers define a hierarchy between departure time and route choice. Based on this hypothesis the probability of selecting path k and departure interval r on day w by individual i is expressed as :

$$P_{k,r}^{i,w} = P_r^{i,w} * P_{k/r}^{i,w} \qquad [4.12]$$

where :

$P_r^{i,w}$ is the probability of selecting departure interval r by individual i on day w.

$P_{k/r}^{i,w}$ is the probability (on day w) of selecting route k given that the user has selected departure interval r.

Both probabilities in Equation 4.12 are represented by logit models. Expressions for choice probabilities are derived from previous studies [Ben-Akiva et al. 1986, Ben-Akiva and Lerman 1985] in this area. Departure time in existing discrete choice models is either treated as continuous or as discrete (in which case it is known as departure interval). It should be noted that the departure interval is an ordinal number. Therefore, we use the ordered logit model for departure time choice. The structure of the nested logit model based on above description is presented in Figure 4.1.

The main sources of disutility which affects drivers' route and departure time selection are : (1) travel time and (2) schedule delay. The basic form of the utility function

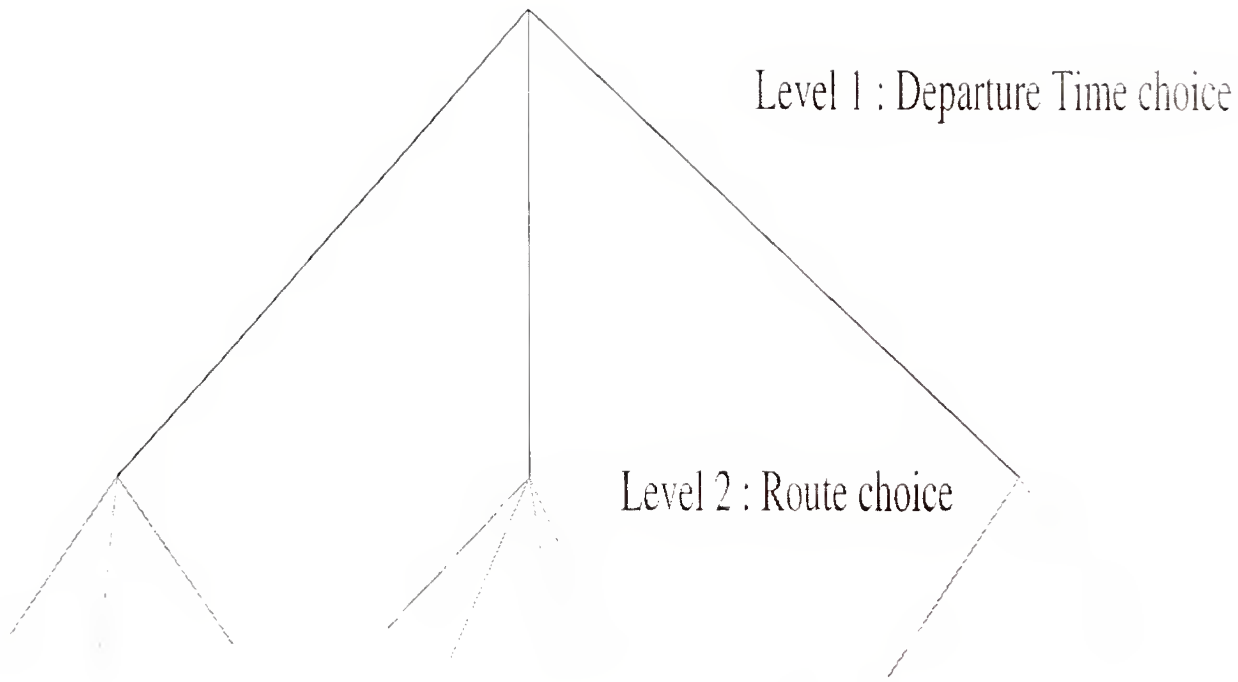

Figure 4.1 Structure of the Nested Logit Model

used in our model is adopted from a previous study [de Palma et al. 1983]. Following this study, the systematic part of the total utility can be expressed as :

$$V^{i,w}_{k,r} = -\alpha(tt^{i,w}_{k,r}) - \beta\theta^{i,w}_{1,k,r}(D^{i,w}_{k,r}) - \beta\gamma\theta^{i,w}_{2,k,r}(E^{i,w}_{k,r}) \qquad [4.13]$$

where :

$V^{i,w}_{k,r}$ is the systematic part of the utility for individual i on day w for path k and departure interval r.

$tt^{i,w}_{k,r}$ is the perceived travel time of user i on day w for path k and departure interval r.

D is the anticipated schedule delay by user i on day w for late arrival for path k and departure interval r. If A is the preferred arrival time then D is given by : $D^{i,w}_{k,r} = T_r + tt^{i,w}_{k,r}$ - A, where $T_r$ is the mid-point of interval r.

E is the anticipated penalty for early arrival.

The $\theta$s are indicator variables and are defined as :

$$\theta^{i,w}_{1,k,r} = 1 if D > 0; 0 \text{ otherwise.}$$
$$\theta^{i,w}_{1,k,r} = 1 if E > 0; 0 \text{ otherwise.}$$

A fundamental difference between our utility function and the existing ones is that we use perceived travel time instead of the travel time actually observed or calculated from the traffic flow model. This has two advantages : (1) using an individual's perceived travel time in the utility function is more realistic (2) overcoming the mathematical tractability issues [Vythoulkas 1990] involved in the derivation of an analytical solution for departure rate using the complex relationships involved in a demand model and a travel time model.

## 4.5 Simulation Experiments : Preliminary Results

Models described in Section 4.3 and 4.4 are integrated with DYNASMART, a dynamic traffic simulator developed at the University of Texas at Austin [Jayakrishnan et al. 1994]. A simulation framework is developed to study *day-to-dynamics* in the network. The simulation framework is represented in the form of a flowchart in Figure 4.2. A detailed description of the simulation framework can be found elsewhere [Jha et al. 1995]. It should be noted that according to the framework, the time varying OD matrices are updated in real time. However, at this point in our research, we have implemented only route choice dynamics. Three experiments have been conducted to date. The first goal of our experiments is to check the final state of the traffic pattern. All the experiments reported in this paper are carried out for the same purpose. The test network in the experiment consists of 50 nodes and 168 links. Network is divided into 10 zones. Simulation is run for 35 minutes of peak period traffic. The statistics reported here are based on the vehicles generated between t = 5 (simulation starts at t = 0) and t = 25. This assures that the vehicles we consider are neither in warm-up time nor in the end time. During those two periods traffic would be substantially less than the peak and the result might be misleading. *Day-to-day* dynamics are initiated by closing 6 links on day 3. They are reopened on day 7. Perception of each driver is updated separately. Hence, we do not aggregate the results. The algorithm for simulation experiments is described below in the form of *pseudo-code.*

### Algorithm

```
For day = 1 to no-of-days
    For dep-interval = 1 to time-of-interest
        For user = 1 to interval-demand
            if (day == 1) or (change-in-network-structure) then
```

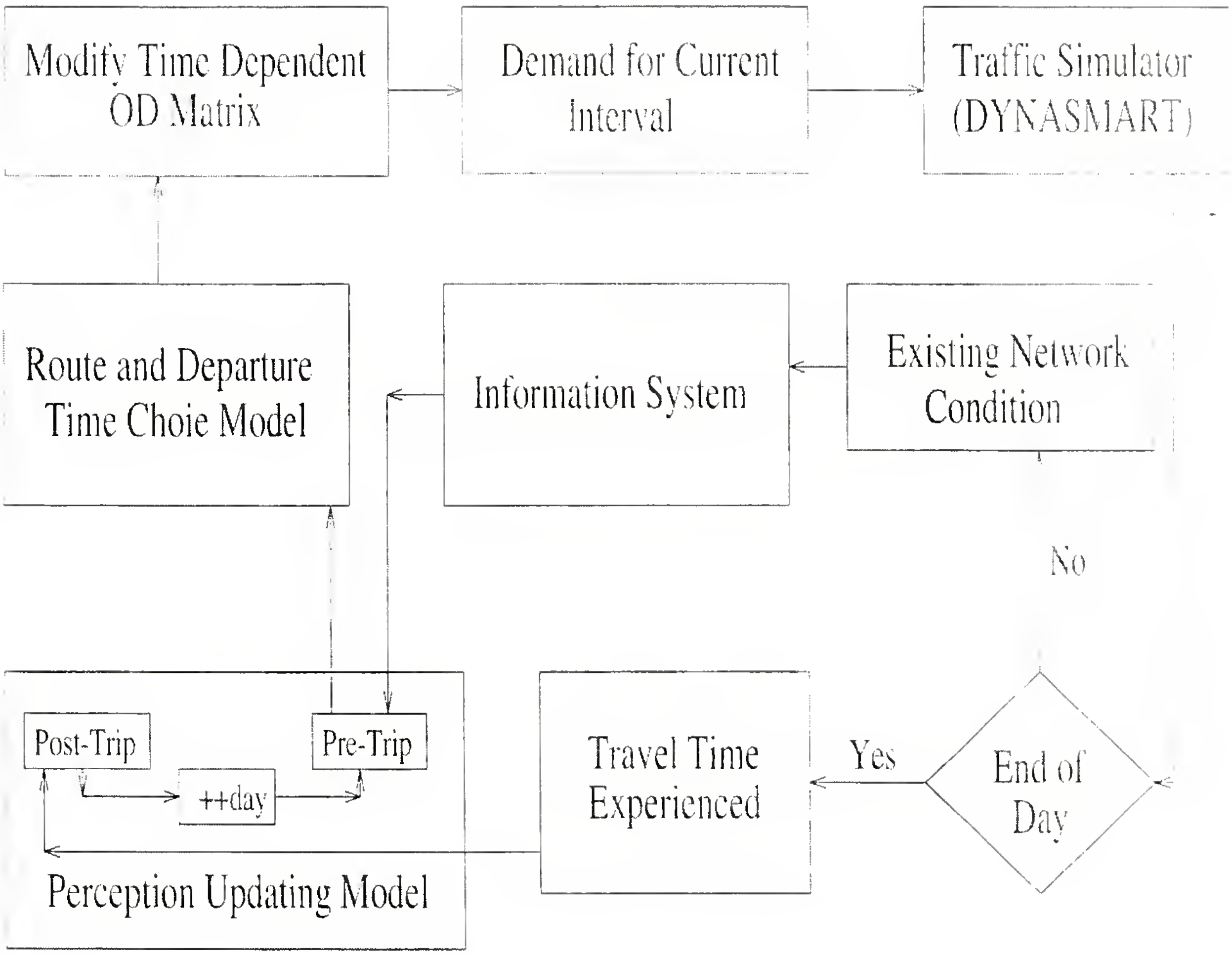

Figure 4.2 Simulation Framework

```
                initialize users' perception to information
            else: for all reasonable paths do
             1. Get existing network condition from DYNASMART;
             2. Generate error term in Eq. 4.2;
             3. Find perceived information time from Eq. 4.2;
             4. Pre-Trip Updating; Eq. 4 and 5;
             5. Generate Error term in Eq. 6;
             6. Find utility from Eq. 15;
             7. Find probabilities of path selection from Eq. 12;
             8. Generate a random number from U(0,1);
             9. Assign path; Simulate;
            10. Get experienced time from DYNASMART;
            11. Generate error term for Eq. 7;
            12. Find perceived experience;
            13. Post-trip updating;
            end else
        endfor
    endfor
endfor
```

Before presenting results from experiments it is worth describing some of the salient features of the algorithm. Also, this provides an overview of the experimental set-up.

1. *Change-in-network-structure* means any physical change in the network configuration e.g. capacity reduction, link closure etc. Note that when a physical change in the network takes place, users' historical perception is no more useful for estimating network condition. Therefore, when links are closed in the experiment users' perception is initialized to information.

2. Set of reasonable paths for a user consist of $k$ best path (based on $\tau$) for the user. $k$ in our experiments is 5.

3. Currently, the travel time provided to users is based on existing network condition. An ideal approach would be to provide information based on predicted network condition. We also propose an approach for modifying the travel time based on existing network condition in order to provide a more accurate information.

4. Drivers' trust on ATIS is modeled through the variance of the error term generated in step 2. The relative importance of experience in updating travel time perception is modeled by the variance of the error term generated in step 11. Drivers' confidence in travel time estimates is obtained in step 4. Note that drivers' confidence is used for finding perceived travel time and hence utility. Thus we explicitly account for drivers' confidence (in their travel time estimates) in estimating choice probabilities.

Next, we describe some preliminary results from three experiments. All the experiments are based on the algorithm described above. Information is provided to every user on day 1 and whenever *day-to-day* dynamics are initiated. In all the experiments, *day-to-day* dynamics are initiated on day 3 (link closures) and day 7 (reopening of links). All the parameters for every user are kept same. Unless stated otherwise, best paths provided by information is based on existing network condition.

**Experiment 1** : Every user is provided with four shortest paths at the beginning of the trip. Four possible scenarios are evaluated. In the first scenario, no updating is performed. Users are simply assigned to the best path based on current traffic condition. In the second scenario, we assume only *pre-trip* updating. The third scenario is the other extreme which is the no-information case, i.e. only *post-trip* updating is performed. The fourth scenario lies between the second and the third. In the fourth scenario, all the drivers are assumed to have equal weights for both *pre-trip* and *post-trip* updating. The average travel times in the system corresponding to the

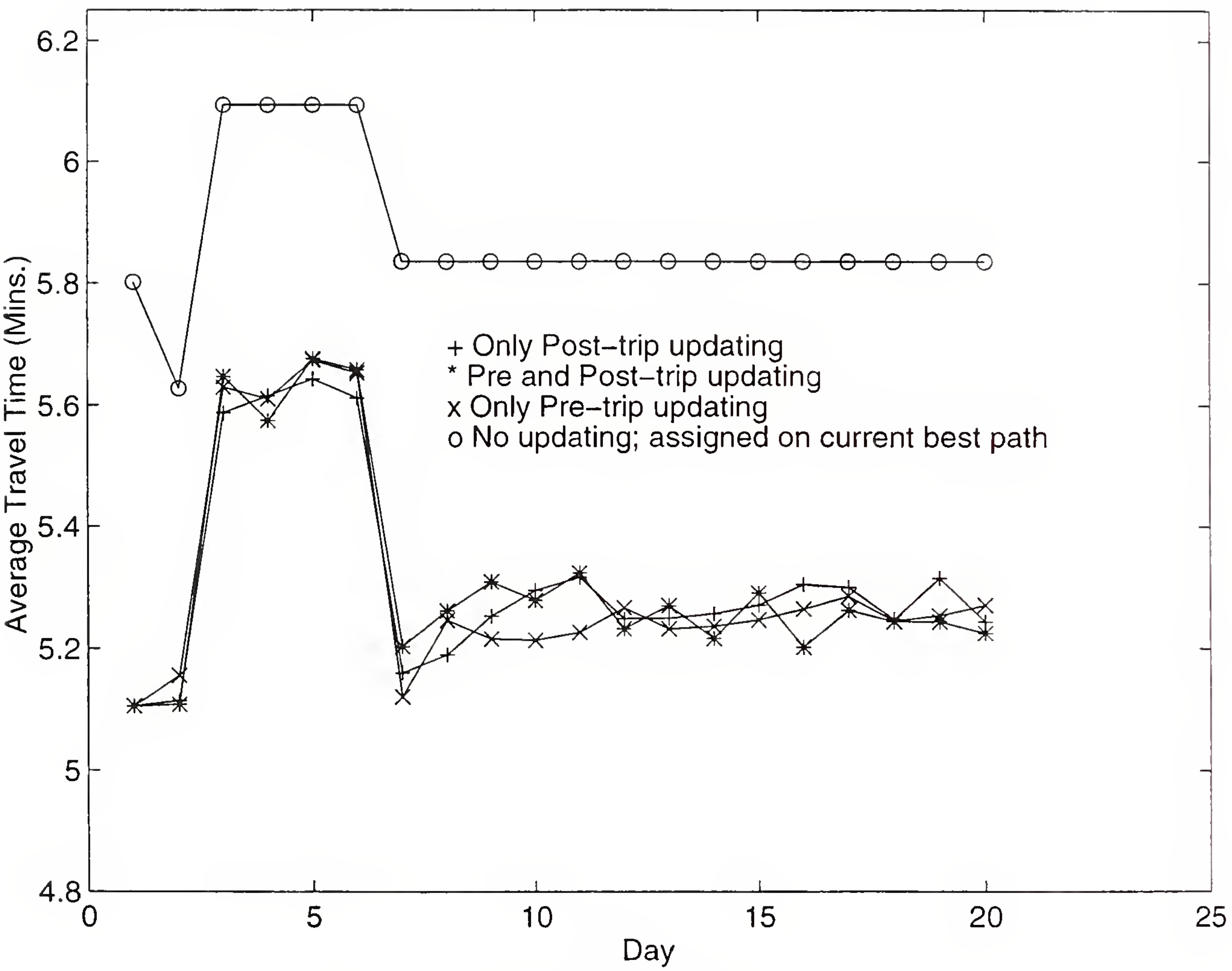

Figure 4.3 Various Updating Scenarios

four scenarios are presented in Figure 4.3. It is clear that the no-updating scenario performs worst. Given that path assignments in scenario 1 are based on current network conditions which are sub-optimal, it is possible for users to improve their travel times through learning from experience and information. The same information was provided in the other three scenarios but path choices were made based on a realistic user behavior model. Clearly, perception updating contributed to improving system performance. For the three cases involving perception updating, the average travel times are comparable. This result may be explained as follows : in all experiments users' knowledge was initialized by providing information on the four best paths. Thus, whether ATIS information was provided to them or not, users had sufficient knowledge of the travel times on several alternatives, especially because there was no departure time flexibility. In an attempt to improve on the quality of current traffic information, we modified the information travel time in the next experiment.

**Experiment 2:** The modified information travel time used in this experiment is given by :

$$T_{mod} = \mathrm{T} + \delta$$

The correction term $\delta$ is the average difference between the information travel time and the experienced travel time in the previous 5 days.

In this experiment, the average travel times corresponding to various levels of accessibility to ATIS are compared. Thus, the goal of this experiment is to analyze the impact of market penetration on system performance. Four scenarios are evaluated for this purpose. The first scenario is when all users have access (accessibility level 100%) to ATIS. The other three scenarios correspond to accessibility levels of 20% 15% and 10%. Modified information is provided to users and both *pre-trip* and *post-trip* updating is performed. The results are shown in Figure 4.4. The results clearly indicate that providing information to all users in the system gives rise to inferior system performance in comparison to the case when only a fraction of users are provided information. Further, average travel times corresponding to 10% and

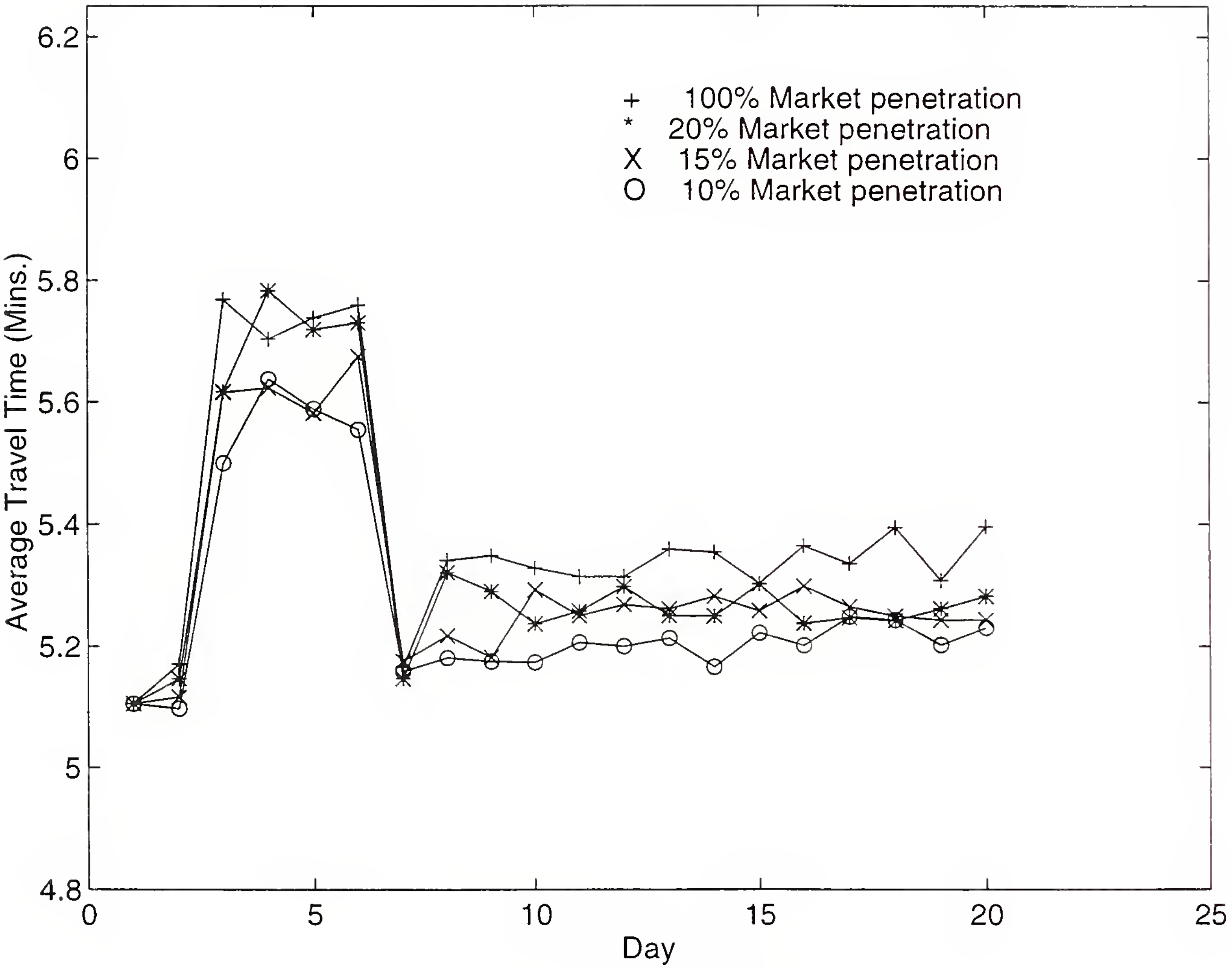

Figure 4.4 Test for Optimal Market Penetration

15% accessibility levels are lower than those corresponding to the 20% accessibility level. This suggests that the fraction of users who should be provided information in order to obtain optimal system performance lies somewhere between 10% and 20%. The result is consistent with previous studies [Mahmassani and Jayakrishnan 1991] that address the effect of information provision on system performance.

# 5. SUMMARY AND RECOMMENDATIONS

A literature review was conducted to identify various work zone traffic control management techniques and general guidelines were provided for the selection of appropriate strategies. It was recognized that more innovative techniques are needed to provide a safe and efficient traffic flow in and around the work zone because MUTCD guidelines alone may not be sufficient.

It was demonstrated through field data that the impact of work zones spread far beyond the affected roads, depending on the road network structure and O-D pattern. Therefore, for a realistic estimation of the change in traffic pattern on the network due to work zones, a network analysis approach is necessary. Using a static network equilibrium model, it was found that the delay on the work zone affected roads was only a part of the total network delay caused by work zones. Furthermore, a network analysis approach can be helpful in finding efficient schedules when more than one project are to be undertaken during one construction season. Findings from a network approach for work zone impact analysis includes:

- The current practice of corridor level work zone impact analysis is inadequate.
- Work zone impact on adjacent roads can be too significant to be ignored.
- The current practice of assuming a constant fraction for route diversion can substantially under(over) estimate the change in traffic pattern.
- In case of multiple work zones, it is possible to schedule them in such a way that the total additional user delay is reduced. An inefficient scheduling can lead to unnecessary hardships for road users.

It was noted in Chapter 3 that the total impact due to work zones consists of two parts: one when the network is in a transition period and the other is after the network reaches an equilibrium state. A dynamic model was presented in Chapter 4 for finding the traffic pattern during the transition period. Several models were presented in the the dynamic framework. One of the important features of the dynamic network model for *day-to-day* dynamics is that it explicitly accounts for drivers' learning. Note that drivers' learning can take place by several ways e.g. his/her own experience, information by ATIS or a media (for example TV, newspaper etc.). Findings from the dynamic modeling of work zone impacts are:

- If travelers systematically combine their past experiences to update perceptions, then historical information has little impact on network performance and traffic patterns.
- The number of departure time switchings is less than the number of route switchings.
- The utility function of the travel choice model has a very significant impact. In the simulation experiments, a higher penalty for schedule delay caused a higher average travel time, less switchings and more pronounced peaking. All three observations are self explanatory.
- In all experiments, the departure rate reached a steady state.
- The average travel time, the number of route and departure time switchings reached a stable state, albeit at different rates.

DYNASMART, a dynamic traffic simulator developed at the University of Texas at Austin for FHWA, is needed to run the software for dynamic analysis of work zones. DYNASMART is currently available for only research purposes. Therefore, this part of the research can be implemented in the field only after DYNASMART is available for public use.

In brief, this research provided a literature review on work zone traffic management. Work zones were considered at both the link level and the network level. Various traffic control strategies were evaluated at link levels, whereas, the travel impact of work zones was considered at the network level. Further, *day-to-day* dynamics caused by work zones were also studied at the network level.

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# APPENDIX

# APPENDIX
# USERS' MANUAL ON SOFTWARE FOR NETWORK LEVEL WORK ZONE DELAY ESTIMATION

This appendix is written to describe the software and its requirements. The description is organized as follows: first, two basic data structures for representing a transportation network in the form of directed graph are introduced. Forward start representation is used for the development of this software. Later, the input required by the software to predict traffic pattern on the network is described. The software needs this input in a particular format. The required format is described to help creating input file. An example of input file is also presented. After input description, a step-wise procedure is provided to run the software. Also, a sample run is demonstrated. the appendix is concluded with a discussion on possible uses of the software.

## A.1 Adjacency Matrix Representation

The connectivity of the network is represented by an N * N matrix where N is the number of nodes in the network. The matrix is called an adjacency matrix. Each entry of the adjacency matrix (say A) is either 0 or 1. Typically, an entry is 1 if nodes are connected and 0 otherwise. For example, if a link exists from node i to node j in the network then A(i,j) is 1. Links are described by an identification number, origin node, destination node and the travel time. Thus, corresponding to every link there are four entries. Adjacency matrix representation of the network is demonstrated with a simple network, that was used in Chapter 3 of this report (Figure 3.3). The adjacency matrix for the network in Figure 3.3 is given by:

$$A = \begin{pmatrix} 1 & 1 & 1 & 1 \\ 0 & 1 & 0 & 0 \\ 0 & 1 & 1 & 0 \\ 0 & 1 & 0 & 1 \end{pmatrix}$$

In the above matrix, A(1,3) is 1 but A(3,1) is 0, indicating that there exists a link from node 1 to node 3 but no link goes from 3 to 1. Thus, both one way as well as two way streets can be represented in this form.

**Link Identification:**

There is no strict rule for assigning identification numbers to links in the adjacency matrix representation. For example, in Fig 4.3, link going from 1 to 3 can be numbered as 1 or link going from 3 to 2 can be numbered as 1 or for that matter any link can be numbered as 1. However, every link should have a unique identification number (called link number) associated with it. One possible link identification scheme can be as follows:

| $Link-number$ | $From-node$ | $To-node$ | $Travel-time$ |
|---|---|---|---|
| 2 | 3 | 2 | $t_2$ |
| 3 | 1 | 4 | $t_3$ |
| 4 | 4 | 2 | $t_4$ |
| 5 | 1 | 3 | $t_5$ |

The main disadvantage of this representation is that it requires $N^2$ spaces for memory, independent of the number of links in the network. Note that transportation networks are normally sparse (ratio of number of links to number of nodes not too high) and hence this representation may lead to much redundant memory spaces in the computer. However, simplicity of the adjacency matrix makes it preferable for the smaller network. A modified form of the adjacency matrix, which is often used to represent network, is adjacency list representation where links emanating from a node is stored in the form of a list. This avoids storage space for all the 0s in adjacency matrix. Next, we describe a more sophisticated data structure which not only occupies less memory in computer but is also efficient for the computer implementation of the shortest path algorithm.

## A.2 Forward Star Representation

Forward star is a very efficient data structure for representing network configuration, where links are numbered in an ordered fashion. They are sorted in such a way that all links emanating from the same node are stored adjacent to each other. Mathematically, for any two links $i->j$ and $k->l$, if $i<k=>$ link number of $i->j$ is less than that of $k->l$. Each link in the forward start representation is represented by only end node. A pointer is kept for each node, indicating the position of first link emanating from that node. The data structure will be clear by the following example.

**Example:** Forward star representation is demonstrated by the same example network (Fig. 4.3). Note that links are to be numbered according to the rules described above. Existing numbering scheme of links violates the requirement for forward star representation. One of the violations, for example, is link number 2 and link number 3. All links emanating from 1 should have been numbered before links emanating from other nodes. Thus, renumber links in the following way:[1]

| $Link-number$ | $From-node$ | $To-node$ |
|---|---|---|
| 1 | 1 | 2 |
| 2 | 1 | 3 |
| 3 | 1 | 4 |
| 4 | 3 | 2 |
| 5 | 4 | 2 |

---

[1] Links emanating from one node can be numbered in any order,e.g. link number 1 and 2 are interchangeable.

Two arrays are needed for the implementation of forward start form. One array, F, of size N (number of nodes) stores the identification number of the first emanating link from a node. Thus, F(i) indicates link number of the first link emanating from i. Second array, E, is of size M (number of links) and stores the end point of the link. Thus, E(i) stores the node number of head of link i. For the example network, F and E arrays are given by:

| $Farray$ | $Earray$ |
|---|---|
| $F(1) = 1$ | $E(1) = 2$ |
| $F(2) = 4$ | $E(2) = 3)$ |
| $F(3) = 4$ | $E(3) = 4$ |
| $F(4) = 5$ | $E(4) = 2$ |
| | $E(5) = 2$ |

Note that in the forward star form, all links emanating from a node are stored adjacent to each other and hence can be scanned efficiently. This makes the implementation of shortest path algorithm efficient. Finally, an array of size M is maintained to store travel time on each link.

### A.3 Input requirements for the software

Following input are needed for the software :

1. Network configuration: Links in the network should be numbered according to the rules described above for forward star form. The configuration needs to be coded in forward star form
2. Free flow travel time on each link (minutes)
3. Number of lanes in each link
4. OD matrix

The above input are sufficient to find traffic flow pattern (User Equilibrium flow) on the network. After getting the UE flow for original network, the work zone specification can be provided interactively. Next section describes how to create the input file in a format that is compatible with the requirement of the software.

## A.4 Creating input file

There are four sections in the input file:

**Head node and free flow travel time:** First, there are two entries for each link. First entry is an integer and indicates the head (forward end) node of the link and the second entry is the free flow travel time. After all the links are done, 0 and 0.0 are entered to send a signal that this part of the input is complete. Note that the head node information in this section of the input creates array E described above.

**Forward star form:** This part of the input creates array F. It consists of N + 1 (number of nodes in the network) entries where $i^{th}$ entry is the link number of the first link emanating from node i. $(N+1)^{th}$ entry is M + 1, where M is number of links in the network. $(N+1)^{th}$ entry is used for terminating this part of the input.

**Number of lanes:** After creating F array the next set of input is number of lanes for each link. So there are M (number of links) entries in this set of input. Software automatically computes N and M from the given data and hence they need not be specified explicitly. The next two entries in the input file are peak hour factor and growth factor.

**Trip table:** All that is needed after this point to complete the input requirements for the software is the trip table. Currently, the trip table is provided in the form of node-to-node demand. Three entries are needed for each pair of OD nodes. The first entry is origin node, the second one is destination node and the third entry is average annual daily traffic. Again, to send a signal that the OD matrix is complete three entries of 0 are given. This completes the input file.

## A.5 An example of the input file

The road network in Figure 3.1 was coded in the form of a directed network. A file "indy.net" is created from this network. This section describes the entries in this input file. First set of input in file "indy.net", as described in the previous section, consists of two entries for every link: the head node of the link and free the flow travel time (in minutes) on the link. For example, first line in the file "indy.net" indicates that the head of the first link is node number 7 and the free flow travel time is 0.3 minutes. There are 137 links and 64 nodes in the network in Figure 3.1. Therefore, the first set of the input consists of 137 * 2 entries. After the head node and the free flow travel time are entered for each link, there are two entries, 0 and 0.0 respectively. These two entries are used to send a signal to the software that this set of input is completed. The next set of input in the file, 1 2 4 6 8 .... 132 135 138, describes the forward star form of the network. For example, the first entry is 1 which indicates that the first link emanating from 1 is numbered 1. Similarly,the third entry in this set of input is 4 indicating that the link number of the first link emanating from node 3 is 4. Note that there are 65 entries in this set of input. The last entry, 138, is greater than the total number of links in the network. This number is used just for indicating that this part of the input is complete. When a new input file is created, one must make sure that there are N + 1 entries in this part of the input and $(N+1)^{th}$ entry is M + 1. The next set of input consists of M (137 in this case) number of integers, each integer indicates the number of lane on that link. For example, the first three entries are 1, 3 and 1, indicating that number of lanes on link number 1, 2 and 3 are 1, 3 and 1, respectively. No terminal signal (like 0 or 0.0) is needed in this part. The next two entries in the input file is the peak hour factor and the growth factor. They are 0.11 and 1.0 respectively. The growth factor is useful to analyze the impact of work zones in future. Finally, the input file is completed with the description of the trip table. There is no restriction on the number of OD pairs in the software. Corresponding to each OD pair three items are needed: node number of origin, node number of destination and number of trips between origin and destination. For example, the first line in this part of the input file is 2 61 22892, indicating that the number of trips from node 2 to node 61 is 22892. Again three entries of 0 are given to indicate that the trip table is complete.

## A.6 Description and step-wise demonstration of the computer program

A user friendly computer program is written to evaluate the network level delay due to one or more work zones. The program is written in C language and can be run on PC 386 and higher as well as on any Unix based Workstation. A C compiler is needed if any modification is done in the source code. Overall, the program is well structured and hence a possible modification of the program should not be difficult.

**Step-wise demonstration of the software:**

- **Step 1 Graph representation:** Represent the given road network in the form of nodes and links. Figure A.1 represents a part of the road network in Figure 3.1. Roads that are represented in Figure A.1 are:
  I-70: East(Nodes: 2-4-27-34-36-40-42-) and West (Nodes: -41-39-35-33-3-1-)
  Lynhurst: North(Nodes: 28-27-26-25) and South (Nodes: 25-26-27-28)
  Holt: North (45-44-43-38-37) and South (Nodes: 37-38-43-44)
  Washington: East (Nodes: 18-20-25-37) and West (Nodes: 37-25-20-18)
  Airport Ex: East (Nodes: 9-12-26-30) and West (Nodes: 29-26-11-10)
  I-465: North (Nodes: 51-6-8-14-16-22) and South (Nodes: 23-21-15-13-7-5-51)
  Note that roads are divided into number of segments. Furthermore, some cross points where there are exit and entry ramps are divided into number of nodes. This kind of representation of road network helps in analyzing the impact of ramp closures[2].

- **Step 2 Link and node number:** Assign an identification number to each node in step 1. There is no prescribed rule for numbering nodes. After all the

---

[2] for clarity of graph, ramps are not shown

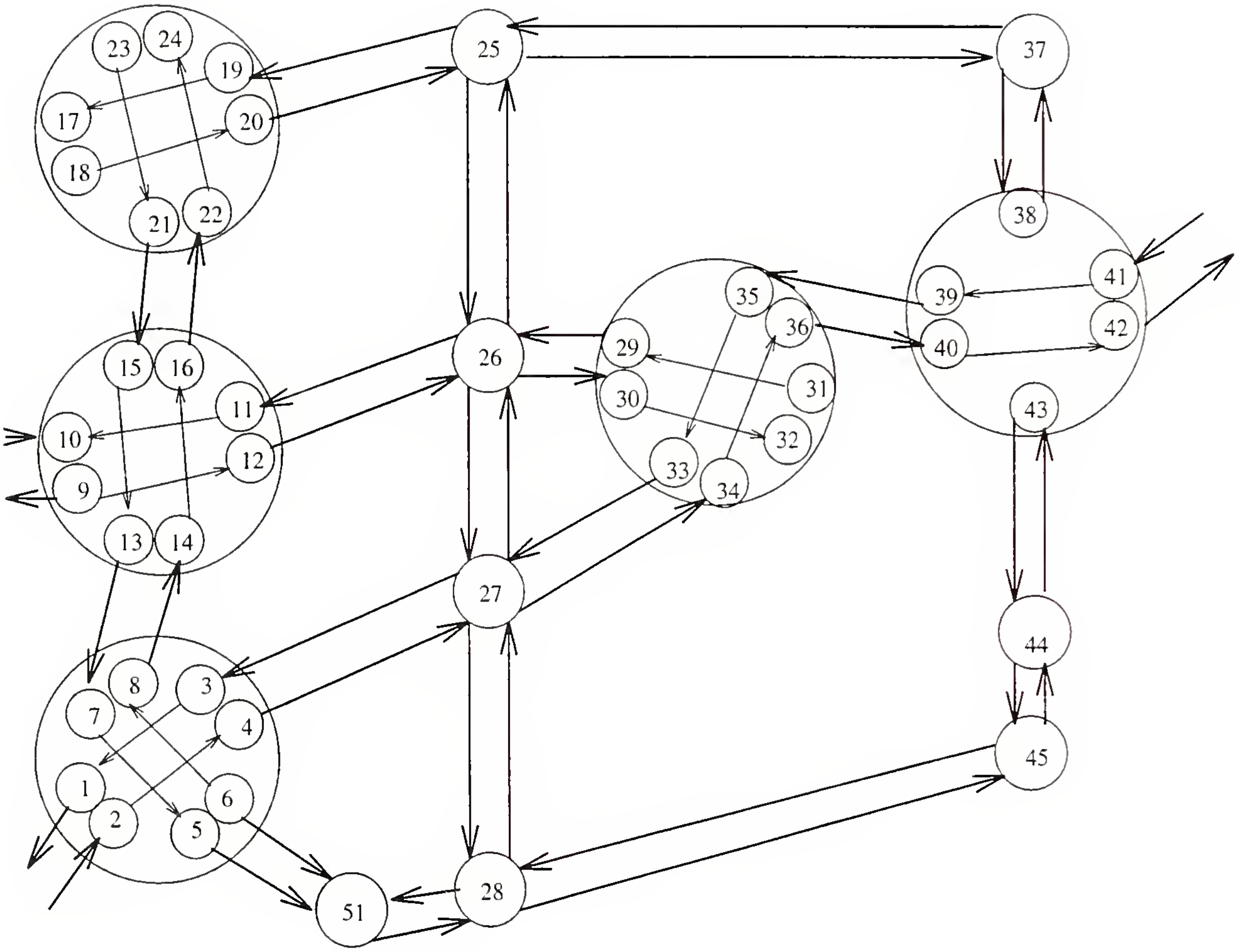

Figure A.1 Graph Representation of Road Network nodes are assigned a unique number, assign an identification number to each link in a manner which is compatible with forward star form (described above).

- **Step 3 Prepare input file:** By now, one has all the input that are required for running the computer program. Create an ASCII file with an editor (e.g. vi in Unix or edit in DOS) and follow the format described above for input file. One can give any desired name to the input file.
- **Step 4 Run the program:** Source code of the computer program is provided to facilitate the modification and execution. The name of the main executable file is "proj. c." Thus, the first step towards running the program is to compile "proj. c" with a C/C++ compiler. After "proj. c" is compiled, write the name of the executable file and the software will ask the name of the input file and the output file. When the name of the input file and the output file are provided, the software automatically creates an output file (with the given name) which contains traffic flow and travel time on each link, as well as the total travel time (in minutes) in the entire network without any work zone.
- **Step 5 Work zone analysis:** The information regarding work zones is given interactively. Once software calculates the network traffic pattern without work zones, it asks for the type and location of work zones. There are several options available from the software at this point. For example, typing 1 at this point allows the user to add roads in the network, typing 2 allows the user to close roads, and option 3 allows the user to change the number of lanes. The location of a work zone is specified in terms of what link number the work zone(s) is/are located. After work zone descriptions are entered, the software generates all the possible combinations (with not more than two work zones at a time) of work zones and provide traffic flow, travel time, and additional delay due to work zones corresponding to each combination. For example, if link 1, 2, and 3 are to be closed, then the software provides traffic pattern resulting from closing 1,2, and 3; 1 and 2; 1 and 3; and 2 and 3. This will assist planners in effective scheduling of road closures.

### A.6.1 Running Software

A sample run of the software is demonstrated in this section. Since input file is discussed in detail in previous sections, the focus here is on running the software and getting output. Road network in Figure 3.1 is used for this demonstration. OD matrices used here is based on a previous INDOT study (Boruff 1993). Input file for this demonstration is "indy.net". In the following, statements starting with > is input provided by software user. Comments are within /* and */ which explains input and output.

```
Write input file name
> indy.net
# of ORIGINS = 26
Travel Time on 1 is 0.300000
Travel Time on 2 is 0.000000
Travel Time on 3 is 0.200000
.............
/* intermediate results are deleted for brevity */
..................
Travel Time on 137 is 1.497047
FLOW on Link# (head 7) 1 is 0
FLOW on Link# (head 4) 2 is 2518
FLOW on Link# (head 5) 3 is 0
FLOW on Link# (head 1) 4 is 0
.................
/* intermediate results are deleted for brevity */
................
FLOW on Link# (head 63) 137 is 1649
Total cost = 169479.968750
/* Above output describes network traffic pattern without work zones. Next, software
```

```
asks for work zone description */
Select one of the following options
0 for Exiting from the program
1 for adding a road section
2 for closing a road section
3 for changing number of lanes
> 2
/* Option 2 indicates that link closure is to be studied */
Link # on which work is to be done
When you are done write 0
> 22 49 0
/* Above line of input indicates that Airport Exway, from I-465 to Lynhurst is closed
Next, software provides traffic pattern for three scenarios : Only link 22 is closed,
only 49 is closed and both are closed */
LINK closed is 22
/* Case 1: only 22 is closed */
# of ORIGINS = 26
Travel Time on 1 is 0.300000
Travel Time on 2 is 0.000000
........................
Travel Time on 137 is 1.497047
FLOW on Link# (head 7) 1 is 0
FLOW on Link# (head 4) 2 is 3294
.................................
FLOW on Link# (head 63) 137 is 1649
Change in cost= 4950.921875
/* Change in cost is additional delay due to work zones (in minutes) */
/* Case 2: links 22 and 49 closed */
Links closed are 22 49
```

```
# of ORIGINS = 26
Travel Time on 1 is 0.300000
Travel Time on 2 is 0.000000
..........................
Travel Time on 137 is 1.497047
FLOW on Link# (head 7) 1 is 0
FLOW on Link# (head 4) 2 is 3343
.......................
FLOW on Link# (head 63) 137 is 1649
Change in cost= 10401.593750
/* Case 3: Only link 49 is closed */
LINK closed is 49
# of ORIGINS = 26
Travel Time on 1 is 0.300000
Travel Time on 2 is 0.000000
.....................
Travel Time on 137 is 1.497047
FLOW on Link# (head 7) 1 is 0
FLOW on Link# (head 4) 2 is 2518
.......................
FLOW on Link# (head 63) 137 is 1649
Change in cost= 4095.250000
/* Session complete */
```

# APPENDIX
# ESTIMATING ORIGIN-DESTINATION TRIP TABLES

## B.1 Introduction

One of the major inputs to the software for calculating network level work zone impacts is the origin-destination (O-D) matrix. Traditional zone-to-zone O-D matrix is not suitable for the present study. This is due to the following reason: the network over which the impact of work zone is expected to be realized may consist of only a part of a zone. Therefore, a more detailed and a micro level O-D matrix is needed for the present study. In other words, zones have to be small enough so that the network which is to be analyzed should consist of several zones. At the same time zones should be large enough for computational and practical purposes. For example, each node of the network can not represent a zone. This appendix is written to assist INDOT personnel in preparing a realistic O-D table which can be used for evaluating the network level work zone impact with the software (discussed in Chapter 3).

There exists several methods for estimating the O-D matrix. Existing approaches can be classified into two broad categories, namely parameter calibration techniques and matrix estimation approaches. Parameter calibration techniques are based on gravity models, whereas matrix estimation methods estimate trip table by utilizing prior trip table and link volume data. Gravity models need zonal data for estimation of parameters. Since it is difficult to get zonal data in the context of small networks (like the one which was studied in Chapter 3) we suggest a matrix estimation method for O-D matrix estimation. Furthermore, one of the existing matrix estimation procedures also accounts for prior trip tables. This method estimates O-D based on link volumes only but has a tendency towards matching the prior trip table as closely as possible. Thus, this method has two-fold advantage: from the data collection point of view it does not need much effort for preparing a zonal data base and from the accuracy point of view the method does provide a refinement procedure if such zonal data are available or can be collected. Thus, the approach needs link count as an essential input whereas zonal data are optional input. Next we describe this procedure for estimating trip table for the software.

The approach assumes the existence of a user equilibrium. It should be noted that the software estimates the work zone impact based on a user equilibrium flow pattern. Thus, the O-D estimation procedure does not impose any further assumption on the model. Before going into the approach description, we first define the problem. The problem of trip estimation from traffic counts can be mathematically expressed as:

$$V_a = \sum_i \sum_j p^a_{i,j} x_{i,j} \qquad [B.1]$$

where: $V_a$ is the volume of traffic on link a.
$p^a_{i,j}$ is the proportion of trips between origin i and destination j.
$x_{i,j}$ is the number of trips between zone i and zone j.

Equation B.1 states that the volume of traffic on a link is equal to the sum of the number of trips between all those O-D pairs that use this link. $V_a$ needs to be observed in the field; $x_{i,j}$ is the number to be estimated and $p^a_{i,j}$ is a parameter which depends on travelers' route choice behavior. To determine this parameter the existence of an user equilibrium is assumed. The basic idea behind this approach is as follows:

The O-D matrix for a given network is obtained by minimizing a weighted sum of travel times of all travelers between all O-D pairs, subject to the constraints of observed link volumes. Various approaches exist for solving this problem. We suggest an approach [Sivanandan et al. 1994] which is based on linear programming. This does not necessarily require zonal data, but if such data are available they are used to guide the solution trip tables. First, we describe the approach to find O-D matrices from link counts only and then an extension will be provided to account for zonal data.

## B.2 A linear programming formulation

The problem is to determine $x_{i,j}$ (in Equation B.1) for all (i,j) $\in$ O-D. The number of trips between i and j is equal to the sum of trips on all paths connecting i and j and can be expressed as (path decomposition):

$$x_{i,j} = \sum_{k=1}^{n_{i,j}} x_{i,j}^{k} \qquad [B.2]$$

where: k in the above equation stands for $k^{th}$ path between an OD pair. Thus. Equation B.2 states that the number of trips between any O-D is equal to the sum of volumes on all links which are part of any path between the given O-D. Based on observed flows on links, the travel time on each link can be found from any link performance function (for example [BPR 1964]). Let $t_a$ represents travel time on link a. Note that under the user equilibrium condition, only those paths (between any O-D) will be used whose travel time is minimum. In other words, all used paths between any O-D will have equal travel time and no unused path can have less travel time then used paths. Thus, according to the Wardrop's principle, the equilibrium solution should be able to find a solution to Equation B.1, satisfying the following condition:

$x_{i,j}^{k} > 0$ If and only of $k_{th}$ path between i and j is the shortest path. This observation can be formulated into a linear program of the following structure:

$$Minimize \sum_{(i,j)\in OD} \sum_{k} t_{i,j}^{k} x_{i,j}^{k} \qquad [B.3]$$

$$Subject\ \ to \sum_{(i,j)\in OD} \sum_{k} p_{i,j}^{k} ti,j^{k} = x_{i,j} \qquad [B.4]$$

$$x_{i,j} => 0 \qquad [B.5]$$

where: $p_{i,j}^{k}$ indicates a link-path incidence relationship. $p_{i,j}^{k}$ for a link is 1 if $k_{th}$ path between i and j consists of this link; otherwise $p_{i,j}^{k}$ is 0 for that link,
$t_{i,j}^{k}$ is the travel time from zone i to zone j on $k^{th}$ path.

Any linear programming package, such as LINDO, can be used to solve the linear program described above. Note that the solution to the linear program (Equation B.3) gives OD matrices which can directly be used for preparing input file for the software. The most important reason for suggesting this method is that only link counts are needed for OD estimation. Also, the problem is formulated as a simple and solvable linear program.

### B.2.1 Extension of the approach to accommodate prior OD

As mentioned earlier, to estimate zonal OD data for this kind of small networks is very difficult and may not be feasible. Nevertheless. if local city planning offices or similar organizations have such data, they can be utilized within the framework of this approach. The basic idea behind incorporating prior OD into the linear program is to impose a penalty in the objective function (Equation B.3); the penalty is a function of the deviation of the O-D flow $x_{i,j}$ from the observed trip table. Thus, this penalty function guides the solution of the linear program to the observed OD. Other advantage of this approach is that partial prior O-D matrices can also be used to improve the O-D estimation. The resulting formulation is not shown here. It is a simple extension of Equation B.3 and can be found elsewhere [Sivanandan 94].

## B.3 Summary

Much research has done in the area of O-D estimation with their applicability varying from situation to situation. An approach, which is preferable from both the efficiency point of view as well as from the practical standpoint, to estimate O-D was described in this chapter. The approach can be presented in a step-wise fashion as follows:

Step 1: Represent the network in graph form (see Appendix A). Enumerate paths between all O-D pairs and determine $p_{i,j}^k$ for each link.
Step 2: Traffic volume on each link in the network should be observed. The reference period for data collection can be restricted to only peak hour traffic. No turning movements or intersection flows need to be observed.
Step 3: Based on observed link counts, calculate travel time on each link ($t_a$; for all a) through BPR link performance function (see Equation 3.1).
Step 4: When travel time on each link is known, find travel time on each path ($t_{i,j}^k$). This cane be done as follows: consider a path which is enumerated in Step 1; add the travel time for each link (obtained in Step 3) on this path, this gives the travel time.
Step 5: At this stage, all the necessary inputs are determined. Use a software to solve the linear program described above.

It is worth mentioning that there are several commercial software packages available for O-D estimation. One such software is SATURN. However, these software packages were not tested in the present study.

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