JOINT TRANSPORTATION RESEARCH PROGRAM
INDIANA DEPARTMENT OF TRANSPORTATION AND PURDUE UNIVERSITY

Network-Level Scheduling of Road Projects During the Construction Season Considering Network Connectivity

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SPR-4160 • Report Number: FHWA/IN/JTRP-2019/25 • DOI: 10.5703/1288284317105

RECOMMENDED CITATION

Woldemariam, W., Agyemang, A., Miralinaghi, M., Abraham, D. M., & Sinha, K. (2019). *Network-level scheduling of road projects during the construction season considering network connectivity* (Joint Transportation Research Program Publication No. FHWA/IN/JTRP-2019/25). West Lafayette, IN: Purdue University. https://doi.org/10.5703/1288284317105

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ACKNOWLEDGMENTS

The research team acknowledges the valuable support and feedback of the Study Advisory Committee members: Samy Noureldin (INDOT Research & Development Division); Louis Feagans, Joel Bump, and Kevin Munro (INDOT Headquarters); Eryn Fletcher (FHWA Indiana Division); Kelly Ellis (INDOT Fort Wayne Division); and Paul South (INDOT LaPorte Division). We also acknowledge the support provided by graduate student Abdullah J. Nafakh during the pilot study of this project.

Our thanks go to Qualtrics LLC as well, particularly Marian Strong, for administering our questionnaire survey in a timely manner and for sending emails and status updates regarding survey responses on a regular basis.

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NOTICE

TECHNICAL REPORT DOCUMENTATION PAGE

1. Report No. FHWA/IN/JTRP-2019/25	**2. Government Accession No.**	**3. Recipient's Catalog No.**
4. Title and Subtitle Network-Level Scheduling of Road Projects During the Construction Season Considering Network Connectivity		**5. Report Date** November 2019 **6. Performing Organization Code**
7. Author(s) Wubeshet B. Woldemariam, Augustine Agyemang, Mohammad Miralinaghi, Dulcy M. Abraham, and Kumares Sinha		**8. Performing Organization Report No.** FHWA/IN/JTRP-2019/25
9. Performing Organization Name and Address Joint Transportation Research Program Hall for Discovery and Learning Research (DLR), Suite 204 207 S. Martin Jischke Drive West Lafayette, IN 47907		**10. Work Unit No.** **11. Contract or Grant No.** SPR-4160
12. Sponsoring Agency Name and Address Indiana Department of Transportation (SPR) State Office Building 100 North Senate Avenue Indianapolis, IN 46204		**13. Type of Report and Period Covered** Final Report **14. Sponsoring Agency Code**
15. Supplementary Notes Conducted in cooperation with the U.S. Department of Transportation, Federal Highway Administration.		

16. Abstract

INDOT implements several hundred highway projects annually. One of the unintended (and adverse) consequences of road work is the establishment of work zones or full or partial closure of certain road links and the subsequent impairment of network connectivity during the construction season. The temporary reduction in network connectivity can lead to reduced mobility and decreased accessibility to businesses. The user costs incurred during highway construction can be significant, particularly where the affected links have very high traffic volumes or offer few opportunities to detour. Delay also inflicts costs on the non-traveling public, such as when it is necessary to reroute school buses in communities. Delay-related costs also impact the traveling public and shippers of raw materials and finished products. In some cases, construction-related disruptions cause adverse impacts on adjacent businesses. The main objective of this study was to develop a methodology and software tool that INDOT's Construction and Contracts Division could use to evaluate the systemic impacts of work zones on a network. The optimal schedules developed using the methodology were checked using data from past projects and was validated by comparing the reduction in user costs compared to actual past construction schedules. The case study results showed that, compared with INDOT's current plan, the developed framework would greatly reduce the user and business disruption costs associated with network-wide construction plans by providing optimal construction schedules. The developed network-level project scheduling methodology and software tool will help INDOT to plan various construction projects in a given district while considering user and business disruption costs.

17. Key Words project scheduling, user cost, business disruption cost, optimization		**18. Distribution Statement** No restrictions. This document is available through the National Technical Information Service, Springfield, VA 22161.	
19. Security Classif. (of this report) Unclassified	**20. Security Classif. (of this page)** Unclassified	**21. No. of Pages** 64 including appendices	**22. Price**

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

EXECUTIVE SUMMARY

Introduction

INDOT implements several hundred highway projects annually. One of the unintended (and adverse) consequences of road work is the establishment of work zones, or full or partial closure of certain road links, and the subsequent impairment of network connectivity during the construction season. The temporary reduction in network connectivity can lead to reduced mobility (resulting in higher road user costs in the form of delay, safety, and inconvenience) and decreased accessibility to businesses (resulting in driver frustration, business disruption, and reduced economic production and productivity). The user costs incurred during highway construction can be significant, particularly where the affected links have very high traffic volumes or offer few opportunities to detour. Delay also inflicts costs on the non-traveling public, such as when it is necessary to reroute school buses in communities. Delay-related costs also impact the traveling public and shippers of raw materials and finished products. In some cases, construction-related disruptions adversely impact adjacent businesses. In Lafayette, Indiana, for example, the local Journal and Courier newspaper (J&C, 2016) reported that the city's road projects not only increased worker commute times but also impaired access so severely that some companies were being put out of business. The Rohrman Group, a prominent local car dealer, threatened to sue INDOT, and Wabash National, a key manufacturing employer in the state, expressed serious concerns about the traffic situation (Bloyd, 2016). If this trend continues, such incidents can result in adverse public relations for INDOT. The Indianapolis Business Journal (IBJ, 2019) reported that a $15,000,000 road-widening project in Westfield, Indiana, would disrupt downtown businesses when the construction project commences in 2022. Addressing this problem must be preceded by the recognition that a given set of projects need to be implemented in a given construction season, and multiple combinations of projects must be scheduled for implementation at specific time slots. The challenge is to select the optimal combination of projects (start and end dates) within a specified construction season and to establish the criteria upon which INDOT can establish the most appropriate project schedules. Assuming that there is no difference in agency cost across the different candidate sets of project schedules, the user cost associated with each schedule can be used as a basis to identify the best set of schedules. User cost, in turn, is strongly associated with the network connectivity (or impairment thereof) associated with each schedule.

The main objective of this study was to develop a methodology that INDOT's Construction and Contracts Division can use to evaluate the systemic impact of work zones on a network. For this purpose, a software tool was developed that can (1) assess the user and community consequences of any given construction schedule in an area or region of interest and (2) optimally schedule a given number of projects within a specific construction season. This tool is expected to help INDOT quickly evaluate the network connectivity (and hence the user delay consequences) of alternative sets of project schedules.

Findings

Case studies were used in this project to illustrate the developed methodology. The optimal schedules developed using the methodology were checked using data from past projects and were validated by comparing the reduction in user costs to actual past construction schedules. The case study results showed that, compared with INDOT's current plan, the developed framework would greatly reduce the user and business disruption costs associated with network-wide road construction plans by providing optimal construction schedules.

Implementation

INDOT will be able to use the developed network-level project scheduling methodology and software tool to plan various road construction projects in a given district while considering user and business disruption costs. The developed tool has the potential to help INDOT avoid or minimize project implementation problems associated with users and businesses, such as user complaints associated with increased travel time and business complaints about the impact of road construction projects with work zones in the network.

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1. INTRODUCTION

Highway infrastructure is generally intended to enhance mobility and accessibility, and the numerous road projects carried out at various years and at various locations in the state, help the highway agency pursue this goal incrementally and successfully. However, implementation of infrastructure projects can increase road user and community costs if they are not planned and implemented in a systematic manner. This chapter presents the background information, motivation, objectives, and scope of the study.

1.1 Background Information

One of the unintended (and adverse) consequences of roadwork is the establishment of work zones or full or partial closure of certain road links and subsequent temporary impairment of the network connectivity during the road construction season. The temporary impairment of network connectivity can in turn lead to reduced mobility (resulting in higher user costs of delay, safety, and inconvenience) and decreased accessibility to business locations (resulting in driver frustration, business disruption, and reduced economic production and productivity).

The costs incurred by road users during highway construction and other projects can be very significant, particularly where the affected links have very high traffic volumes or little opportunity to detour. User-delay unit costs can range from \$5.08/hr to \$17.34/hr (2004 dollars) for passenger cars, and \$10.16/hr to \$66.86/hr (2004 dollars) for trucks (Sadavisan & Mallella, 2015). For example, if 20,000 drivers suffer 30 minutes of delay daily over a 90-day work zone duration, considering \$40/hr as the travel time cost, the overall user delay cost could be as high as \$36 million for that link alone. This estimate, however, does not include the costs of reduced safety, discomfort, and user inconvenience or lost business sales. The user cost is not only a metric for measuring the impacts on the roadway users but also serves as a surrogate for assessing the community costs (i.e., the impact of roadway construction/disruptions on the affected communities). Community costs could be expanded to go beyond the business costs to include noise costs, and how noise is generated by the traffic to mitigate the social and health problems associated with the traffic noise (Dare et al., 2012; Woldemariam et al., 2012a,b).

It is important to point out the difference between *ex ante* and *ex poste* studies that investigate the impact of highway project work zones. *Ex ante* studies are conducted before the project is implemented and often use network simulation or other modeling tools to predict the user delay. On the other hand, *ex poste* studies are performed when the road construction is taking place and the analyst measures, in real time, the delays encountered by the road users. The present study is intended to be an *ex ante* study. The scope is expected to cover city, county, region, or state levels.

1.2 Motivation for the Present Study

Delay-related costs impact the traveling public and shippers of raw materials and finished products. In the City of Lafayette, for example, the Journal and Courier (J&C, 2016) reported that the city's road projects not only increased worker commute times but also impaired access so severely that some companies were being put out of business. The Rohrman Group, a prominent local auto dealer threatened to sue INDOT, and Wabash National, a key manufacturing employer in the state, expressed serious concerns about the situation (Bloyd, 2016). If this ominous trend continues, it could cause adverse public relations for INDOT.

To confirm these assertions, the research team conducted pilot study interviews in West Lafayette, Indiana to collect feedback from businesses that were being affected by the State Street Redevelopment Project (Plenary Group, n.d.). Seventy-five percent (75%) of the businesses indicated that they received useful information and assistance from local authorities and contractors regarding the project before it began, during the road construction phase, and after the project was completed; while 25% of all the responding businesses indicated that they were somewhat informed, suggesting that they were not well aware of the impact of the project on their businesses. Furthermore, 75% of the surveyed businesses responded that they lost a significant portion of their customer base (15%–40%) due to the project. Only 25% of the surveyed businesses experienced an increase in customers due to the project.

These survey results confirmed one of the challenges to communities that INDOT faces when selecting the optimal combination of projects based solely on their start and end dates within a specified road construction season. Assuming that there is no difference in the agency cost across the different candidate sets of project schedules, the user cost associated with each schedule also needs to be part of the process of identifying the best set of schedules because the user cost is strongly associated with the associated network connectivity (or impairment thereof).

1.3 Study Objectives and Scope

The objective of this study was to develop a methodology that INDOT's Construction and Contracts Division can use to evaluate the systemic impacts of work zones on a network. Using the developed methodology, a spreadsheet and visualization tool was developed that INDOT can use to (1) assess the user and community consequences of any given road construction schedule in an area or region of interest and (2) optimally schedule a given number of projects within a specific road construction season.

Thus, the deliverables of this study will assist INDOT in quickly evaluating the network connectivity (and hence, the user delay consequences) of alternative sets of project schedules. Numerical and survey-based case studies were utilized to illustrate the developed methodology. The methodology was validated in terms of the reduction of user costs compared to actual past road construction schedules.

1.4 Report Organization

This report presents the framework for evaluating the impact of road projects on user cost and community cost at the network-level. The developed framework was demonstrated using a case study and the results of the case study were analyzed to show the importance of the developed framework.

Chapter 1 presents background information on INDOT infrastructure projects and associated user cost, the motivation, the objectives, and the scope of this study. Chapter 2 provides a literature review relevant to the research, such as the importance of network connectivity and accessibility, the economics of the disruption costs associated with road maintenance work zones, and how to manage the work zone, including project scheduling methods, in order to minimize such disruption costs. Chapter 3 provides a detailed description of the research methodology and discusses each component of the study framework as well as well as the methodology to quantify the impacts of road construction projects on businesses and road users. Chapter 4 presents a case study that was conducted to demonstrate the developed methodology and an optimal project scheduling plan using the developed framework and compares it with INDOT's current plan. Chapter 5 provides details on the development of spreadsheet and optimization tool, explains the user interface components, and provides guidance on preparing input data and interpreting outputs.

2. LITERATURE REVIEW

Maximizing the mobility of system users should be a high priority in any infrastructure and transportation project, and the selection of projects should take place with regard to their impacts on local areas (Sinha & Labi, 2011). The impacts of network-level scheduling of road maintenance and rehabilitation projects on user and business costs should be considered to optimally plan network-wide construction projects (Miralinaghi et al., 2019a; Miralinaghi et al., 2020b). This chapter presents a literature review on road maintenance and rehabilitation projects and associated concepts such as road disruption costs, work zone management, and road construction scheduling methods.

2.1 Road Disruption Costs

The economics of districts and regions and, from a broader perspective, the economics of a country, is associated with the efficiency of their transportation systems. Any disconnection in the network can cause millions of dollars in revenue losses; and road closures can cause serious conflicts of interest between the citizens and their governing agencies.

Salem et al. (2013) performed a comprehensive evaluation of user costs in pavement construction and rehabilitation using the initial pavement construction and maintenance cost as the baseline for finding the most economically efficient pavement rehabilitation. However, their approach is unable to provide the most cost-efficient list of projects since the user costs were not considered in the analysis.

User costs can be very significant in a pavement's life cycle, and hence should be considered in the decision-making process to ensure the selection of economically efficient projects.

Roadway maintenance, rehabilitation, and reconstruction activities impose a significant user cost to the administration, municipality, society, etc., especially in view of the increasingly congested roadways worldwide. Any changes in a road's pavement condition and consequently its capacity can cause changes in the road user costs. The cost of additional travel time or delay, crashes, operating vehicles in normal situations and in work zone conditions, and environmental costs, are among the most important user costs (Lewis, 1999; Reigle & Zaniewski, 2002). User costs are generally considered an aggregation of user delay costs, crash costs, and operating costs (Walls & Smith, 1998). Disruption to the normal flow of traffic is inevitable when work zones are created for pavement rehabilitation and construction. The necessity of creating a work zone is the main cause of delays in the traffic flow and thus is the major contributor to user costs. The reduced speed of vehicles required while going through or approaching a work zone and the time and energy consumption required to "catch up" to regular speed on the road are among the main causes of increased user costs (Jiang, 2001).

The traffic demand, frequency, time, and duration of work zones, the facility capacity, and the excess mileage driven due to road closures and detours are among the crucial factors which should be considered in the calculation of work zone user costs. These factors should be included in any life-cycle cost analysis (LCCA), which is the calculation of the initial life-cycle costs, the rehabilitation costs, and the incurred user costs. It has been reported that more than 80% of the projects related to highway infrastructure in the U.S perform LCCA; however, there is no promising evidence that user costs are included in the actual analyses (Chan et al., 2008). The LCCA including annual maintenance expenditures could be considered as part of the agency cost criteria in the problem of construction scheduling (Woldemariam et al., 2016). While most of the methods that are used to find the optimum usage of available funds for the repair and rehabilitation of infrastructure are agency-based life-cycle costs without consideration of user costs, the user costs are in fact known to play a significant role in projects where heavy traffic is involved. Therefore, instead of using absolute values for user costs, utilizing a weight factor is recommended (Hall et al., 2003). Quantitative analysis of user costs in the evaluation of pavement rehabilitation strategies was performed by the Ohio Department of Transportation (ODOT). A questionnaire survey of DOTs was used, where LCCA and the role of life-cycle cost in pavement rehabilitation strategy selection and the type of pavement rehabilitation alternatives was addressed. Among the 22 agencies that responded to the survey, 14 agencies did not consider user costs in their selection strategies. The ways that LCCA was considered in pavement selection also differed from state to state; for instance, in Michigan, LCC was the only factor which was implemented in the pavement rehabilitation selection strategy. Whereas, the following two-step process was employed in other states. The first step is to calculate the LCC of all the alternatives within which LCCAs are not included. The winning alternative is the one with the lowest LCC; however, if the differences are close to each other (according to the predetermined percentage values in Table 2.1), then the other factors should be analyzed subjectively, such as type of pavement in the vicinity of the project, constructability, weather, drainage, sub-grade, traffic, etc.

New Jersey and Indiana consider the weighted user costs in a separate category than agency costs in order to ensure that the agency costs are not overwhelmed by user costs. User costs are kept at 10% of agency costs (identified in an "ad hoc" manner) in some project evaluations by INDOT. New Jersey assumes user costs as 50%–75% of the agency costs in some project evaluations (Salem et al., 2013).

The user cost components are as follows: delay, travel time, and vehicle operating costs. Although the cost of congestion is a crucial element in the decision-making process, few agencies have monetized the cost since identifying universally acceptable values is a difficult task. U.S DOTs have strived to come up with a solution to consider unit values as shown in Table 2.2.

The discounted life-cycle costs calculations by Salem et al. (2013) for a specific project in Warren County in Ohio are presented in Table 2.3. The rubblize and roll strategy was chosen as the first-choice strategy, which includes rubblizing and rolling the existing concrete pavement (with an overlay of 12.5″ of asphalt concrete) followed by removing the existing asphalt. The user cost was calculated assuming that two out of three lanes were open to traffic, the closure hours were set for 8 PM to 6 AM, and the work zone capacity was considered to be 1,390 vehicles per lane per hour.

TABLE 2.1
Predetermined Percentage Values for LCCs for Pavement Alternatives

State	Percentage Values
Michigan	N/A
Indiana, Ohio, and Colorado	10
Washington and Maryland	15
Louisiana	20

TABLE 2.2
Value of Travel Time ($/h)[1]

State	Reference Year	Personal Passenger Car Travel	Business Passenger Car Travel	Trucks
Colorado	1999	17	17	35
Indiana	2004	17	17	35
Louisiana	2005	14.83	23.75	28.58
Ohio	2006	17	17	31.50
Maryland	1996	11.50	18.50	22.50
Michigan	1996	14.83	14.83	26.17
New Jersey	2006	15.21	15.21	25.35
Washington	1996	10–13	10–13	17–24

[1]Adopted from Salem et al., 2013.

TABLE 2.3
Life-Cycle Cost Calculations for a Specific Project in Warren County in Ohio

Activity		Rubblize and Roll ($)	Unbonded Concrete Overlay ($)	Flexible Replacement ($)	Rigid Replacement ($)
Discounted User Costs	Initial Construction	7,707,717	4,817,323	10,177,180	8,689,890
	12 Years	246,461	—	246,461	—
	22 Years	3,829,717	3,101,531	3,829,717	3,101,531
	32 Years	—	5,904,234	—	5,904,234
	34 Years	2,098,638	—	2,098,638	—
	Total	*13,882,532*	*13,823,088*	*16,351,995*	*17,695,655*
LCC Without User Costs		23,115,293	26,014,438	27,543,667	34,823,591
LCC With User Costs		36,997,825	39,837,526	43,895,662	52,519,246

2.2 Work Zone Management

A work zone is defined in the 2009 Manual on Uniform Traffic Control Devices (MUTCD) (FHWA, 2009) as an area on a highway with construction, maintenance, or utility work activities. Depending on the type of road maintenance or construction, different work zone management measures are employed. Temporary traffic control measures, such as the use of flaggers, traffic signals, barricades, temporary lane makings, temporary constructed lanes, may be used depending on the type of work.

It is essential to carefully estimate the capacity of a work zone to enable the proper work zone TTC measures to be put in place. Several attempts were made in the past literature to capture capacities using different methodologies. Krammes and Lopez (1994) proposed a base capacity value of 1,600 pcphpl for all short-term freeway lane closure configurations after examining the capacity counts at 33 different work zones on freeways in Texas involving five different lane closure configurations. Using non-linear speed-density models, Racha et al. (2008) calculated work zone capacities on two-lane roads when one of the lanes was closed for short-term construction work (less than 24 hours).

Edara et al. (2012) conducted a study on four different I-70 work zones in urban Columbus, Ohio in an attempt to show the variability of capacity based on various methodologies, such as the HCM method, and also conducted a survey of U.S DOTs in order to compare the values obtained for the research with the values they used. Capacity values were computed under 15-minute saturated flow, 85th percentile flows, and cumulative curve flows (pre-queue discharge flow and queue discharge flow). Since no pre-queue discharge flows were recorded in their study, they reported average capacities of 1,149; 1,267; and 1,301 vphpl for QDF, 85th percentile flow, and 15-minute sustained flow, respectively. The authors concluded that the capacity values used by U.S DOTs were reasonably higher than they obtained, and the definition of capacity by a particular DOT played a major role in the capacity value obtained. Ng (2012) proposed a stochastic mathematical programming work zone model for a two-lane to one-lane closure in order to simulate vehicles arriving at the work zone and to determine an efficient way to reduce work zone delay.

Contractors and agencies need to figure out how to assign tight construction spaces to the lanes and the shoulders, and how this road space allocation could influence (or could be influenced by) construction scheduling. For example, a lane and shoulder optimization framework developed by Labi et al. (2017) could be used for this purpose.

2.3 Optimization Approach in Road Construction Project Scheduling

Optimization methods aim to develop a schedule of road construction projects such that the planner achieves the predetermined goals of the minimization of total road construction and/or user costs. In the optimization approach, the two important factors are the horizon duration to complete the projects and the extent of the road construction zone (a single highway or network-wide), which usually depends on the type of road construction and the goal of the planner. Based on these factors, the literature can be classified in two contexts: operation and planning.

2.3.1 Operation Context

The associated literature in this context deals with road construction projects in a single work zone which must be finished within a short-term planning horizon (less than four to five hours). Based on each author's focus, these studies can be classified into the following two groups: dealing with work zone length or dealing with scheduling:

2.3.1.1 Work zone length. This class of studies investigated the optimal work zone length during a short-term horizon. McCoy, Pang, and Post (1980) proposed a framework to optimize the length of a work zone on a four-lane highway with a crossover to minimize the total cost, which included travel delay, safety, and traffic control costs based on 1979 data in Nebraska. Martinelli and Xu (1996) estimated the traffic delay due to freeway work zones where traffic delay included speed reduction and congestion delays and concluded that the speed reduction delay depended on the ADT and the percentage of trucks and further varied with the terrain condition. They demonstrated that congestion delay depends on the queue upstream of a work zone, which increased with the hourly volume and the truck percentage, and the optimal work zone length increased with an increase in the ADT and the length of the project.

McCoy and Mennega (1998) derived an optimal work zone length for a four-lane highway with a single-lane closure while aiming to minimize the user and traffic control costs. The traffic control costs included the maintenance, relocation, and installation and removal costs of traffic control devices. Schonfeld and Chien (1999) optimized the work zone length and traffic control cycles on a two-lane, two-way highway with one closed lane considering the minimization of both maintenance and user costs. They demonstrated that reducing the work zone length increased the discharge rate and reduced the user cost, however, the maintenance cost increased as well. They later optimized the work zone length for four-lane highways by minimizing the costs of users, accidents, and agency (Chien & Schonfeld, 2001).

2.3.1.2 Work zone scheduling. This class of studies dealt with scheduling the work zone construction over a short time horizon. Chien, Tang, and Schonfeld (2002) optimized the work zone lengths and schedules for a two-lane highway maintenance project by minimizing the agency and user costs, which included the labor and equipment idling costs, from which they derived the optimal maintenance duration and work breaks for controlling traffic passing through work zones. Jiang and Adeli (2003) optimized the work zone length and the start time of the work zone using average hourly traffic data for a multi-lane highway. By factoring the lane closures, darkness factor (for nighttime work), and seasonal variation travel demand, the total work zone cost, which included user delay, accidents, and maintenance costs, was minimized. Chen and Schonfeld (2004) developed an efficient scheduling and traffic control plan that minimized the total cost subject to the start time of project. They divided the project into smaller work zones and then determined the optimal start time and length for each work zone. Work pauses between different successive zones also were determined. Their study demonstrated that the optimal work zone schedule and length depends on the average work zone setup cost, idling time cost, and work zone duration.

Meng and Weng (2013) derived an optimal work zone strategy from the contractor's perspective with the goal of minimizing the total work zone maintenance cost. Their strategy was subject to two sets of constraints per predetermined thresholds regulated by the highway department: (1) the travel time of trips could not exceed a predetermined threshold, and (2) the queue lengths could not exceed predetermined thresholds. The authors proposed an efficient enumeration method to determine the optimal work zone length and project start time. Qian and Zhang (2013) assessed the effects of three alternative plans for a highway construction project in the Sacramento, California metropolitan area: (1) full closure, (2) partial closure with regular road construction methods, and (3) partial closure with efficient construction methods which could lead to less road construction, yet more expensive, than the second alternative. The durations were two, six, and four months in the first, second, and third methods, respectively. Their results indicated that the first alternative led to lower total delay in the traffic network because partial closure can lead to long queues in the traffic network. However, the second and third alternatives led to lower emissions and vehicle miles traveled.

2.3.1.3 Network-wide scheduling. This class of studies explored the optimal schedule of multiple short-term road construction projects in a traffic network. Ma et al. (2004) developed a hybrid genetic algorithm-traffic assignment-distributed simulation methodology to select an optimal lane closure schedule with the objective of reducing the average total delay of road users by scheduling lane closures for a few hours at a time on multiple links of the traffic network. Their numerical experiments illustrated that the planner needs to avoid lane closures during the evening to reduce the delay costs of road users. Cheu et al. (2004) proposed a hybrid genetic algorithm-simulation scheduling method for the planner who aims to schedule pavement maintenance projects spanning a few hours to minimize delays in a traffic network. They assumed that road users were not informed about road construction projects and hence did not change their routes. The all-or-nothing assignment was implemented to obtain the flows in each link. A microscopic simulation method was implemented to obtain travel times by capturing the queueing and lane changing behaviors of road users. Their numerical experiments indicated that the planner should not close any lanes during the morning and evening peak periods under the optimal schedule.

2.3.2 Planning Context

This class of studies aimed to develop optimal scheduling of projects over a long planning horizon. This context dates back to Morine and Esogbue (1971) when they investigated the optimal sequencing of water supply projects using dynamic programming. They proposed an efficient algorithm to solve the problem for large-scale models developed for urban areas. In this stream of research, Venezia (1977) implemented a dynamic programming technique to develop the optimal sequence of highway construction projects under demand uncertainty. The goal was to minimize the construction costs of projects assuming that the projects were independent. Further, they ignored congestion delay and obtained an optimal solution for an uncongested traffic network. To demonstrate the importance of considering interdependency among projects, Fernandez and Friesz (1981) used the optimal control theory to demonstrate that if the interdependency among different projects was not factored, the optimal sequence of projects would not be derived.

While early studies in this approach tackled the problem using either control theory or dynamic programming, Janson et al. (1991) developed a mathematical program to develop the selection and scheduling of route improvement strategies for U.S highway networks. The improvements were either to (1) make every link at least four lanes but without median or control access or (2) make every link at least four lanes with median and control access. They proposed two approaches with and without consideration of the interdependencies between route-improvement strategies. In the first approach, they formulated a multi-period planning problem where it was assumed that the link improvements were mutually exclusive. By recognizing the interdependency of different route improvements, they developed a heuristic method which ordered and scheduled different alternatives according to their benefit-cost ratios. They concluded that their heuristic method obtained a good solution for a simple highway network while the optimality of the solution could not be guaranteed in the proposed heuristics method.

Eldessouki et al. (1998) developed a mathematical program to investigate the optimal scheduling of improvement projects for highways where each project involved either increasing capacity or constructing highways. In this mathematical program, the goal was

TABLE 2.4
Summary of Literature Review

Context	Single/Multiple (Network-Wide) Work Zones	Author	Determination of:
Operation	Work zone length	McCoy, Pang, and Post (1980)	Travel delay, safety and traffic control costs
		Martinelli and Xu (1996)	Travel delay and traffic control costs
		McCoy and Mennega (1998)	User and traffic control costs
		Schonfeld and Chien (1999)	Maintenance and user costs
		Chien and Schonfeld (2001)	User, accidents, and agency costs
	Work zone scheduling	Chien, Tang, and Schofeld (2002)	Agency and user costs
		Jiang and Adeli (2003)	User delay, accident, and maintenance cost
		Chen and Schonfeld (2004)	User cost
		Meng and Weng (2013)	Total work zone maintenance cost
		Qian and Zhang (2013)	User delay cost
	Network-wide scheduling	Ma et al. (2004)	User delay
		Cheu et al. (2004)	User delay
Planning	Network-wide scheduling	Venezia (1977)	Total construction cost
		Fernandez and Friesz (1981)	Total construction cost
		Janson et al. (1991)	Total user delay
		Eldessouki et al. (1998)	Total travel time
		Hosseininasab and Shetab-Boushehri (2015)	Total travel time
		Shayanfar et al. (2016)	Total travel time
		Gong and Fan (2016)	Total travel time
		Kumar and Mishra (2018)	Road users' increased travel time

to minimize the total travel time over a few years and entailed the benefit estimation of each combination of projects in a traffic network in terms of the travel time savings considering the road construction cost. They concluded that if the planner scheduled projects given a priority solely based on the benefit-cost ratio, there would be higher delay for road users compared to system optimal road construction scheduling. Their enumeration technique to estimate the benefits of a combination of projects made the proposed algorithm computationally expensive. Jong and Schonfeld (2001) developed a genetic algorithm to schedule project investment planning problems for general purposes, such as highway infrastructure or waterway systems, without a specific structure for the objective function. They applied the model to a waterway system with 20 nodes and estimated the service delays under different combinations of projects using simulation. Later, Shayanfar et al. (2016) reformulated the objective function as the total system travel time and integrated it with the genetic algorithm proposed by Jong and Schonfeld (2001). They also investigated other metaheuristic methods such as Tabu Search and Simulated Annealing. Further, they factored the possibility that a candidate project may become economically unjustifiable after implementation of other projects in the same area. These metaheuristic methods were applied to the Sioux Falls, South Dakota network. While Tabu Search and Simulated Annealing outperformed the genetic algorithm in the initial iterations, their convergence rate to the optimal solution was lower compared to the genetic algorithm. Hence, they concluded that the genetic algorithm was the most efficient method for converging to the optimal solution in these types of problems.

Hosseininasab and Shetab-Boushehri (2015) integrated selection and scheduling projects into a single optimization problem where the objective was to minimize the total system travel cost in the traffic network. They factored the resources availability, budget, and technical limitation constraints and used the genetic algorithm to derive the near optimal solution for selecting and scheduling projects. Gong and Fan (2016) developed an optimization model and solved it using genetic algorithms to minimize the travel time delay in the system by deriving the optimal starting date of projects in the traffic network. These projects led to capacity reduction for different links in the traffic network. They assumed that all work zone activities needed to be completed by a predetermined deadline. Kumar and Mishra (2018) proposed a two-step methodology to optimally determine the sequence of projects. In the first step, they determined the optimal capacity improvement for a set of links. In the second step, the optimal sequence of projects was determined as the one which maximized the travel time savings of road users and minimized their increased travel time due to a road construction zone. They assumed that the road construction costs were equally distributable across periods. There are several other studies that also investigate the network-level impact of construction scheduling (Miralinaghi et al., 2019a; Miralinaghi & Peeta, 2020; Miralinaghi et al., 2020a). See Table 2.4 for a summary of the literature review.

2.4 Summary and Conclusions

Road maintenance and rehabilitation projects can significantly increase road disruption costs as far as road users and businesses; but as shown in this chapter, such impacts currently are not often considered at the project scheduling stage. Chapter 3 presents the approach developed in this study to attain a much needed methodology that incorporates user and business costs when planning transportation infrastructure projects at the network-level.

3. RESEARCH METHODOLOGY

The main research question that was considered in this study is as follows. How can we quantify the road user and business costs associated with project work zones at the network level for a given road construction season scheduling plan? The methodology developed in this study incorporates the impacts of road construction projects on road users and businesses and attempts to quantify the impacts considering various factors that affect the degree of the impact. In this chapter, this new methodology is discussed.

3.1 Optimization of Construction Scheduling to Minimize User and Business Impacts

Scheduling of transportation infrastructure projects has received significant attention in metropolitan areas. Although these projects are intended to enhance mobility and accessibility in metropolitan areas, they cannot be implemented without establishing short-term and/or long-term construction work zones with full or partial closure of roads in the network. Work zones have several negative impacts on users, such as increased traffic delays, and on the community when the safety of the traveling public and construction workers may be reduced. Road users experience significant traffic delays during their morning and evening peak period commutes. For example, the congestion delay cost rose to $115 billion in 2011 compared to $24 billion in 1982 (Sadasivan & Mallela, 2015). Based on a Federal Highway Administration (FHWA) 2004 report, 10% of traffic delay is due to highway construction work zones. Furthermore, in 2015, more than 96,000 accidents were reported to have occurred in the U.S due to construction work zones, which was a 42% increase since 2013 (National Highway Traffic Safety Administration, 2014). Therefore, to minimize the negative impacts associated with work zones, it is essential to develop a framework that helps minimize those impacts through scheduling construction work zones.

The associated literature in this context can be classified into two groups based on the duration of projects. The first group deals with scheduling projects for a few hours at a time (e.g., two hours) or few days (e.g., two to three days) (Cheu et al., 2004; Chien et al., 2002; Daganzo, 1985; Jiang & Adeli, 2003; McCoy et al., 1980; Meng & Weng, 2013; Schonfeld & Chien, 1999).

The second group deals with projects requiring a few months (e.g., two months). This group can be further classified into two subgroups depending on the goal of the central planner. The first subgroup schedules the projects to minimize the impact on users. While early studies in this field tackled the problem using either control theory or dynamic programming, Janson et al. (1991) formulated a mathematical program to schedule network improvement strategies for U.S highway networks with the goal of minimizing the total user delay. The network improvement strategies of this program are either to (1) make every link at least four lanes but without median or control access or (2) make every link at least four lanes with median and control access. The authors' heuristic method provides a good solution for a simple highway network with few highways and intersections while the optimality of the solution cannot be guaranteed.

3.1.1 Formulation of Optimal Project Scheduling Problem

In this study, the optimal project scheduling problem is formulated as a bi-level model. Several transportation problems are modeled using the bi-level model (Miralinaghi & Peeta, 2016; Miralinaghi & Peeta, 2018; Miralinaghi, 2018; Miralinaghi & Peeta, 2019; Miralinaghi et al., 2019b; Miralinaghi & Peeta, 2020). In the upper-level, the planner's goal is to schedule road construction work zones to minimize the impacts on both users and community. The goal, which is related to user impact, is to minimize the total user delays in the traffic network. When considering the impacts on the community, the planner must consider how road construction work zones could decrease the accessibility of road users to socio-economic locations, and subsequently can cause decreases in revenue (referred to as business disruption) to businesses residing in the work zone influence area. For example, the Indiana Department of Transportation (INDOT) implemented a $22 million project in Lafayette, Indiana that caused a significant reduction in revenue to some businesses along the road construction work zones. Consequently, it received significant opposition from neighborhood businesses. In the lower level of the formulation, road users make travel decisions regarding their choice of routes based on the road construction schedule derived in the upper level. Hence, this study developed a multi-objective optimization program for scheduling road construction work zones to minimize the user delays and business disruption costs.

In this new methodology, the planner divides the road construction season into multiple periods where each period is on the order of a few months. The projects are scheduled subject to budget constraints during the road construction season, which is on the order of a few years. It is assumed that the excess road construction funds in each period can be carried over to future periods. The set of projects includes road capacity expansion and rehabilitation projects where the project durations are on the order of a few months and must be completed by the end of the road construction season.

During the construction of road capacity expansion projects, the road capacities decrease and after completion of these projects, the capacities increase. For road rehabilitation projects, the road capacities decrease during road construction and return to normal condition after road construction. The travel demands and road capacities are assumed to be constant in each period, but they can vary across periods. The travel demands are assumed to be elastic and a decreasing function of travel delay. The road construction scheduling problem is a mixed-integer nonlinear program with complementarity constraints. This type of model is very difficult to solve because they are classified as NP-hard problems. Hence, a local decomposition method (Zhang et al., 2009) was chosen to efficiently solve the problem in finite iterations.

3.1.1.1 Upper-level model. In the upper-level of the bi-level optimization formulation, the planner decides about the optimal sequence of the road construction projects to minimize the weighted sum of the travel delay and businesses disruptions costs due to construction work zones during the construction season on the order of a few years (e.g., three years). To do so, the construction season is divided into τ periods on the order of a few months (e.g., three months). There are two sets of projects: (1) road capacity expansion to increase capacity and (2) road rehabilitation with identical road capacity after completing a project compared to the capacity before implementing the project. During these projects, there can be full closure lanes or partial closures with reduced capacity. The project durations are expressed in the number of periods. For example, if each period is one month and four months are required to complete a project, then the project is said to have four periods. These projects must be completed before the end of the road construction season. The construction budget B^t in each period is known *a priori* and can vary across periods. The leftover funds in each period can carry over to future periods. Descriptions of the mathematical formulation of the bi-level model is given in Appendix A.

3.1.1.2 Lower-level model. In the lower-level of the bi-level optimization formulation, road users make their travel decisions based on the sequence of projects scheduled in the upper level. The travel demand of each origin-destination (O-D) is assumed to be an elastic and decreasing function of the travel delay. Road users choose the routes with the minimum travel delays between each O-D pair. The mathematical formulation of the bi-level model is given in Appendix A.

3.1.1.3 Bi-level model. This section integrates the upper-level and lower-level models into the bi-level model. Figure 3.1 presents the structure of the road construction scheduling problem as a bi-level model. In the upper-level, the transportation planner determines the optimal schedule of the road construction projects based on the traffic network characteristics (e.g., free flow travel time and capacity), the construction budget, the projects' durations and the road users' decision-making behavior. Given the optimal project schedules in the lower-level model, road users make their travel decisions (i.e., whether to travel or not and route choice) based on the travel decisions of other road users, the network travel times, and the schedule of road construction projects obtained in the upper-level. The travel decisions are captured based on the user equilibrium condition which implies that road users have perfect information about the travel times on various routes in the traffic network. The perfect information of travel times can be gained by road users using Global Positioning System (GPS) devices and previous travel history. The mathematical formulation of the bi-level model is given in Appendix A.

3.1.1.4 Solution algorithm. This section discusses the development of the solution algorithm to solve the road construction scheduling problem. As presented in Section 3.1.1.3 and Appendix A, the proposed bi-level model for road construction scheduling contains integer variables and complementarity constraints. This

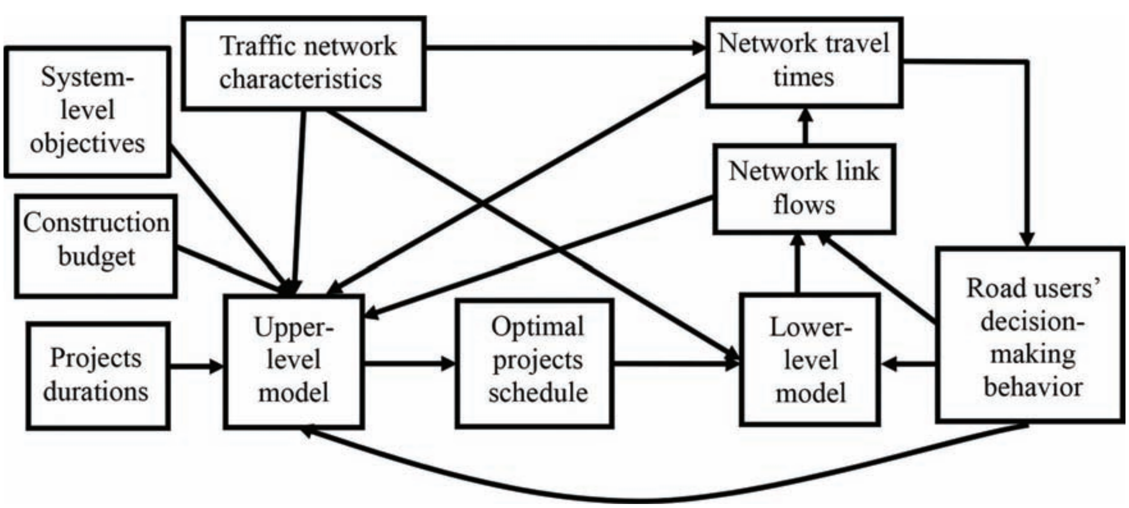


Figure 3.1 Structure of bi-level model.

mathematical program with complementarity constraints (MPCC) is very difficult to solve since it is nonconvex and violates the Mangasarian–Fromovitz constraint qualification (MFCQ) at every feasible point (Scholtes & Stöhr, 1999).

Various techniques have been proposed in the literature to solve MPCC, such as non-smooth penalization (Scholtes & Stöhr, 1999), smooth regularization (Bayındır et al., 2007), directly relaxing complementarity constraints and solving MPCC as nonlinear programs (Yin & Lawphongpanich, 2007). These techniques require approximation or relaxation of the complementarity constraints. However, the proposed MPCC ((6)-(25), (32)) consists of integer variables. Even with the use of relaxation methods, the MPCC is still a mixed-integer nonlinear variable, which is extremely difficult to solve. The mathematical formulation of the solution algorithm is given in Appendix A.

3.2 Summary and Conclusions

In this chapter, the research methodology was presented, and the mathematical formulation of the road construction project scheduling problem was described as a bi-level optimization problem. Chapter 4 presents the case study based on the developed methodology.

4. CASE STUDY

A case study was conducted to demonstrate the application of the developed methodology presented in Chapter 3. Three options for road construction plans were considered in the case study: (1) INDOT's current plan, (2) the base condition (no-construction) plan, and (3) the optimal plan. The optimal plan based on the developed methodology was compared with INDOT's current plan to evaluate its benefits over INDOT's current plan. A random plan also was considered to compare it with INDOT's current plan. The following sections present this case study, including the study area, the case study road network development, the survey administration, and the key observations from the case study.

4.1 Case Study

The case study centered on the City of Fort Wayne was conducted to demonstrate the application of the developed project scheduling framework. Figure 4.1 shows the current project types in the case study area, which include bridge projects, safety projects, road projects, and mobility projects. The Fort Wayne traffic network during the three-year 2017–2019 road construction seasons was considered. The construction season was divided into nine periods where the duration of each period was four months.

4.1.1 Location of Projects

A total of 32 projects were selected for the case study with 20 capacity expansion projects and 12 rehabilitation projects. The project types that were considered in the case study included bridge deck overlay and widening, bridge repair, bridge replacement, repair of pavement joints, new bridge construction, bridge painting, pavement preventive maintenance, and intersection improvement with added turn lanes.

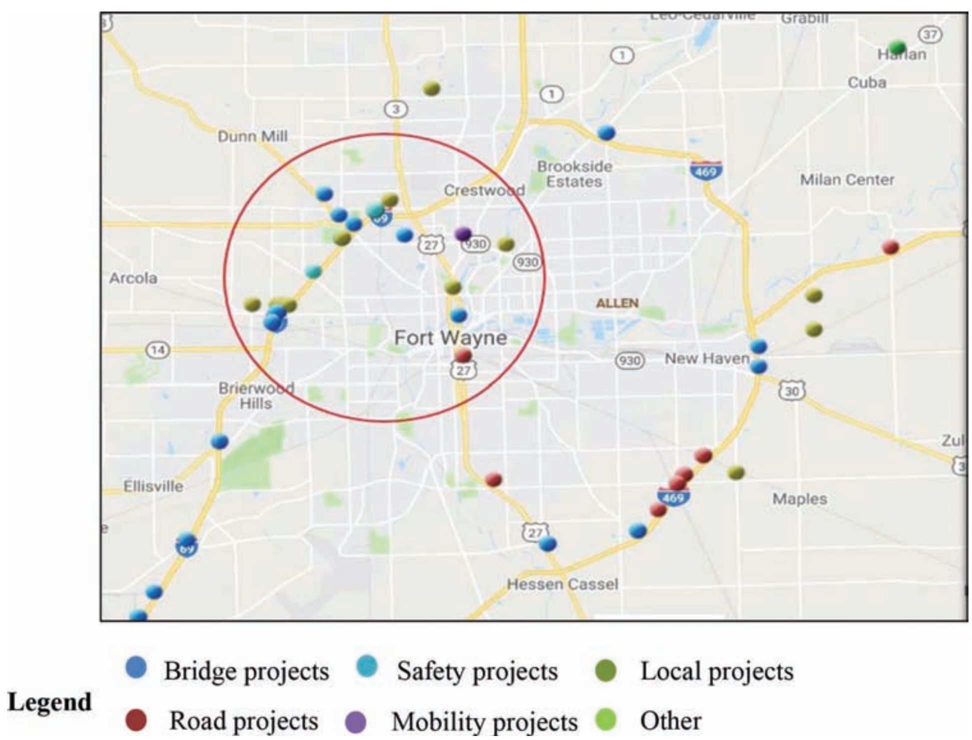


Figure 4.1 Current project types in the case study area.

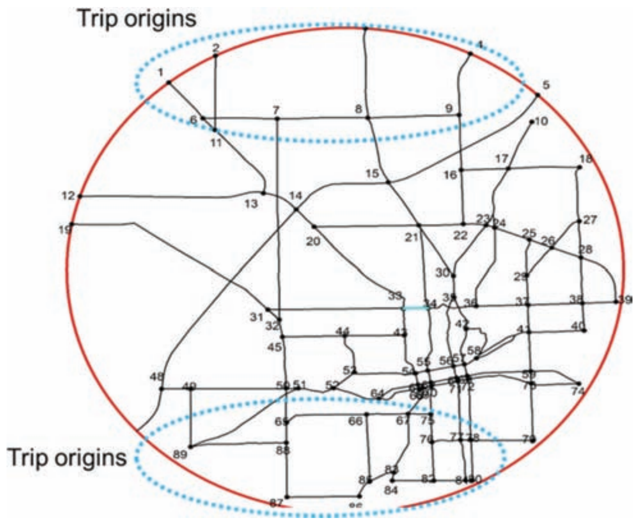


Figure 4.2 Case study network.

4.1.2 Road Network Development

The case study network is shown in Figure 4.2. The network contains 956 nodes and 252 links. The dotted regions show the trip origins that were assumed in the case study. It was assumed that the generated trips visited businesses located in the case study network. In practical cases, trips could be generated from each intersection point (which may represent signalized intersections, zones or regions). In this study, however, trips were assumed to be generated only from those intersection points located inside trip generation regions represented by the dotted regions in Figure 4.2.

4.1.3 Identification of Businesses

Seven businesses located in the study area were considered in the study network (Figure 4.3). In order to consider one of the worst case scenarios, it was assumed that 50% of the road users would seek to make a purchase at these businesses. In real situations, the percentage of business trips that are destined to a particular business area is determined at planning stage, i.e., at trip generation stage of the four-step travel demand modeling (de Dios Ortuzar & Willumsen, 2011). In the proof-of-concept study, the average expenditure of each customer was assumed to be $100 per trip.

4.1.4 Identification of Construction Projects

The road network for the case study was built using ArcGIS. This road network took into consideration only major roads; interstates, freeways, multi-lane highways, major collectors, and some local roads. Each link was given an ID and the characteristics associated with each link, such as length, number of lanes, capacity, and speed limit also were identified. The road lengths were calculated directly from ArcGIS. The capacities were also estimated from the Highway Capacity Manual. Finally, the number of lanes and speed limits were acquired through field inspection. A well-built map of the city road network provided the basis for all the necessary analysis to be conducted.

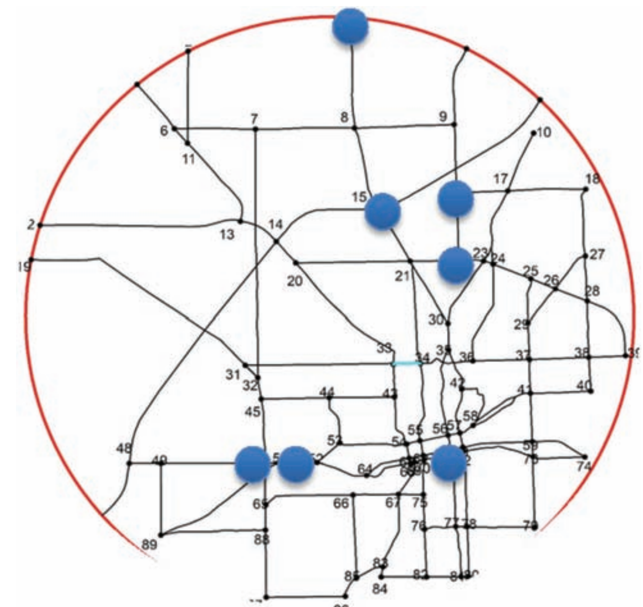


Figure 4.3 Location of businesses used in the case study.

Figure 4.4 shows the locations of road rehabilitation and capacity expansion projects in the case study, which were constructed on road links spatially scattered in the road network.

4.1.5 Questionnaire Survey

Human travel behavior may be influenced by the existence of a road work zone in a transportation network. Information on the travel behavior of road users in a given transportation network is very useful from a transportation planning perspective because it helps planners manage work zones considering how the road users could switch routes in a road network with work zones and affect link traffic volume, which may in turn affect revenues in nearby businesses.

The economic evaluation of highway projects should not be limited to the post-construction impacts but also to their during-implementation impacts as demonstrated by Alqadhi et al. (2018). Therefore, in this study, two surveys were conducted: a road user survey and a business survey. The main purpose of the road user survey was to gather information on how an individual road user's travel behavior is impacted by work zones. The main purpose of the business survey was to gather information about the impact of construction projects on various businesses in the study area. The survey was administered by Qualtrics LLC Company.

4.1.5.1 Road user survey. A survey was conducted in the study area to understand how road users respond to

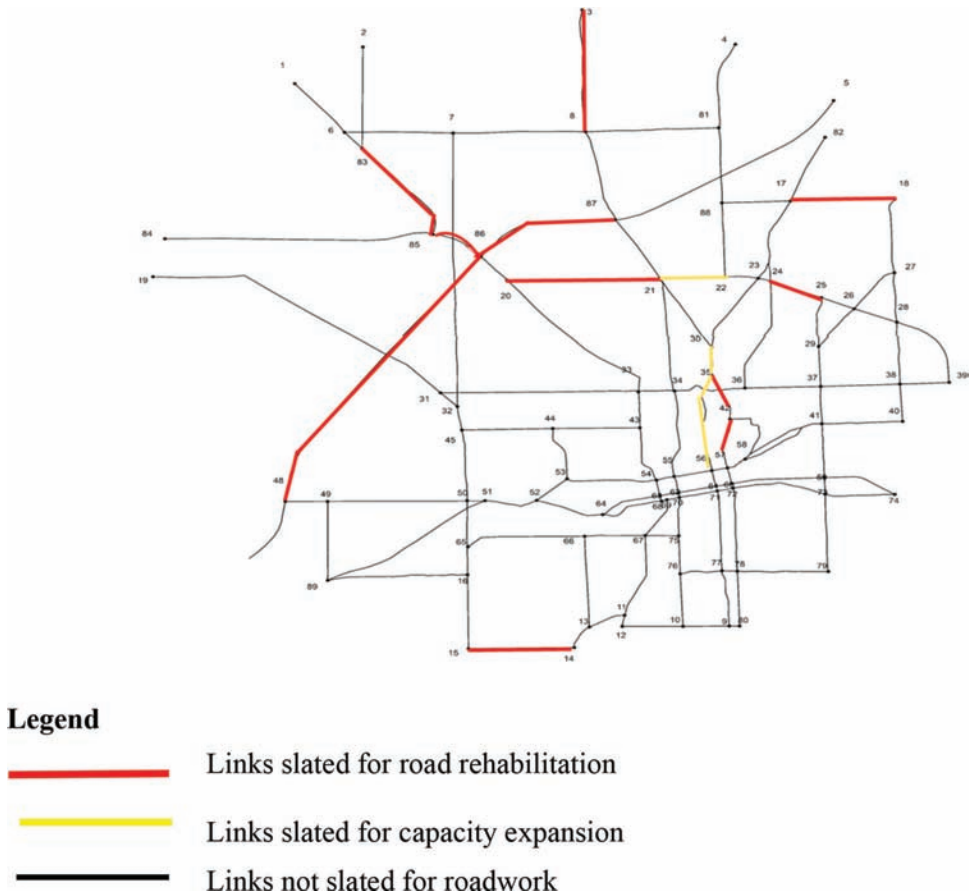


Figure 4.4 Road links slated for road rehabilitation and capacity expansion.

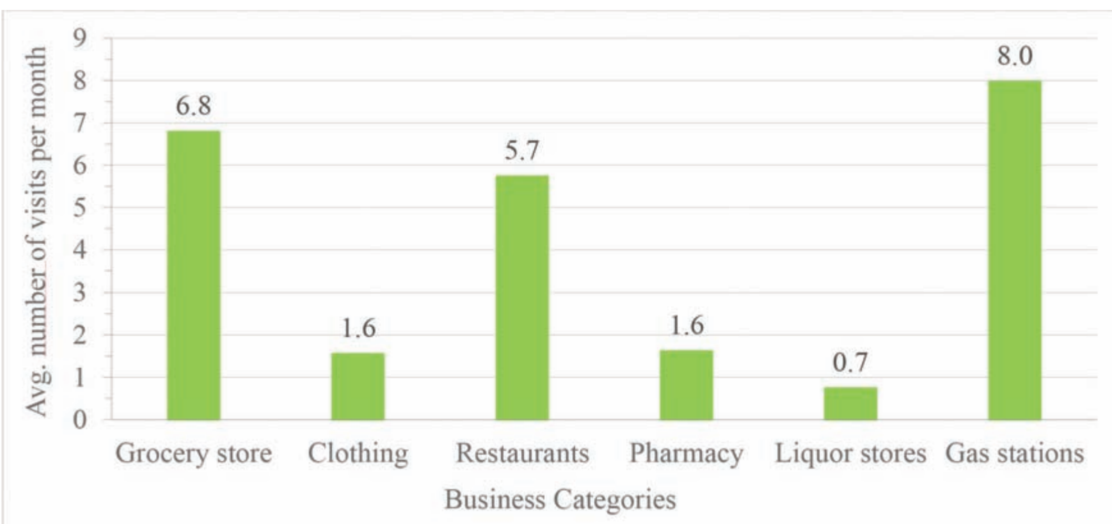


Figure 4.5 Frequency of visits to businesses in the study area.

the presence of work zones in their travel direction. This information was vital to quantifying the road user costs associated with avoiding work zones to reach destinations. A total of 400 road users who regularly traveled the case study network were surveyed.

Figure 4.5 shows the average number of visits per month by business category. Gas stations were the most visited business, followed by grocery stores and restaurants in the study area, and liquor store had the lowest average number of visits.

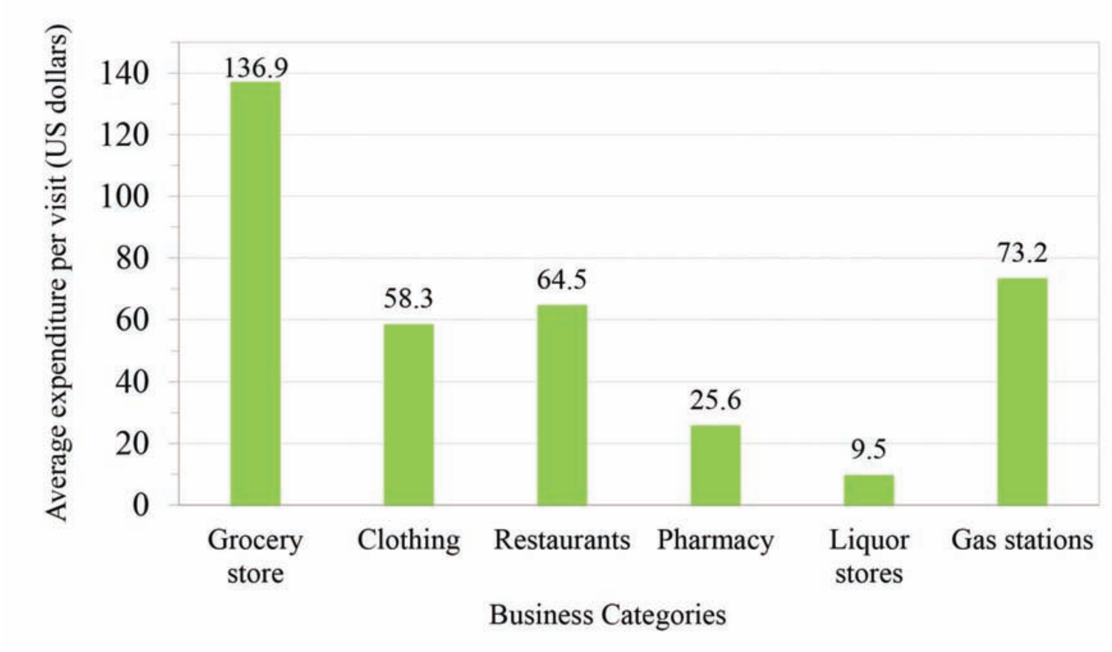


Figure 4.6 Average expenditure per visit to businesses in the study area.

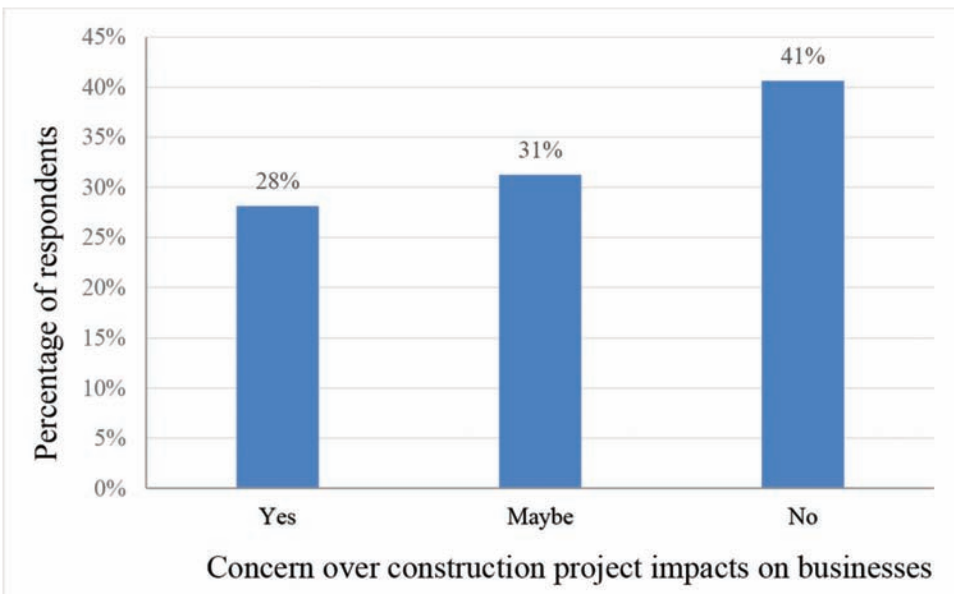


Figure 4.7 Level of concern of businesses on future impacts of construction projects in their business areas.

Figure 4.6 shows the average expenditure per visit to various business categories in the study area. Visitors spent the highest average expenditure per visit in grocery stores in the study area, followed by gas stations, restaurants, clothing stores, pharmacies, and liquor stores. Results such as shown in Figures 4.5 and 4.6 help to understand the degree to which these businesses could be affected if the road links are closed or the capacity is minimized due to work zones, and, thereby help in the appropriate scheduling of network-level construction projects.

4.1.5.2 Business survey. Twenty-five (25) privately-owned businesses located in the study area were surveyed to understand how work zones could impact them with respect to changing the number of customers, revenue, safety and comfort. A total of 28% of the businesses responded that they were concerned about the future impacts of road construction projects on their businesses. In addition, 31% of these businesses expressed concern about the impact of future construction projects on their businesses (Figure 4.7). These results in general show that the majority of the businesses (over 59%) felt that network-level projects should be scheduled and implemented in order to reduce the negative impacts on their businesses. All the surveyed businesses responded that they lost an average of 9% of their customers during the pre-construction period, 9.6% of their customers during the construction period, and 5.7% of their customers during the post-construction period.

The remaining business survey analysis results are provided in Appendix B. Figure B.1 shows that 16% of the surveyed businesses agreed that they experienced a change in revenue due to poor prior information about future construction activities. A total of 16% of businesses also agreed that they had to change the amount of investment to their businesses before the start of the road construction. Among the same set of respondents, 16% agreed that they experienced a change in the number of customers due to prior information about future construction activity. Even though these figures are not high, they show that businesses are concerned about the negative impacts of future construction activities on their businesses. The business owners were asked about their level of agreement on how INDOT's quality of communication regarding construction activities in their business areas affected their businesses (Figure B.2), and 9% of them responded that they agree that INDOT clearly communicated about utilities that would be affected and about the length and duration of construction projects. They also agreed that construction agency contact information was provided and that the contact person was quick to address their problems. Regarding current road construction projects that are underway in their business areas, 6% of the respondents strongly disagreed that the noise levels from the work zone were bearable and vehicle and pedestrian accesses were available to their businesses; 9% of them strongly disagreed that the road construction zones were safe to pass through; 28% of them experienced a change in revenue during the road construction period; 31% of them experienced a change in the number of customers and had to reduce their amount of investment to their business during the construction period, showing the impact of the construction activities on their businesses (Figure B.3).

The businesses were also asked about the impact of the road construction after its completion (Figure B.4). Nineteen percent (19%) of the businesses experienced a change in the number of customers after the completion of the road construction; 16% of them experienced a change in revenue and had to change in amount of investment to their businesses after the road construction was completed. As shown in Figure B.5, 83% of the businesses were concerned about safety when passing through work zones; 83% had concerns about noise levels in their business areas; 67% of them were concerned about vehicle parking space and vehicle access to their businesses; and 50% of them were concerned about pedestrian access to their businesses. Based on these survey results, it can be concluded that network-level road construction projects should be carefully planned to maximize safety, minimize noise levels, and ensure vehicle and pedestrian accessibilities to businesses.

4.1.6 Comparison of Project Scheduling Plans

INDOT's current project scheduling plan was compared to a random scheduling plan in order to evaluate INDOT's network-level project scheduling practices. Also, INDOT's current plan was compared with the optimal scheduling plan recommended by the developed framework. These comparisons were made considering both the travel cost to road users and the impacts of scheduling on businesses. INDOT does not conduct any construction project during the winter months (January through April). Therefore, for the case study, winter months (no construction) were assumed during the January–April time frame. Figure 4.8 shows the road construction projects that were implemented in the study area, which formed the basis for INDOT's current plan. In this project, the value of time was assumed to be equal to $15 per hour (U.S Department of Transportation, 2016). To understand the impact of road construction projects on business revenues, the traffic volumes in the traffic network in the base case were derived, assuming that no construction projects would be implemented over a three-year period. For the proof-of-concept study, the average expenditure of each customer at a business was assumed to be $100 per trip. The total business revenue over a three-year period without the road construction projects (the base case) was equal to $82,769,541.

4.1.6.1 INDOT's current plan. INDOT's current construction projects shown in Figure 4.8 were scheduled for implementation as shown in Figure 4.9. To understand the impacts on business revenue, the route choices of road users given the construction schedule were investigated using the methodology described in Appendix A. These road construction projects impacted the road users' choices and thereby affected the traffic volumes, travel times, and business revenues. For the proof-of-concept study, the average expenditure of each customer at a business was assumed to be $100 per trip. During the three-year period, the business revenue under INDOT's current plan was estimated to be equal to $80,580,879. The total system travel time was equal to 929,830 veh.hr during the three-year period; and by assuming the value of time equal to $15 per hour (U.S Department of Transportation, 2016), the equivalent road cost was estimated to be equal to $13,947,450. The total system road user cost under this plan was equal to $94,528,329.

4.1.6.2 Random project scheduling. To create a random plan, the start date of each project follows a discrete uniform distribution where all projects should start such that they are completed within the construction horizon. The only constraint on the start dates of projects was the infeasibility of conducting construction projects during January through April. For the

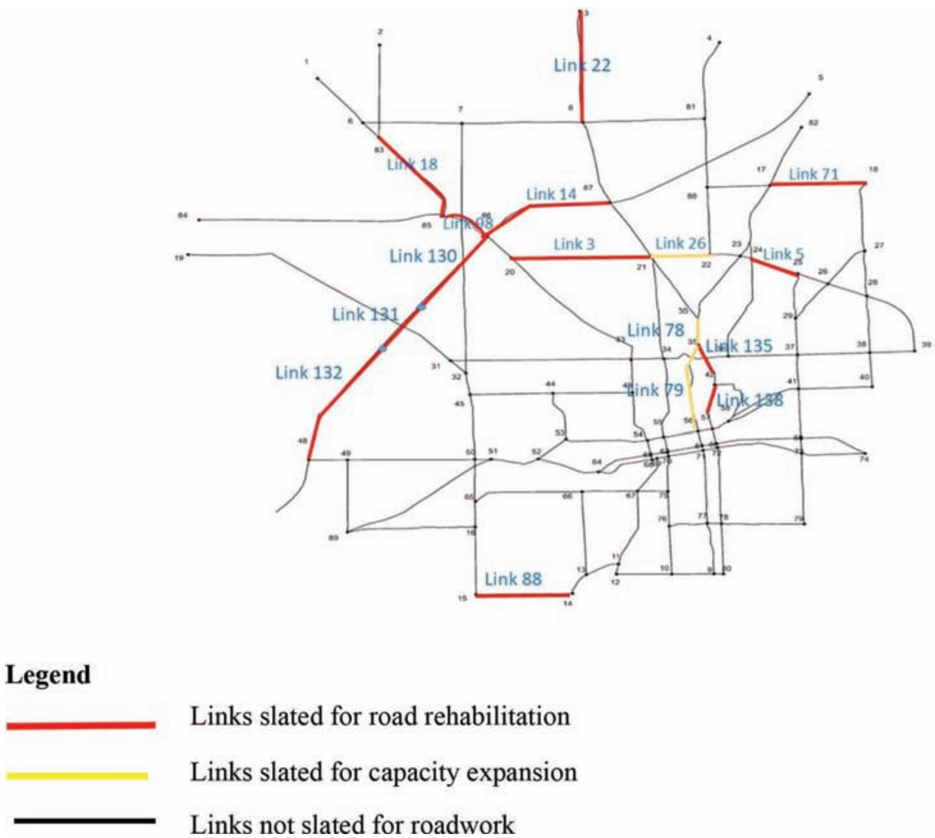
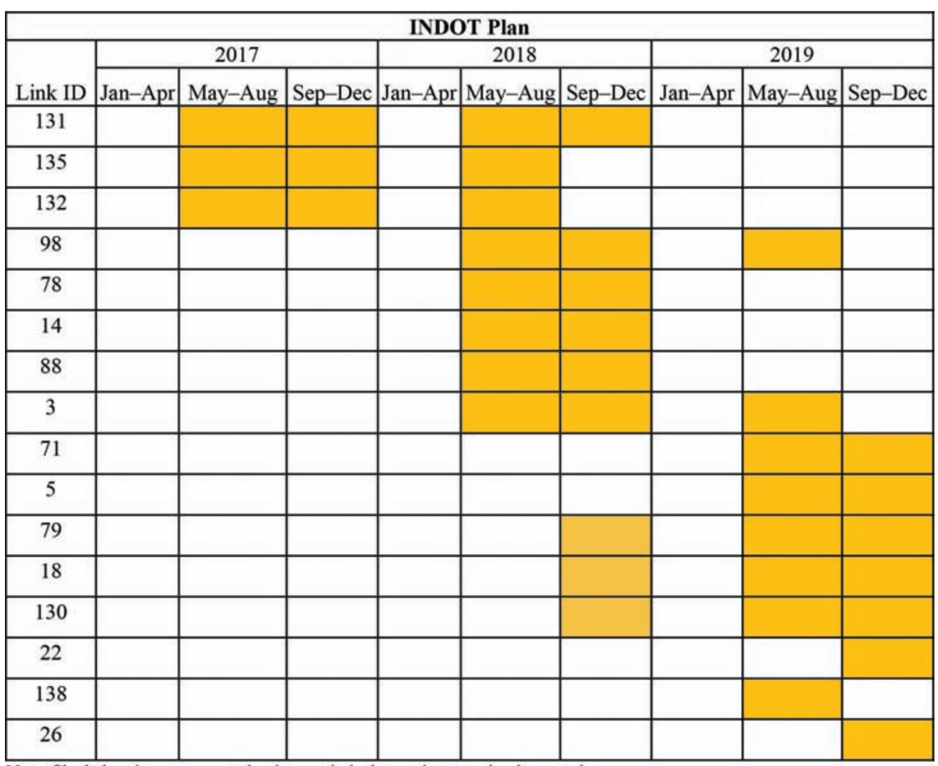


Figure 4.8 Link IDs for INDOT's current road construction projects in the study area.



Note: Shaded regions represent the time periods that projects are implemented.

Figure 4.9 INDOT's current project scheduling plan (INDOT, 2019).

proof-of-concept study, the average expenditure of each customer at a business was assumed to be $100 per trip. During the three-year period, the business revenue under the INDOT plan was estimated to be equal to $77,235,963; the total system travel time was equal to 893,058 veh.hr; and by assuming the value of time equal to $15 per hour (U.S Department of Transportation, 2016), the equivalent road user cost was estimated to be equal to $13,395,870. The total system cost under this plan was equal to $90,631,833, implying that under a random construction plan, the business disruption cost would increase by 252% compared to INDOT's current plan. The random project plan is shown in Figure 4.10.

4.1.6.3 Optimal plan considering travel cost and impact on businesses. Using the methodology described in Appendix A, the optimal road construction plan was derived where it was assumed that the road projects were completed within the construction period. Figure 4.11 shows the optimal road construction plan based on the developed methodology. For the proof-of-concept study, the average expenditure of each customer at a business was assumed to be $100 per trip. During the three-year period, the business revenue under the random plan was estimated to be equal to $81,150,120; the total system travel time was equal to 941,949 veh.hr; and by assuming the value of time equal to $15 per hour (U.S Department of Transportation, 2016), the equivalent cost was estimated to be equal to $14,129,235. The total system cost under this plan was equal to $95,279,355, implying that if the optimal road construction plan was used, the business disruption cost would be reduced by 27% compared to INDOT's current plan.

Table 4.1 compares the three scheduling plans with respect to their common characteristics, differences, and assumptions made in calculating the revenues associated with each plan. Each plan was evaluated over a three-year planning period; and a travel time value of $15/hr was assumed (U.S Department of Transportation, 2016).

Figure 4.12 shows a comparison of the percent revenue loss for the three plans based on the base condition (no construction) over a three-year (2017–2019) planning horizon.

4.1.6.4 Short- and long-term impacts of capacity expansion and preservation projects. The focus of this study was to understand the impacts of road construction

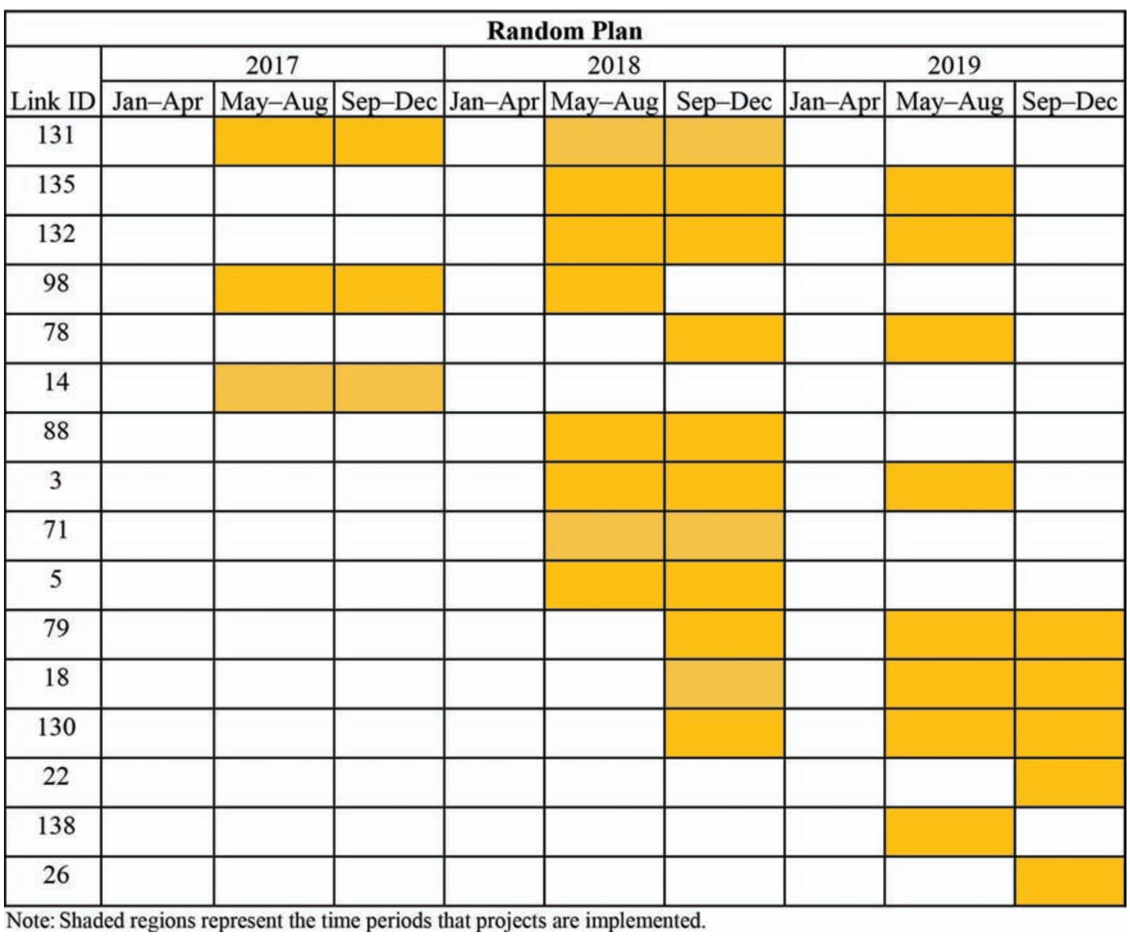


Figure 4.10 Random project scheduling plan.

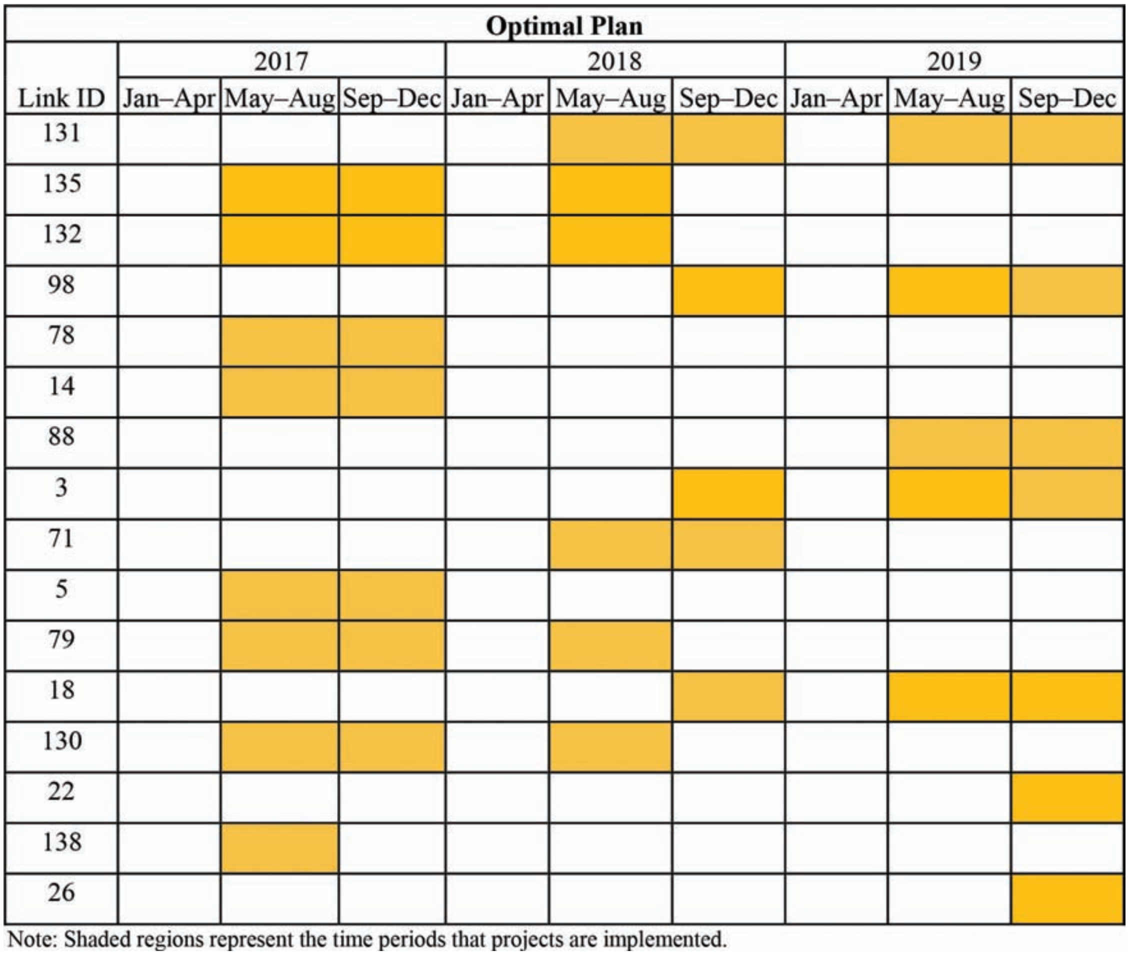


Figure 4.11 Optimal project scheduling plan.

TABLE 4.1
Comparison of Project Scheduling Plans

Plan	Name	Common Characteristics	Differences	Revenue ($)
1	Base Condition		No construction during 3 years (2017–2019)	82,769,541
2	INDOT's Current Plan	3-year planning period No construction between January and April Average expenditure of each customer is assumed to be $100 per trip $15/hr travel time value (U.S. Department of Transportation, 2016)	Based on INDOT's project scheduling practice	80,580,879
3	Random Plan		Developed using discrete uniform distribution	77,235,963
4	Optimal Plan		Developed using methodology described in Appendix A	81,150,120

projects on business revenues during the construction season in order to minimize the disruption costs to businesses. Hence, this project dealt with the short-term impacts of road construction projects on businesses. Potential long-term business impacts were not addressed in this project. After completion of construction projects, the road's condition or capacity returns to normal and accessibility to businesses even may be increased resulting in increased customers and higher revenues compared to the base condition (no-construction plan).

4.1.6.5 Impact of project scheduling considering various lane closure policies. Business disruption costs are mainly due to road users changing their destination choice due to the high travel time on their usual routes to businesses. The capacity of the road plays an important role in travel time for road users. Hence, it is prudent to implement road projects with minimum reduction of road capacities so that business disruption costs can be minimized. In the survey conducted of road users in this study, about 65% of the respondents felt that the travel time had a significant influence

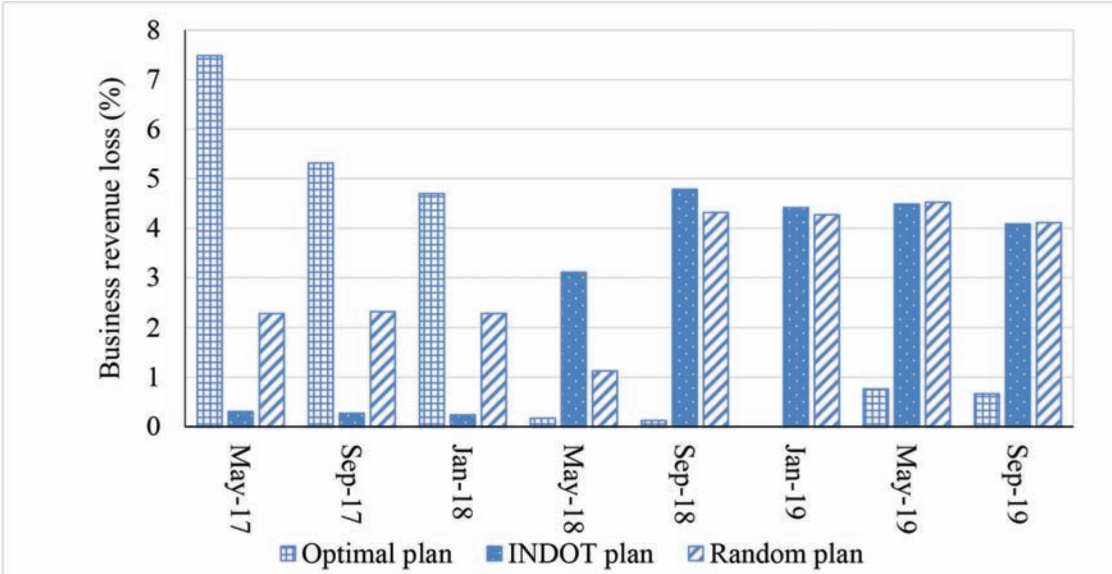


Figure 4.12 Percent revenue loss by businesses under the random, optimal, and INDOT's current plans with respect to the base condition (no-construction) plan.

on their choice of travel route. About 64% of the respondents also indicated that the travel time had a significant influence on their decision to make a trip from one place to another. About 53% of respondents indicated that the travel time in work zones significantly influenced their decisions to avoid roads with work zones. These survey results imply that the impact of lane closure policies for network-level project scheduling should be considered because changes in road capacity may cause increased travel time in work zones for the same traffic conditions in the area, and consequently, may increase road user costs. As a result, the revenues of businesses near work zones may decrease because customers may choose to go to other businesses to avoid the work zone.

4.1.7 Limitation and Future Scope of the Framework

The main challenge in this study was collecting data related to O-D travel demand, the impact of construction projects on road capacities, and the traffic network characteristics. The second challenge was that this study only dealt with business disruption costs due to construction work zones. Investigating the effect of the increased capacities of roads in the traffic network on business revenues in the community once the projects are completed could be another extension of the current work. The third challenge was that this study assumed that travel demands are deterministic throughout the construction season. However, the forecast of travel demands is often uncertain during the construction season, which can span a few years. Hence, it would be helpful to develop a robust project schedule that can mitigate the potential increase in total system cost (user and business disruption costs) due to inaccurate travel demand forecasts. As construction projects may reduce network connectivity, the developed framework could be expanded by considering connectivity as a criterion in road construction scheduling, particularly in sparely populated areas where there is no congestion and therefore traffic assignment is not applicable (Labi et al., 2019; Woldemariam, 2015; Woldemariam et al., 2019).

4.2 Summary and Conclusions

In this chapter, a case study was used to demonstrate the developed methodology. In addition to the base case (which represents a do-nothing alternative), three network-level project scheduling scenarios were considered: (1) INDOT's current plan, which is based on INDOT's project scheduling practices; (2) a random plan developed considering discrete uniform distribution; and (3) an optimal plan developed using the methodology introduced in this study. Under the optimal project scheduling plan, the business disruption cost was reduced by 27% compared to INDOT's current plan, implying the benefits of using the developed methodology during planning network-wide scheduling of road construction projects in a given region. Chapter 5 will present the features of the spreadsheet and visualization tool developed in this study to assist INDOT in network-level scheduling of road construction projects.

5. DEVELOPMENT OF SPREADSHEET AND VISUALIZATION TOOL

Network-level project scheduling requires consideration of factors such as project duration, network size, construction season, work types, etc. Due to the presence of many factors, it becomes difficult to evaluate each scheduling plan with respect to its costs (such as road user and business costs) and benefits (such as travel time and safety savings) because the combined effects of these factors is very complex and requires a software tool to manage associated data and visualize results for better informed decisions. The spreadsheet and visualization tool developed in this study is presented in this chapter.

5.1 Introduction

The proposed bi-level model is solved using the General Algebraic Modeling System (GAMS). GAMS is a high-level modeling system for mathematical optimization that is capable of solving linear and nonlinear optimization problems (Rosenthal, 2015). The system is designed for large-scale modeling applications for solving large models with several variables and equations. The system is available for use on various computer platforms such as Windows, Mac and Linux.

Figure 5.1 shows the general procedure for computing the construction scheduling problem. The inputs used in the structure include the number of O-D pairs and O-D demands, the road capacities and speed limits, construction project characteristics road length, and business characteristics such as the number of customers and sale per customer. The developed tool provides outputs that show the optimal project schedule, that minimize the road user and business costs. The processor of the developed tool is the GAMS software, which is used to implement the algorithm developed in this study. Finally, the processor provides an output Excel file that visually shows the optimal construction plans that are recommended to minimize the total road user and business disruption costs.

5.2 Purpose of the Tool

The main purpose of the tool is to obtain the best scheduling plan for constructing projects at the network level to minimize the impact on the surrounding businesses during construction season. The tool can be used to schedule future network-wide construction projects considering both the road user and the business costs. It also can be used to compare past project scheduling plans to quantify the change in benefits compared with optimal plans that could have been generated using the tool developed in this study.

5.3 User Interface

Figure 5.2 shows the GAMS interface that can be used to input data and to run the algorithm that provides optimal construction scheduling plans. The run button that a user presses to run the developed algorithm is shown in the circle in Figure 5.2. This is the simplest way of running the algorithm since the user does not have to write any code to run the algorithm. Alternatively, the user can run the algorithm from a command line (also shown in Figure 5.2) if they wish to run the algorithm by writing an appropriate code.

5.4 Input Data Preparation

The model input data included the origin-destination (O-D) travel demand in vehicles per hour, the travel time between any O-D pairs, which can be calculated using the road link length and the speed limit on the link. The travel time function parameters α and b are given by

$$a = \frac{road\ length}{speed\ limit}$$

$$b = 0.15\frac{road\ length}{speed\ limit} \cdot \frac{1}{(road\ capacity)^4}$$

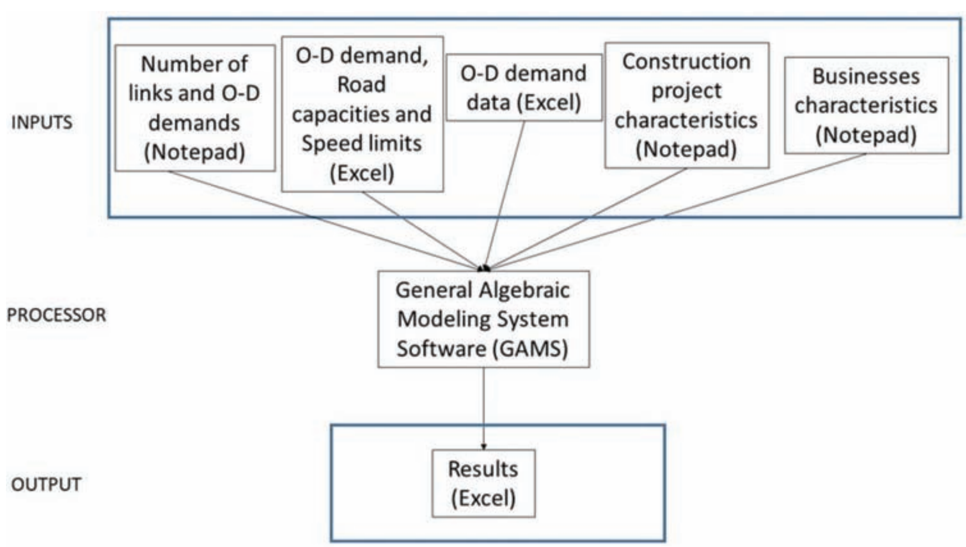


Figure 5.1 Structure of construction project scheduling procedure.

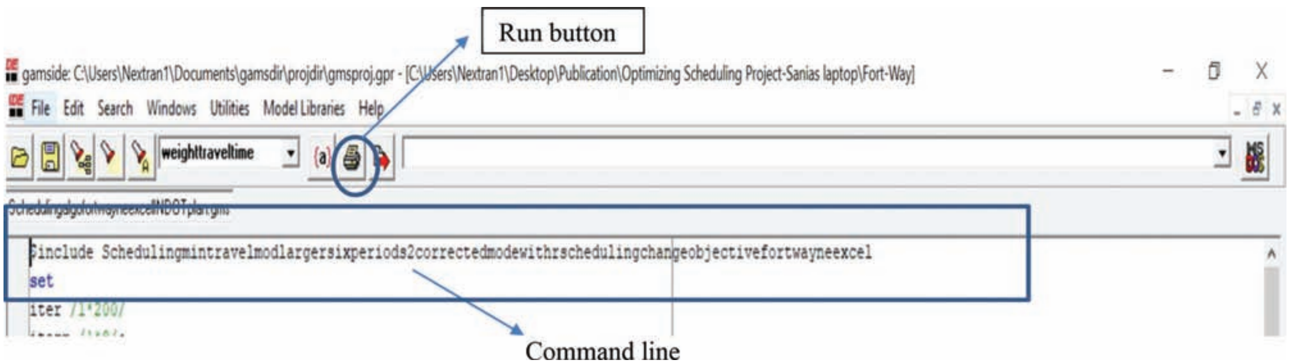


Figure 5.2 The GAMS user interface.

Figure 5.3 shows an Excel input file that provides origin-destination travel demand information for the software algorithm. The columns of the Excel input file represent the O-D ID, the origins, the destinations and the travel demands for each origin-destination. The circled cell shows the travel demand for origin-destination.

Figure 5.4 shows an Excel file with the travel time function parameters between any two origin-destination pairs in the road network. The columns in this Excel file represent the adjacent link nodes and the travel time function parameters. The circled cell shows the travel time function parameters for link 84-84. The travel time function was formulated as follows:

$$\sigma^t_{ij} = a^t_{ij} + b^t_{ij} \cdot (v^t_{ij})^4$$

Where a^t_{ij} and b^t_{ij} are shown in Excel figure.

Figure 5.5 shows a text input file for construction project duration and its impact on road capacity. Column 1 represents the link specifications; for example, the circled cell (83.85) shows link 83–85. Columns 2 through 10 represent the capacity modification factors for the periods after initiating the construction project and show that after initiating the construction project, the capacity dropped by 50% during periods 1 through 3 and increased to normal condition after the completion of the project.

5.5 Output Visualization

Figure 5.6 depicts an Excel output file that shows an optimal construction project scheduling plan for all the projects considered in the analysis. In this Excel output file, the shaded regions represent the time periods during which the projects should be implemented for achieving optimal results with respect to the total cost of the projects in the network, including the road user and business disruption costs.

5.6 Summary and Conclusions

This chapter discussed the spreadsheet and visualization tool that was developed in this study, and the procedure for planning network-wide construction projects was presented. Also, various features of the tool, such as the user interface, required input data and associated files types, and output results were described. The developed tool is expected to help INDOT construction project planners develop optimal construction plans considering both road user and business disruption costs in their analyses.

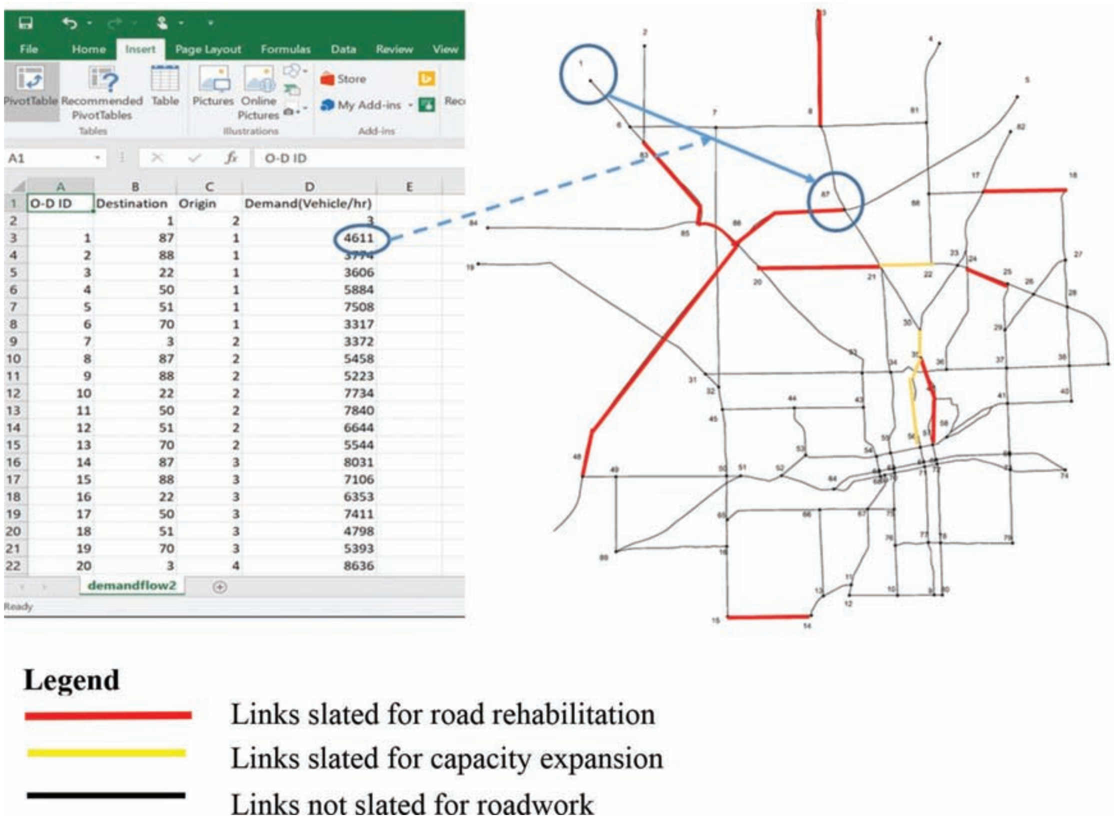


Figure 5.3 Input Excel file for origin-destination travel demand.

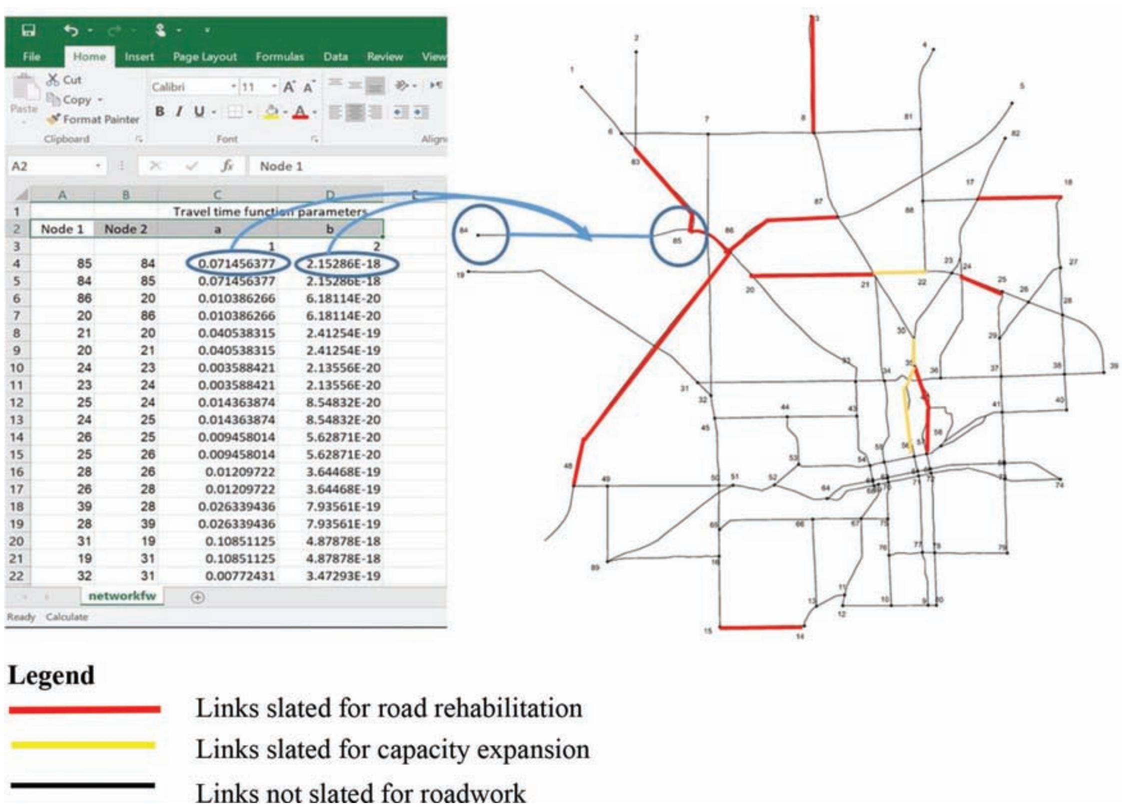


Figure 5.4 Input Excel file for travel time function parameters for each origin-destination pair.

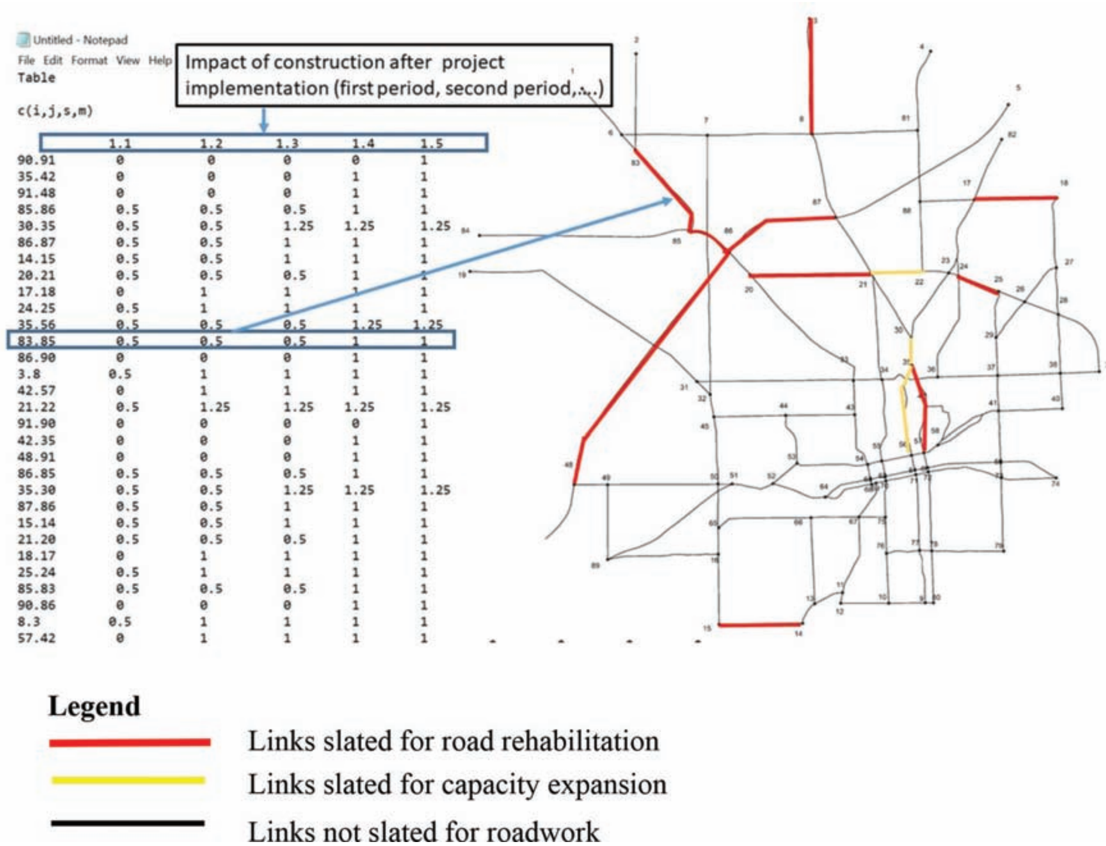


Figure 5.5 Input text file for construction project duration and its impact on road capacity.

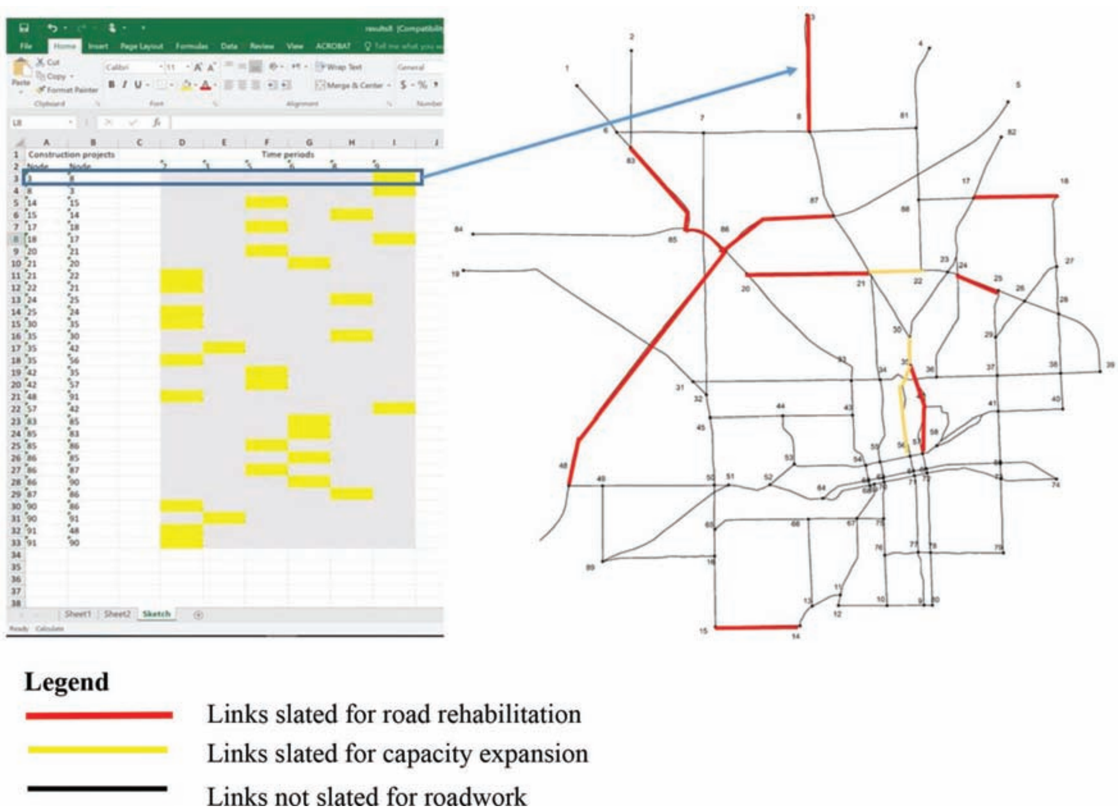


Figure 5.6 Output Excel file showing optimal schedule plan for construction projects.

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APPENDICES

Appendix A. Mathematical Formulation of Project Scheduling Problem

Appendix B. Business Survey Results

Appendix C. Survey Questionnaire

Appendix D. Gams Tutorial for Construction Scheduling

APPENDIX A. MATHEMATICAL FORMULATION OF PROJECT SCHEDULING PROBLEM

A.1 Notations

Notations used in the mathematical formulation of the project scheduling problem are given in this section.

Sets

N	Set of nodes
A	Set of links
$\bar{A}$	Set of capacity expansion projects on existing links
$\bar{\bar{A}}$	Set of road rehabilitation projects on existing links
Γ	Set of time periods

Parameters

T	Number of periods in a construction season
B^t	Construction budget in period t
κ_{ij}^l	Construction cost of link (i,j) after l periods of initiating a project
d_{ij}	Duration of a project on link (i,j)
c_{ij}^l	Modification factor for capacity of link (i,j) after l periods of initiating the project
$f_{ij}^{1,t}$	Free flow travel time on link (i,j) in period t
$f_{ij}^{2,t}$	Capacity of link (i,j) in period t
b_{ij}^t	Travel time function parameter
$\beta_{i,m}^{r,t}$	Percentage of demand of O-D pair (r,i) that is customer of business m of node i in period t
$\varrho_{i,m}^t$	Expenditure of each customer in business m of node i in period t
$\zeta_{i,m}^{0,t}$	Revenue of business m of node i in period t without any construction project
α	Value of time
M	Constant with large value

Variables

Z^U	The objective function in the upper-level model
Z^L	The objective function in the lower-level model
ξ^t	Excess construction budget in period t
$q_i^{r,t}$	Travel demand between O-D pair (r, i) in period t
$\varpi_{i,m}^t$	Business disruption cost of business m of node i in period t
ν_{ij}^t	Flow of link (i, j) in period t
$\nu_{ij}^{r,t}$	Flow of link (i, j) with origin r in period t
σ_{ij}^t	Travel time of link (i, j) in period t
$\pi_i^{r,t}$	Travel time of O-D pair (r, i) in period t
e_{ij}^t	=1 if new road construction project for link (i, j) in period t is implemented; 0 otherwise
γ_{ij}^t	=1 if road rehabilitation project of link (i, j) in period t is implemented; 0 otherwise

In this study, link travel time σ_{ij}^t is assumed to follow the Bureau of Public Roads (BPR) function as follows:

$$\sigma_{ij}^t = f_{ij}^{1,t} + b_{ij}^t \cdot (\nu_{ij}^t)^4 \qquad \forall (i, j) \in A \qquad \text{(Eq. A.1)}$$

where $f_{ij}^{1,t}$ is the free flow travel time on link (i, j) in period t. Travel time function parameter b_{ij}^t can be calculated as follows:

$$b_{ij}^t = \frac{0.15 f_{ij}^{1,t}}{(f_{ij}^{2,t})^4} \qquad \forall (i, j) \in A \qquad \text{(Eq. A.2)}$$

where $f_{ij}^{2,t}$ denote the capacity of link (i, j) in period t. In this study, it is assumed that construction projects only impact the capacity of links. Then, if the construction project of link (i, j) starts in period t, i.e., $e_{ij}^{s,t} = 1$ or $\gamma_{ij}^{s,t} = 1$, its capacity in period $t' \geq t$ is equal to $c_{ij}^{t'-t+1} f_{ij}^{2,t'}$ where $c_{ij}^{t'-t+1}$ is referred as the modification factor for capacity of link (i, j) in $t' -$

$t+1$ periods after initiating the construction project. For example, if $c_{ij}^{t'-t+1} = 0$, it means that the link (i,j) will be fully closed in $t'-t+1$ periods after initiating the construction project. Section 2.1 presents the upper-level model to determine the optimal schedule of construction projects. Section 2.2 formulates the lower-level model as nonlinear program with complementarity constraints. Section 2.3 integrates the upper-level and lower-level models.

A.2 Upper-Level Model

As stated earlier, in the upper level, the transportation planner aims to minimize the weighted summation of travel delay and business disruption costs. The weights of travel delay and business disruption costs are denoted by W_1 and W_2, respectively. If $W_1 > W_2$, it means that the transportation planner weighs travel delay cost higher than business disruption cost. If $W_2 > W_1$, transportation planner weighs business disruption cost higher than travel delay. The upper-level model is subject to available construction budget B^t in each period t. The excess construction budget ξ^t in each period t is carried over to the next period $t+1$.

To measure the construction impacts on surrounding business, let $q_i^{r,t}$ denote the travel demand between origin r and destination i in period t. It is assumed to be elastic, increasing and convex function of travel time between each O-D pair. Further, let $\beta_{i,m}^{r,t}$ denote the percentage of demand of O-D pair (r,i) that is the customer of business m of node i in period t. It is assumed that each customer spends $\varrho_{i,m}^t$ dollars in business b of node i in period t. Then, the revenue of business m located in node i, $\zeta_{i,m}^t$, in period t can be calculated as follows:

$$\zeta_{i,m}^t = \varrho_{i,m}^t \sum_r \beta_{i,m}^{r,t} q_i^{r,t} \qquad \forall t \qquad \text{(Eq. A.3)}$$

Let $\zeta_{i,m}^{0,t}$ be the revenue of business m in period t without any construction. Using this notion, the business disruption cost of business m located in node i in period t can be measured as follows:

$$\varpi_{i,m}^t = \zeta_{i,m}^t - \zeta_{i,m}^{0,t} \qquad \forall t$$

Then, the upper-level model, with objective Z^U, can be formulated as a mixed-integer nonlinear model as follows:

$$\min_{e,} Z^U = W_1 \sum_{t=1}^{T} \sum_{(i,j)\in A} \alpha\sigma_{ij}^t(\nu_{ij}^t)\nu_{ij}^t - W_2 \sum_{t=1}^{T} \sum_{(i,m)} \zeta_{i,m}^t \quad \text{(Eq. A.4)}$$

$$\sum_{(i,j)\in\bar{\bar{A}}} \kappa_{ij}^1\gamma_{ij}^1 + \sum_{(i,j)\in\bar{A}} \kappa_{ij}^1 e_{ij}^1 + \xi^1 = B^1 \quad \text{(Eq. A.5)}$$

$$\sum_{t=1}^{l} \Big(\sum_{(i,j)\in\bar{\bar{A}}} \kappa_{ij}^{l+1-t}\gamma_{ij}^t + \sum_{(i,j)\in\bar{A}} \kappa_{ij}^{l+1-t} e_{ij}^t \Big) + \xi^l = B^l + \xi^{l-1} \qquad l = 2, \dots, \tau \quad \text{(Eq. A.6)}$$

$$\sum_{t=1}^{\tau} t e_{ij}^t + d_{ij} \le \tau + 1 \qquad \forall (i,j) \in \bar{A} \quad \text{(Eq. A.7)}$$

$$\sum_{t=1}^{\tau} t\gamma_{ij}^t + d_{ij} \le \tau + 1 \qquad \forall (i,j) \in \bar{\bar{A}} \quad \text{(Eq. A.8)}$$

$$\sum_{t=1}^{\tau-d_{ij}+1} e_{ij}^t = 1 \qquad \forall (i,j) \in \bar{A} \quad \text{(Eq. A.9)}$$

$$\sum_{t=1}^{\tau-d_{ij}+1} \gamma_{ij}^t = 1 \qquad \forall (i,j) \in \bar{\bar{A}} \quad \text{(Eq. A.10)}$$

$$b_{ij}^{t'} - 0.15 \frac{f_{ij}^{1,t'}}{(c_{ij}^{t'-t+1} f_{ij}^{2,t'})^4} \le M(1 - e_{ij}^t) \qquad \forall (i,j) \in \bar{A}, t' = 1, \dots, \tau, \; t' \ge t, c_{ij}^{t'-t+1} > 0 \quad \text{(Eq. A.11)}$$

$$b_{ij}^{t'} - 0.15 \frac{f_{ij}^{1,t'}}{(c_{ij}^{t'-t+1} f_{ij}^{2,t'})^4} \ge -M(1 - e_{ij}^t) \qquad \forall (i,j) \in \bar{A}, t' = 1, \dots, \tau, \; t' \ge t, c_{ij}^{t'-t+1} > 0 \quad \text{(Eq. A.12)}$$

$$b_{ij}^{t'} - 0.15 \frac{f_{ij}^{1,t'}}{(c_{ij}^{t'-t+1} f_{ij}^{2,t'})^4} \le M(1 - \gamma_{ij}^t) \qquad \forall (i,j) \in \bar{\bar{A}}, t' = 1, \dots, \tau, \; t' \ge t, c_{ij}^{t'-t+1} > 0 \quad \text{(Eq. A.13)}$$

$$b_{ij}^{t'} - 0.15 \frac{f_{ij}^{1,t'}}{(c_{ij}^{t'-t+1} f_{ij}^{2,t'})^4} \ge -M(1 - \gamma_{ij}^t) \qquad \forall (i,j) \in \bar{\bar{A}}, t' = 1, \dots, \tau \; t' \ge t, c_{ij}^{t'-t+1} > 0 \quad \text{(Eq. A.14)}$$

$$e_{ij}^t \in \{0,1\} \qquad \forall t, \forall (i,j) \in \bar{A} \quad \text{(Eq. A.15)}$$

$$\gamma_{ij}^t \in \{0,1\} \qquad \forall t, \forall (i,j) \in \bar{\bar{A}} \quad \text{(Eq. A.16)}$$

where α denotes the value of the time of road users. Objective function (5) is equal to the subtraction of business revenue from total travel delay cost. Constraints (6) and (7) are the budget conservation constraints. Constraint (6) states that in the first period, the budget is equal to the construction costs of all the implemented projects and the leftover budget that carried over into the second period. If the construction project of link (i, j) starts in period t, i.e., $e_{ij}^t = 1$ or $\gamma_{ij}^t = 1$, its construction cost is equal to $\kappa_{ij}^{t'-t+1}$ in period t'. Constraint (7) states that the sum of the construction budget of period t and the leftover budget of period $t-1$ is equal to the sum of construction costs and leftover budget in period t. Constraints (8) and (9) ensure that the road capacity expansion and rehabilitation projects should be completed within the construction season. Constraints (10) and (11) state that the road capacity expansion and rehabilitation projects can start only once during the construction season. Constraints (12) and (13) update the travel time function parameter in period t', $b_{ij}^{t'}$, if the capacity expansion project of link (i, j) starts in period t using modification factor $c_{ij}^{t'-t+1} > 0$. The $c_{ij}^{t'-t+1}$ is greater than one after finishing the construction project. Constraints (14) and (15) state that if the road rehabilitation project of link (i, j) starts in period t, then the travel time function parameter in period t', $b_{ij}^{t'}$, should be updated using modification factor $c_{ij}^{t'-t+1} > 0$. Constraints (16) and (17) denote that e_{ij}^t and γ_{ij}^t are binary decision variables.

A.3 Lower-Level Model

The lower-level model aims to capture the decision-making process of road users under the sequence of projects decided by the transportation planner in the upper-level. Road users aim to minimize their travel delay costs under the optimal sequence. They select the routes with minimum travel delay. Under the equilibrium condition, road users cannot further reduce their travel times by unilaterally changing the route. The O-D travel demands are also elastic and function $D_{r,i}$ of the minimum travel cost of each O-D. Let $\pi_i^{r,t}$ denote the travel delay from node r to node i in period t. Given the construction schedule parameters (e and γ) determined in the upper-level, the lower-level model can be formulated as the following mathematical program with complementarity constraints (MPCC):

$$0 \leq v_{ij}^{r,t} \perp \left(\sigma_{ij}^t\left(v_{ij}^t\right) + \pi_i^{r,t} - \pi_j^{r,t}\right) \geq 0 \qquad \forall (i,j) \in A, \forall r \in N, t = 1, \dots, \tau \qquad \text{(Eq. A.17)}$$

$$q_i^{r,t} = D_{r,i}(\pi_i^{r,t}) \qquad \forall r \in N, \forall i \in N, t = 1, \dots, \tau \qquad \text{(Eq. A.18)}$$

$$\pi_r^{r,t} = 0 \qquad \forall r \in N, t = 1, \dots, \tau \qquad \text{(Eq. A.19)}$$

$$\nu_{ij}^{t'} \leq M \cdot (1 - e_{ij}^{t}) \qquad \forall (i,j) \in \bar{A}, t' = 1, \dots, \tau, \quad t' \geq t, c_{ij}^{t'-t+1} = 0 \qquad \text{(Eq. A.20)}$$

$$\nu_{ij}^{t'} \leq M \cdot (1 - \gamma_{ij}^{t}) \qquad \forall (i,j) \in \bar{\bar{A}}, t' = 1, \dots, \tau \quad t' \geq t, c_{ij}^{t'-t+1} = 0 \qquad \text{(Eq. A.21)}$$

$$\sum_{j:(i,j)\in A} \nu_{ij}^{r,t} - \sum_{j:(j,i)\in A} \nu_{ji}^{r,t} = q_i^{r,t} \qquad \forall r \in N, t = 1, \dots, \tau \qquad \text{(Eq. A.22)}$$

$$\sum_{r \in N} \nu_{ij}^{r,t} = \nu_{ij}^{t} \qquad \forall (i,j) \in A, t = 1, \dots, \tau \qquad \text{(Eq. A.23)}$$

$$\nu_{ij}^{r,t}, \nu_{ij}^{t} \geq 0 \qquad \forall r \in N, \forall (i,j) \in A, t = 1, \dots, \tau \qquad \text{(Eq. A.24)}$$

Constraint (18) is the link-based user equilibrium condition. It states that link (i,j) is utilized in period t by road users originating from node, i.e., $\nu_{ij}^{r,t}$, if it is part of the shortest path tree with origin r to other nodes in the traffic network. Constraint (19) states that travel demand is a function of the travel delay from node r to node i in period t. Constraint (20) states that travel delay from node r to node r is equal to zero. Constraints (21)–(22) ensure that if the road capacity expansion and rehabilitation projects of link (i,j) are initiated in period t and the road is closed in period t' (i.e., $c_{ij}^{s,t'-t+1}$ is equal to zero in period t'), then its flow is equal to zero in period t'. Constraint (23) represents the flow conservation constraint and states that in node i, the inflow is equal to the summation of the outflow and the demand of road users originating from node r. Equation (24) calculates the aggregate link flow. Constraint (25) represents the positive decision variables in the lower-level model. MPCC (18)–(25) can be formulated as the following optimization program:

$$\min_{\nu} Z^L = \sum_t \sum_{(i,j)\in A} \int_0^{\nu_{ij}^t} \sigma_{ij}^t(w)dw - \sum_t \sum_i \sum_r \int_0^{q_i^{r,t}} D_{r,i}^{-1}(w)dw \qquad \text{(Eq. A.25)}$$

$$\sum_{j:(i,j)\in A} \nu_{ij}^{r,t} - \sum_{j:(j,i)\in A} \nu_{ji}^{r,t} = q_i^{r,t} \qquad \forall r \in N, t = 1, \dots, T \qquad \text{(Eq. A.26)}$$

$$\sum_{r\in N} \nu_{ij}^{r,t} = \nu_{ij}^{t} \qquad \forall (i,j) \in A, t = 1, \dots, T \qquad \text{(Eq. A.27)}$$

$$\nu_{ij}^{t'} \leq M \cdot (1 - e_{ij}^{t}) \qquad \forall (i,j) \in \bar{A}, t' = 1, \dots, \tau, \; t' \geq t, c_{ij}^{t'-t+1} = 0 \qquad \text{(Eq. A.28)}$$

$$\nu_{ij}^{t'} \leq M \cdot (1 - \gamma_{ij}^{t}) \qquad \forall (i,j) \in \bar{\bar{A}}, t' = 1, \dots, \tau \; t' \geq t, c_{ij}^{t'-t+1} = 0 \qquad \text{(Eq. A.29)}$$

$$\nu_{ij}^{r,t}, \nu_{ij}^{t} \geq 0 \qquad \forall r \in N, \forall (i,j) \in A, t = 1, \dots, T \qquad \text{(Eq. A.30)}$$

where Z^L denotes the objective function in the lower-level model. It can be easily shown that the first order condition (Karush-Kuhn-Tucker (KKT) condition) of optimization program (26)–(31) is equivalent to MPEQ (18)-(25).

A.4 Bi-Level Model

The bi-level model can be formulated as the following mathematical program with complementarity constraints (MPCC):

$$\min_{e, \ ,\nu} Z^U = W_1 \sum_{t=1}^{T} \sum_{(i,j)\in A} \alpha \sigma_{ij}^{t}(\nu_{ij}^{t}) \nu_{ij}^{t} - W_2 \sum_{t=1}^{T} \sum_{(i,m)} \zeta_{i,m}^{t} \qquad \text{(Eq. A.31)}$$

MPCC ((6)-(25), (32)) consists of integer variables and complementarity conditions which make the problem NP-hard and very difficult to solve. In contrast to existing studies in literature that leverages the heuristic methods, the local decomposition method, which is an exact method, is adopted to solve the proposed bi-level model.

APPENDIX B. BUSINESS SURVEY RESULTS

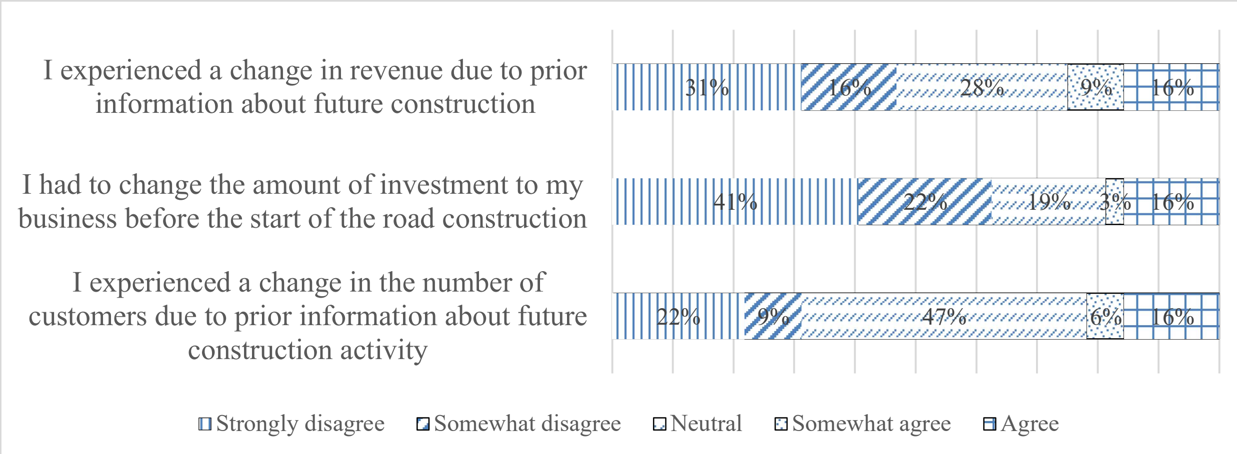


Figure B.1 Level of agreement of businesses with changes in investment, revenue, and number of customers due to future construction activities.

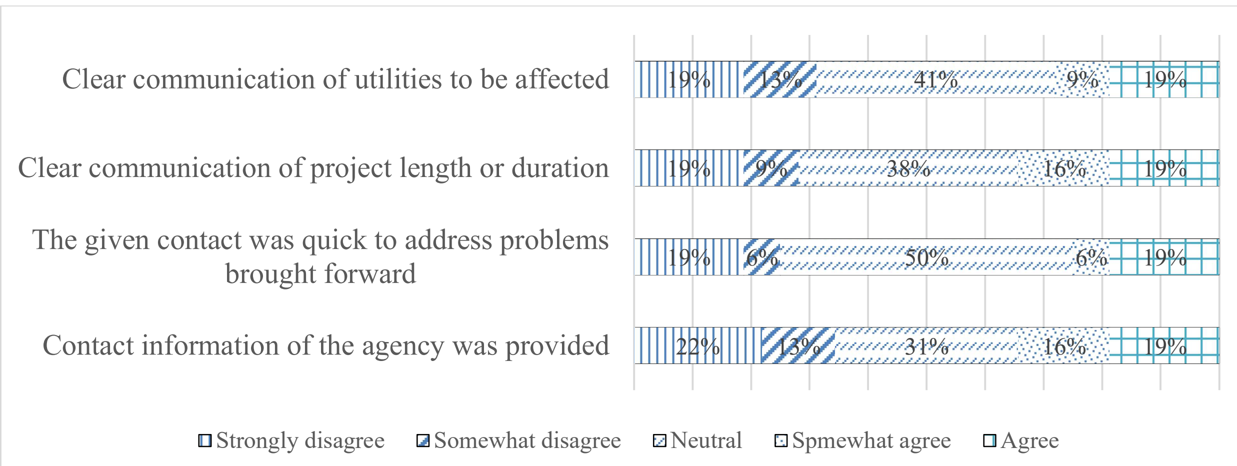


Figure B.2 Level of agreement of businesses with quality of INDOT's communication regarding impact of future construction activities.

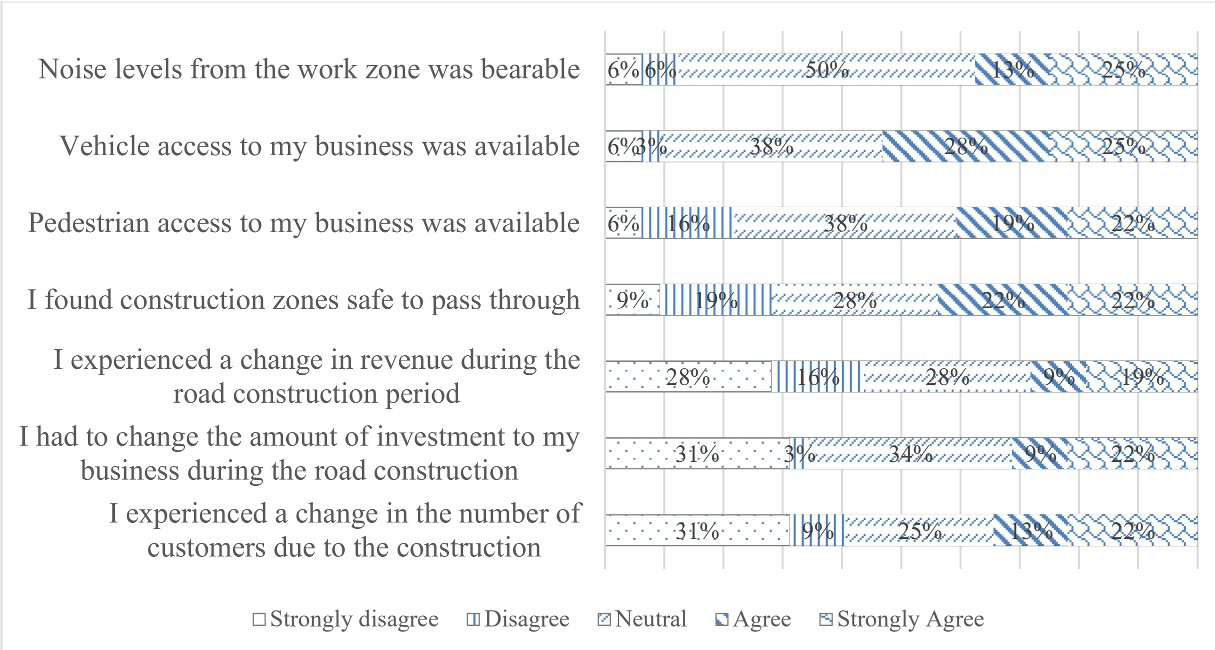


Figure B.3 Level of agreement of businesses with impacts of current construction on noise level, accessibility, safety, and changes in revenue, investment, and number of customers.

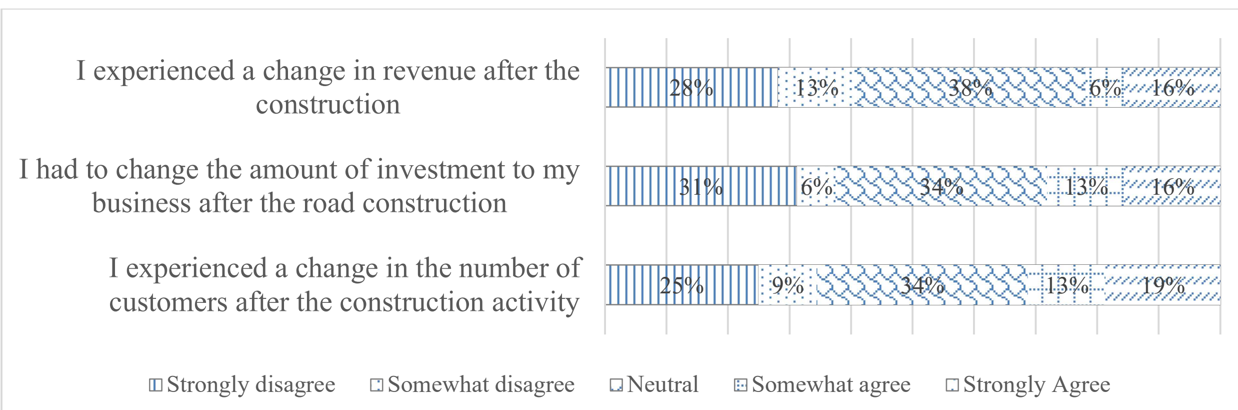


Figure B.4 Level of agreement of businesses with changes in revenue, investment, and number of customers after construction activities.

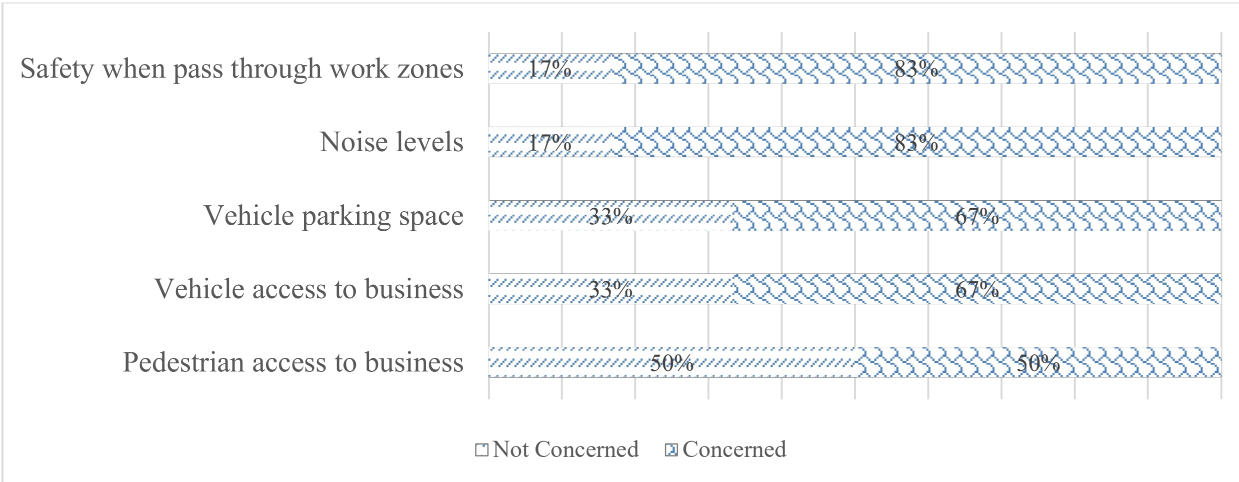


Figure B.5 Level of concern of businesses for safety, noise levels, vehicle and pedestrian accessibility due to presence of work zones.

APPENDIX C. SURVEY QUESTIONNAIRE

C1. Road User Survey Questionnaire

For the businesses given in the table below, please indicate the frequency of your visits per month and the amount spent per visit to the businesses under normal conditions (i.e., before there is any road construction on the route to or near these businesses).

	Frequency of Visits Per Month	Amount Spent Per Visit (U.S. dollars)
Grocery		
Clothing		
Restaurants		
Pharmacy		
Liquor Stores		
Gas Stations		

C2. Business Survey Questionnaire

What is your dominant business category?

O General merchandise
O Grocery store
O Automotive
O Clothing
O Restaurant/Fast food
O Pharmacy
O Liquor store
O Bar/Grill
O Gas station
O Other

Please complete the table below to show your level of agreement with the following pre-construction impacts of road construction projects on your business over the past five (5) years.

	Strongly agree	Somewhat agree	Neutral	Somewhat disagree	Strongly disagree
I experienced a change in the number of customers due to prior information about future construction activity	o	o	o	o	o
I had to change the amount of investment to my business before the start of the road construction	o	o	o	o	o
I experienced a change in revenue due to prior information about future construction	o	o	o	o	o

Please complete the table below to show your level of agreement with the following pre-construction activities of road construction projects on your business over the past five (5) years.

	Strongly agree	Somewhat agree	Neutral	Somewhat disagree	Strongly disagree
Contact information of the agency was provided	o	o	o	o	o
The given contact was quick to address problems brought forward	o	o	o	o	o
Clear communication of project length or duration	o	o	o	o	o
Clear communication of utilities to be affected	o	o	o	o	o

Please complete the table below to show your level of agreement with the impacts of road construction projects on your business during the construction period over the past five (5) years.

	Strongly agree	Somewhat agree	Neutral	Somewhat disagree	Strongly disagree
I experienced a change in the number of customers due to the construction	O	O	O	O	O
I had to change the amount of investment to my business during the road construction	O	O	O	O	O
I experienced a change in revenue during the road construction period	O	O	O	O	O
I found construction zones safe to pass through	O	O	O	O	O
Pedestrian access to my business was available	O	O	O	O	O
Vehicle access to my business was available	O	O	O	O	O
Noise levels from the work zone was bearable	O	O	O	O	O

Please complete the table below to show your level of agreement with the following post-construction impacts of road construction projects on your business over the past five (5) years.

	Strongly agree	Somewhat agree	Neutral	Somewhat disagree	Strongly disagree
I experienced a change in the number of customers after the construction activity	O	O	O	O	O
I had to change the amount of investment to my business after the road construction	O	O	O	O	O
I experienced a change in revenue after the construction	O	O	O	O	O

Please indicate the percentage change in customers experienced during the preconstruction period, if any.

	Percentage
Gain	
Loss	

Please indicate the percentage change in customers experienced during the construction period, if any.

	Percentage
Gain	
Loss	

Please indicate the percentage change in customers experienced during the post-construction period, if any.

	Percentage
Gain	
Loss	

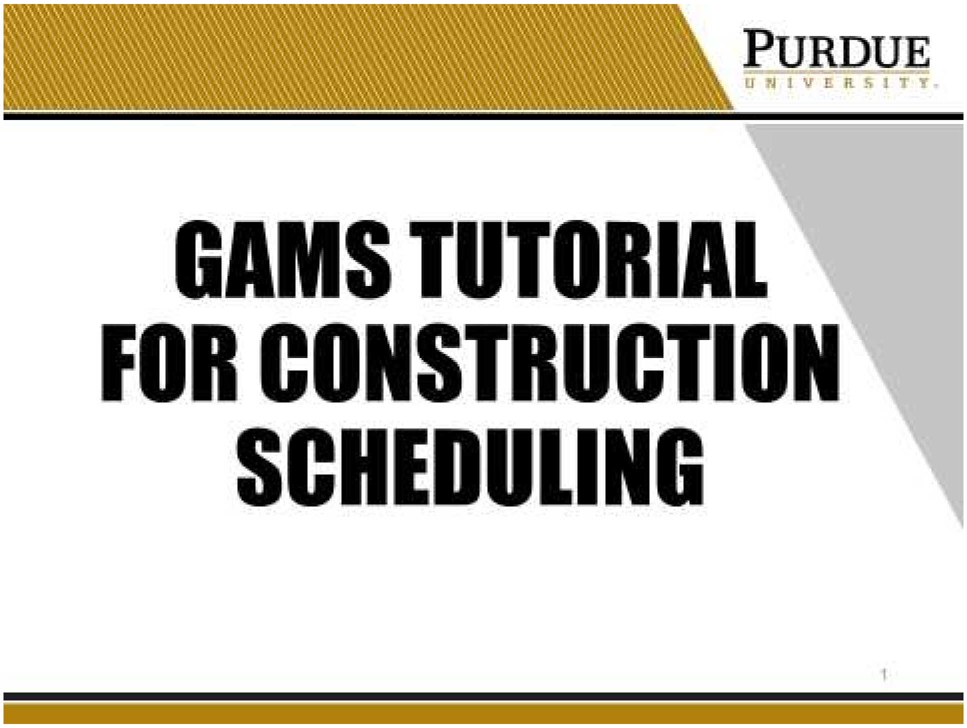
Are you concerned about future impacts of road construction projects in your business area?

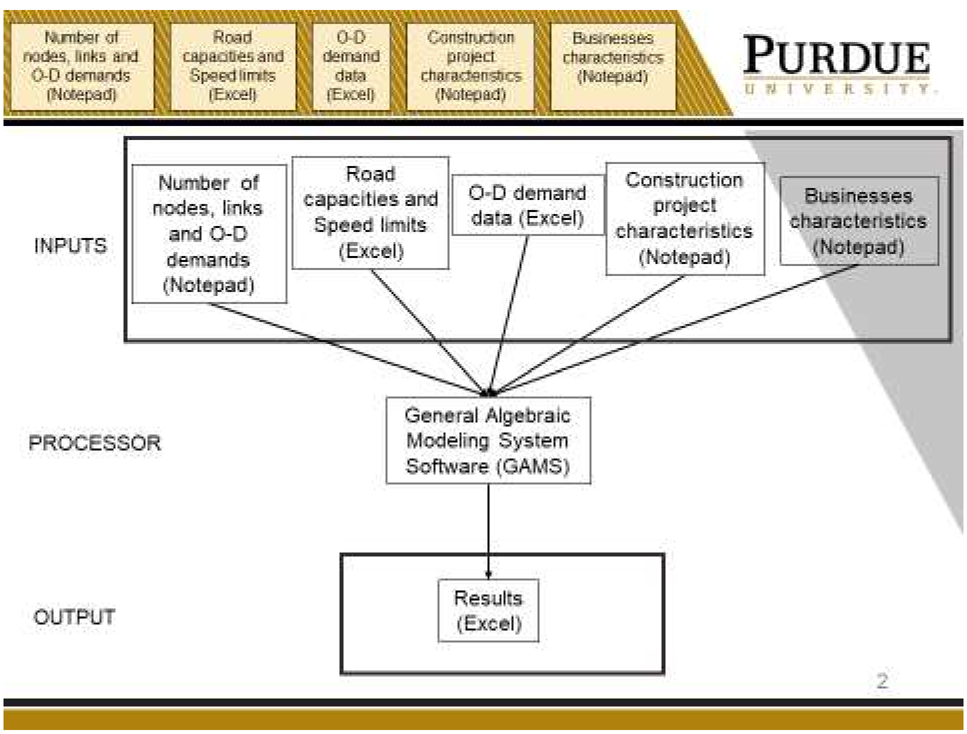
O Yes
O Maybe
O No

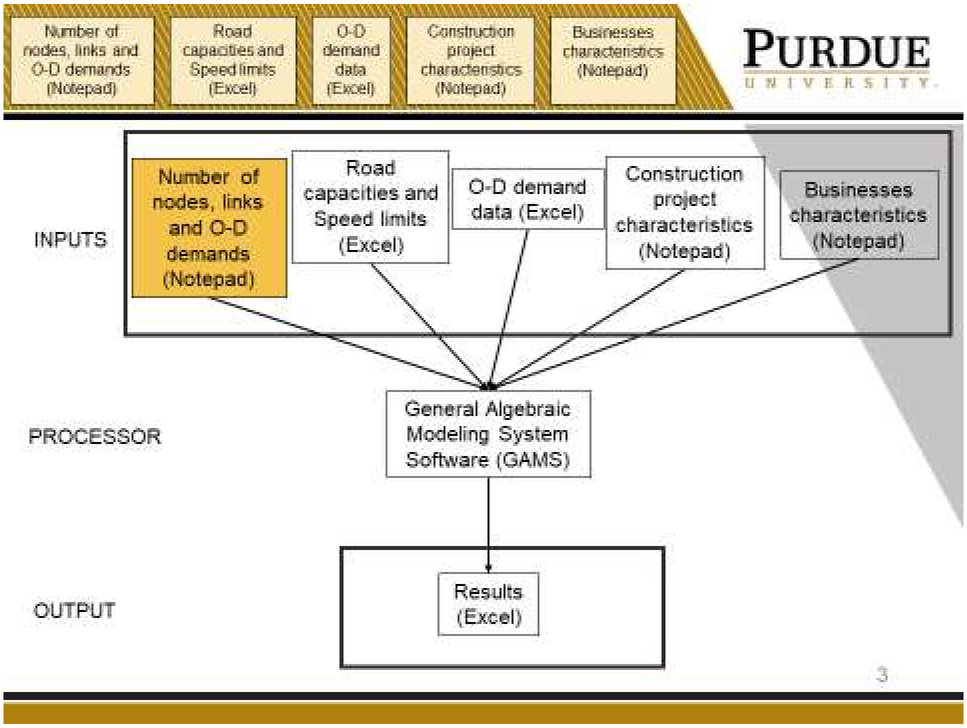
Please indicate which factors you are concerned about if there were to be any future construction near your business. (Check all that apply.)

	Tick if concerned
Pedestrian access to business	☐
Vehicle access to business	☐
Vehicle parking space	☐
Noise levels	☐
Safety when pass through work zones	☐

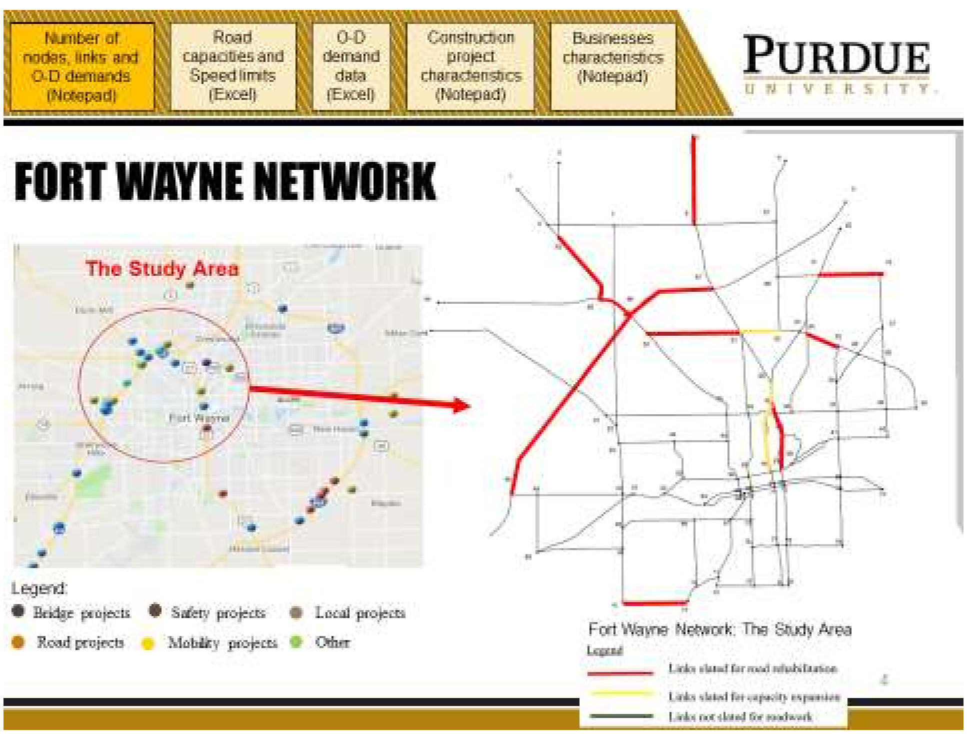
APPENDIX D. GAMS TUTORIAL FOR CONSTRUCTION SCHEDULING







Number of nodes, links and O-D demands (Notepad)
Road capacities and Speed limits (Excel)
O-D demand data (Excel)
Construction project characteristics (Notepad)
Businesses characteristics (Notepad)
PURDUE UNIVERSITY.
INPUTS
Number of nodes, links and O-D demands (Notepad)
Road capacities and Speed limits (Excel)
O-D demand data (Excel)
Construction project characteristics (Notepad)
Businesses characteristics (Notepad)
PROCESSOR
General Algebraic Modeling System Software (GAMS)
OUTPUT
Results (Excel)
3



Number of nodes, links and O-D demands (Notepad)
Road capacities and Speed limits (Excel)
O-D demand data (Excel)
Construction project characteristics (Notepad)
Businesses characteristics (Notepad)
PURDUE UNIVERSITY.
FORT WAYNE NETWORK
The Study Area
Fort Wayne
Legend:
Bridge projects
Safety projects
Local projects
Road projects
Mobility projects
Other
Fort Wayne Network: The Study Area
Legend
Links slated for road rehabilitation
Links slated for capacity expansion
Links not slated for roadwork
4

INPUT.TXT

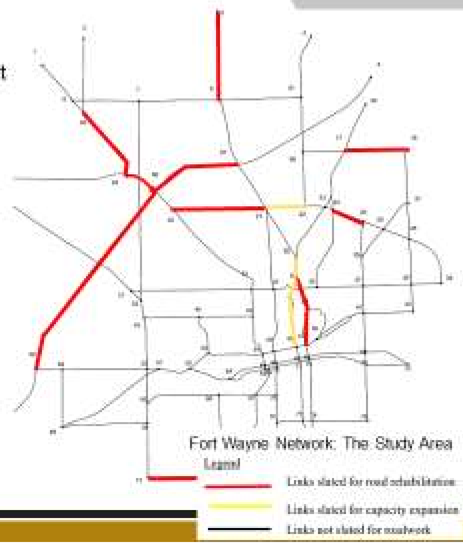
In GAMS, the manner in which input is incorporated is in the form of sets.
For this specific program, each set has the format /1*n/ meaning that the elements in that set are 1,2,…,n.

Define the number of nodes in the network /1*n/ where n is the number of nodes. In this case, n = 95.

```
sets

i network nodes /1*95/
r(i) origin nodes /1*16/
v  travel time parameter    /1*3/
s GAMS set /1/
t time period  /1*9/;

Alias(i,j,ii);
```



Number of nodes, links and O-D demands (Notepad) | Road capacities and Speed limits (Excel) | O-D demand data (Excel) | Construction project characteristics (Notepad) | Businesses characteristics (Notepad)
PURDUE UNIVERSITY

INPUT.TXT

```
sets

i network nodes /1*95/
r(i) origin nodes /1*16/
v  travel time parameter    /1*3/
s GAMS set /1/
t time period  /1*9/;

Alias(i,j,ii);
```

Define the number of origin nodes. In this case, we have 16 origin nodes.

These are the parameters used in the link travel time function. This is always 1 to 3. No need to change. 1 is the free-flow travel time. 2 is the capacity of the link. 3 is the GAMS parameter.

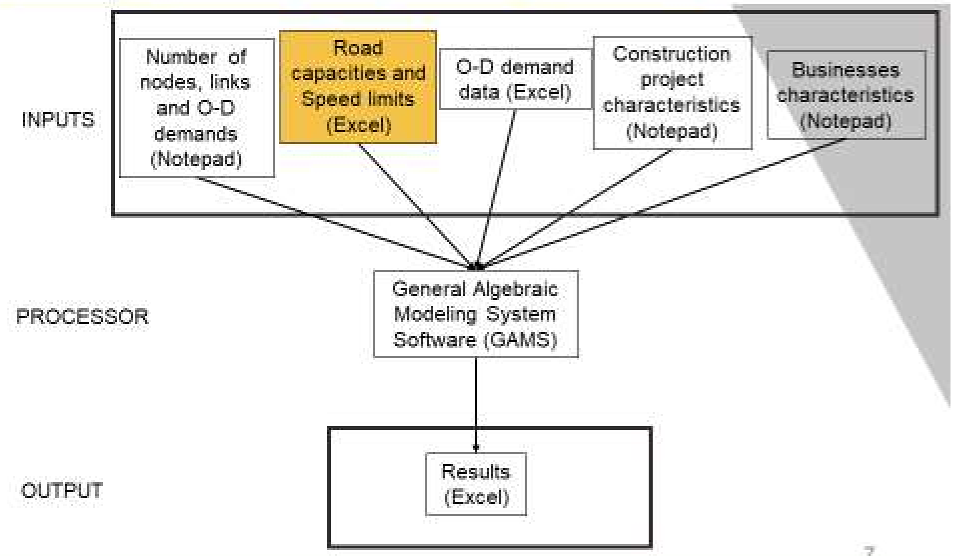
This is the GAMS index and always 1. No need to change.

Blue Squares denote the user input in all slides. For new input files, there is no need to change the other parts.

Define the number of time periods. The construction horizon is 3 years which is divided into 9 periods over which activities take place. The duration of each period is 4 months.

Set definition
In this case, we have used j and ii as other names for the index i for modeling purposes.

6

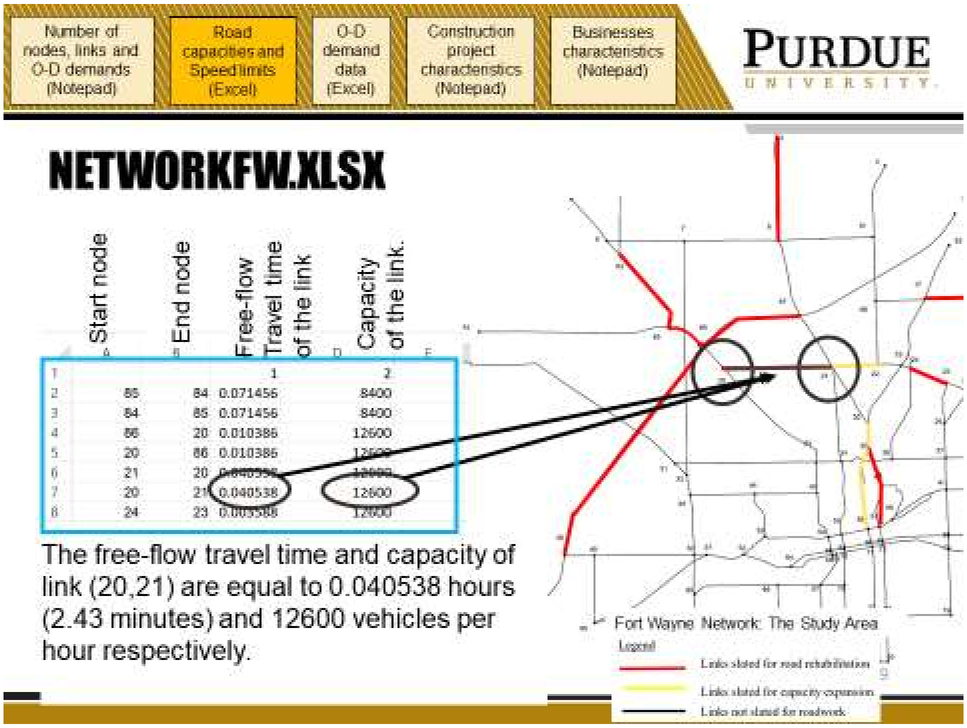


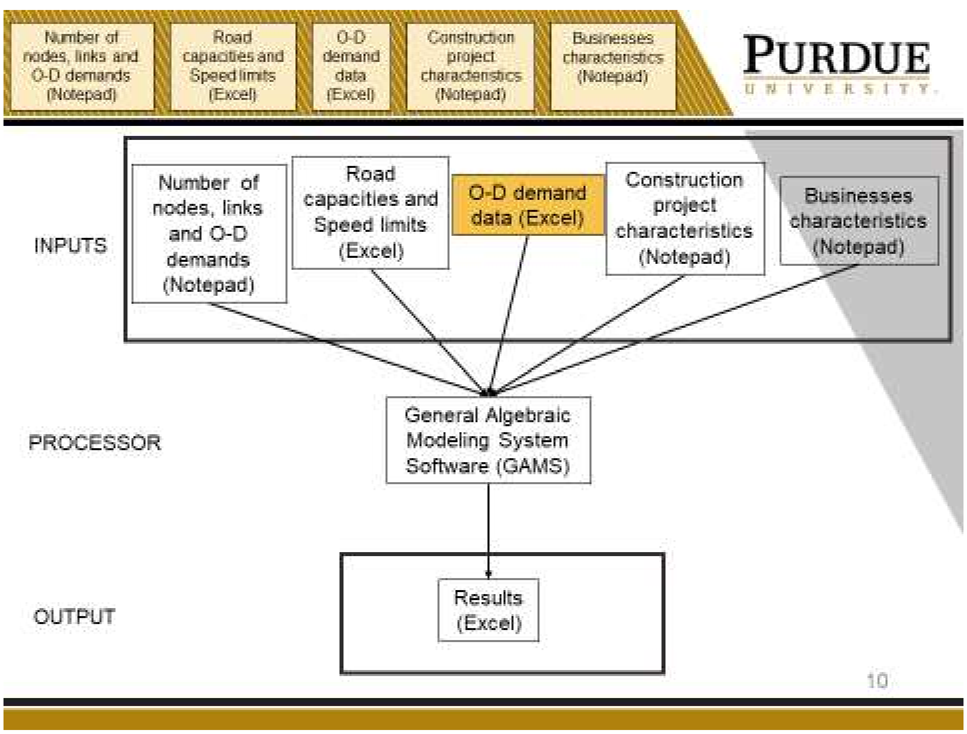
Number of nodes, links and O-D demands (Notepad) | Road capacities and Speed limits (Excel) | O-D demand data (Excel) | Construction project characteristics (Notepad) | Businesses characteristics (Notepad)
PURDUE UNIVERSITY

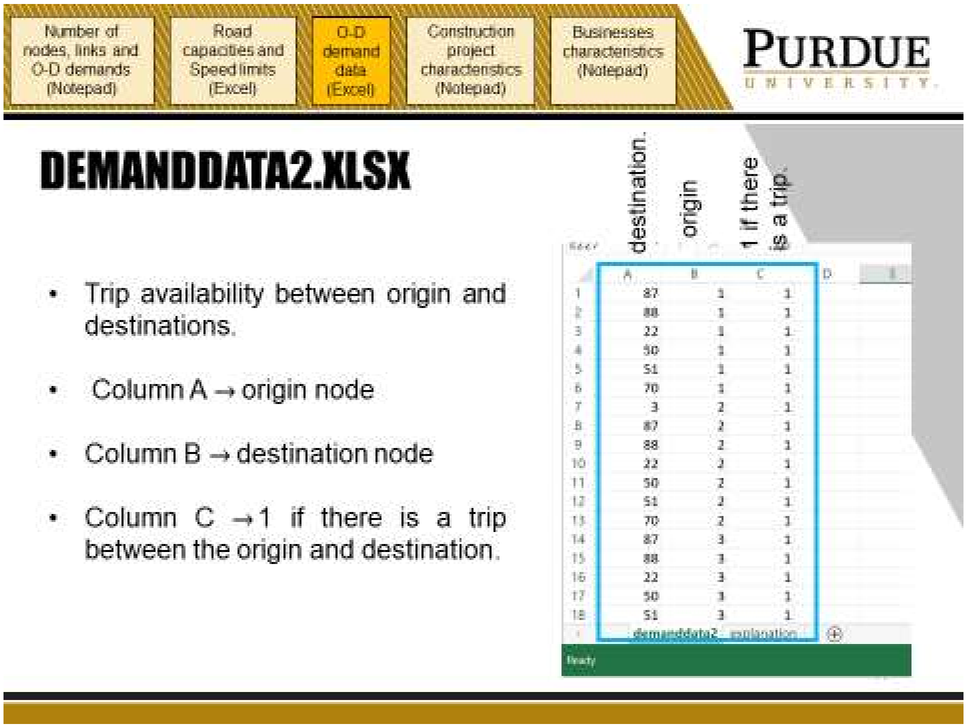
NETWORKFW.XLSX

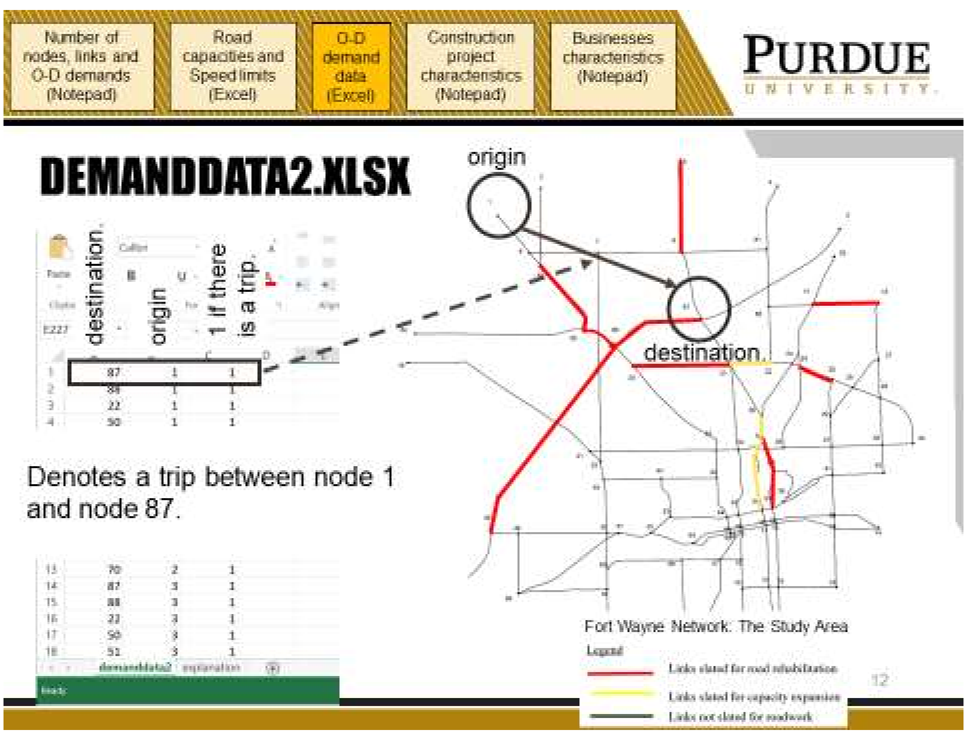
- Column A → start node of the link
- Column B → end node of the link
- Column C → free-flow travel time (in hours)
  - Derived by dividing the link length to the speed limit in the link
- Column D → capacity of the link (in vehicles per hour)

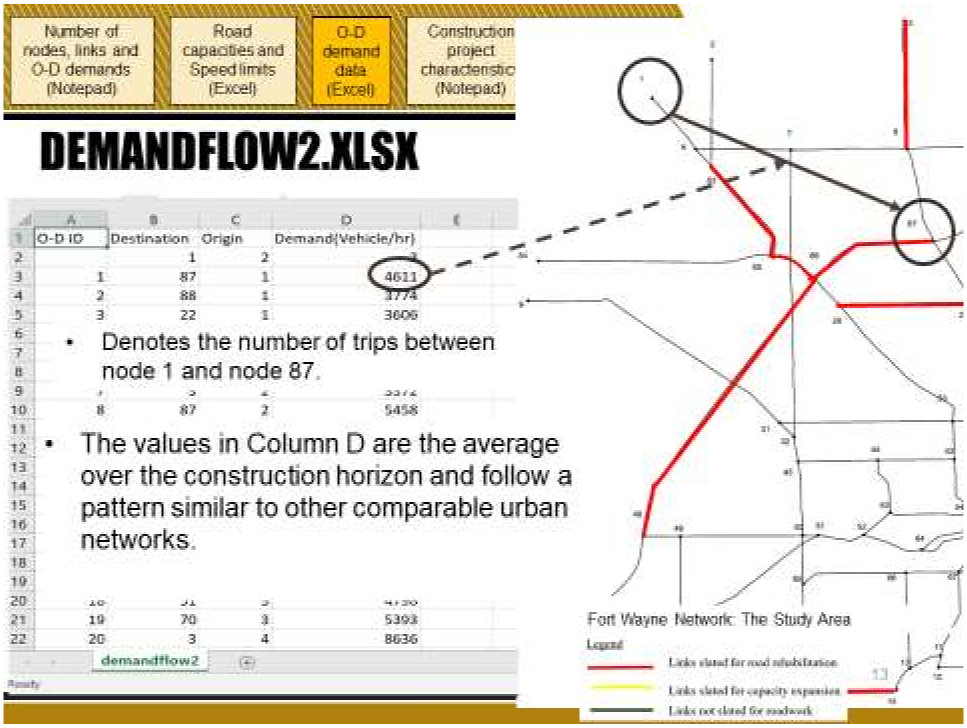
	A (Start node)	B (End node)	C (Free-flow Travel time of the link)	D (Capacity of the link)
1			1	2
2	85	84	0.071456	8400
3	84	85	0.071456	8400
4	86	20	0.010386	12600
5	20	86	0.010386	12600
6	21	20	0.040538	12600
7	20	21	0.040538	12600
8	24	23	0.003588	12600
9	23	24	0.003588	12600
10	25	24	0.014364	12600
11	24	25	0.014364	12600
12	26	25	0.009458	12600
13	25	26	0.009458	12600
14	28	26	0.012097	8400
15	26	28	0.012097	8400
16	39	28	0.026339	8400
17	28	39	0.026339	8400
18	31	19	0.108511	7600

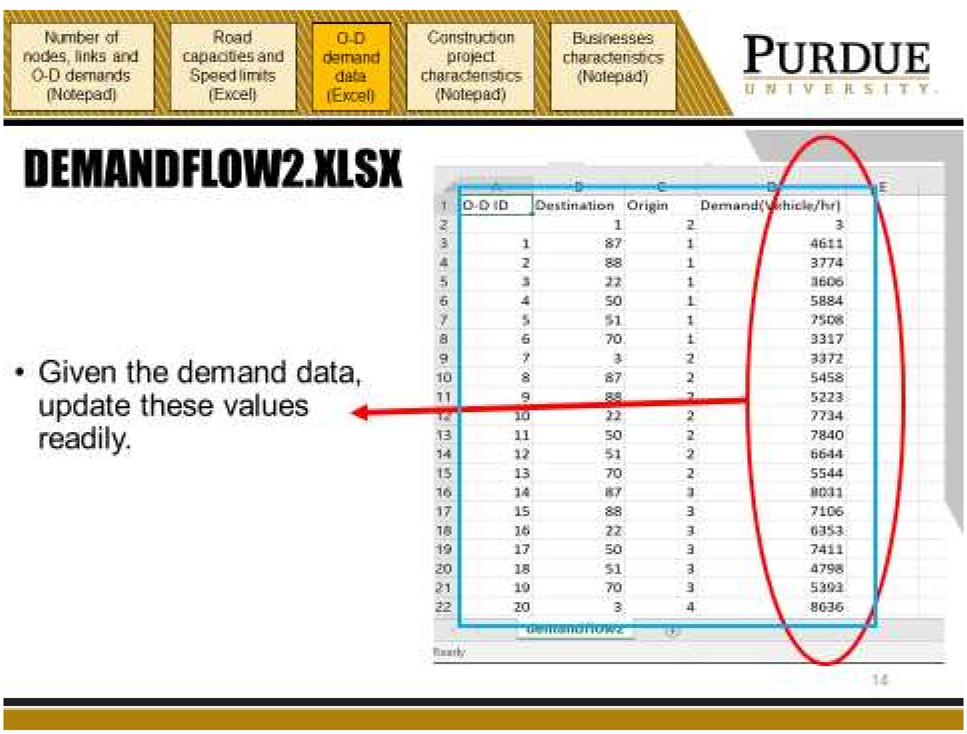

Number of nodes, links and O-D demands (Notepad)
Road capacities and Speed limits (Excel)
O-D demand data (Excel)
Construction project characteristics (Notepad)
Businesses characteristics (Notepad)
PURDUE UNIVERSITY
NETWORKFW.XLSX
Start node
End node
Free-flow Travel time of the link
Capacity of the link.
1 2
85 84 0.071456 8400
84 85 0.071456 8400
86 20 0.010386 12600
20 86 0.010386
21 20
20 21 0.040538 12600
24 23
The free-flow travel time and capacity of link (20,21) are equal to 0.040538 hours (2.43 minutes) and 12600 vehicles per hour respectively.
Fort Wayne Network: The Study Area
Legend
Links slated for road rehabilitation
Links slated for capacity expansion
Links not slated for roadwork


Number of nodes, links and O-D demands (Notepad)
Road capacities and Speed limits (Excel)
O-D demand data (Excel)
Construction project characteristics (Notepad)
Businesses characteristics (Notepad)
PURDUE UNIVERSITY
INPUTS
Number of nodes, links and O-D demands (Notepad)
Road capacities and Speed limits (Excel)
O-D demand data (Excel)
Construction project characteristics (Notepad)
Businesses characteristics (Notepad)
PROCESSOR
General Algebraic Modeling System Software (GAMS)
OUTPUT
Results (Excel)
10

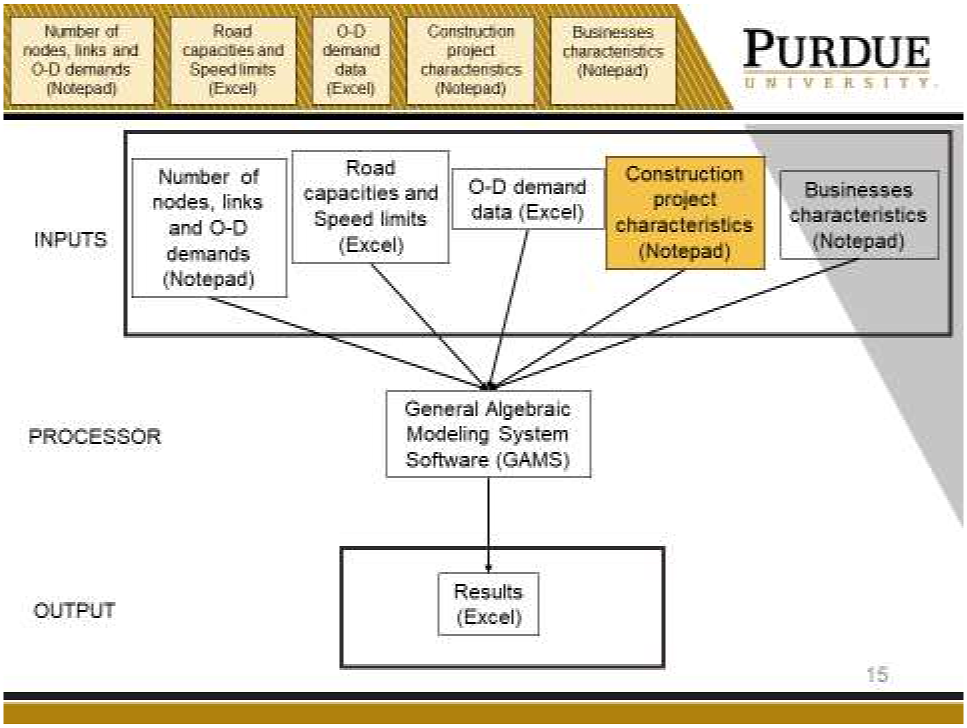

Number of nodes, links and O-D demands (Notepad)
Road capacities and Speed limits (Excel)
O-D demand data (Excel)
Construction project characteristics (Notepad)
Businesses characteristics (Notepad)
PURDUE UNIVERSITY
DEMANDDATA2.XLSX
• Trip availability between origin and destinations.
• Column A → origin node
• Column B → destination node
• Column C →1 if there is a trip between the origin and destination.
destination.
origin
1 if there is a trip.
A B C D
1 87 1 1
2 88 1 1
3 22 1 1
4 50 1 1
5 51 1 1
6 70 1 1
7 3 2 1
8 87 2 1
9 88 2 1
10 22 2 1
11 50 2 1
12 51 2 1
13 70 2 1
14 87 3 1
15 88 3 1
16 22 3 1
17 50 3 1
18 51 3 1
demanddata2 explanation
Ready

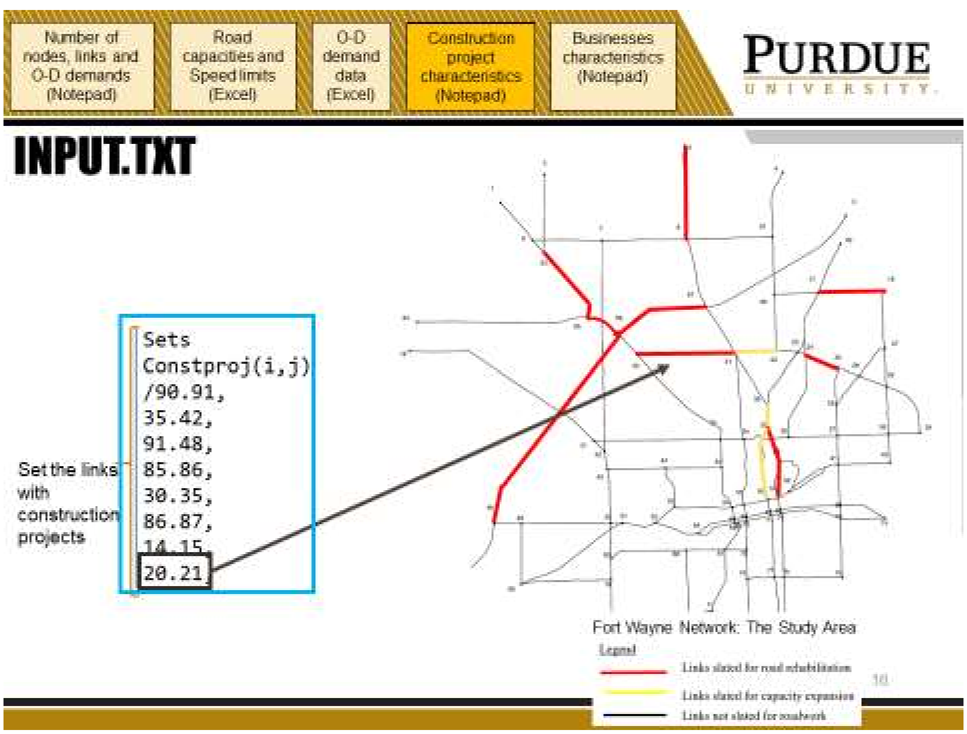

Number of nodes, links and O-D demands (Notepad)
Road capacities and Speed limits (Excel)
O-D demand data (Excel)
Construction project characteristics (Notepad)
Businesses characteristics (Notepad)
PURDUE UNIVERSITY
DEMANDDATA2.XLSX
destination.
origin
1 if there is a trip.
1 87 1 1
2 88 1 1
3 22 1 1
4 50 1 1
Denotes a trip between node 1 and node 87.
13 70 2 1
14 87 3 1
15 88 3 1
16 22 3 1
17 50 3 1
18 51 3 1
demanddata2 explanation
Ready
origin
destination.
Fort Wayne Network: The Study Area
Legend
Links slated for road rehabilitation
Links slated for capacity expansion
Links not slated for roadwork
12





O-D ID	Destination	Origin	Demand(Vehicle/hr)
	1	2	3
1	87	1	4611
2	88	1	3774
3	22	1	3606
4	50	1	5884
5	51	1	7508
6	70	1	3317
7	3	2	3372
8	87	2	5458
9	88	2	5223
10	22	2	7734
11	50	2	7840
12	51	2	6644
13	70	2	5544
14	87	3	8031
15	88	3	7106
16	22	3	6353
17	50	3	7411
18	51	3	4798
19	70	3	5393
20	3	4	8636


Number of nodes, links and O-D demands (Notepad)
Road capacities and Speed limits (Excel)
O-D demand data (Excel)
Construction project characteristics (Notepad)
Businesses characteristics (Notepad)
PURDUE UNIVERSITY.
INPUTS
Number of nodes, links and O-D demands (Notepad)
Road capacities and Speed limits (Excel)
O-D demand data (Excel)
Construction project characteristics (Notepad)
Businesses characteristics (Notepad)
PROCESSOR
General Algebraic Modeling System Software (GAMS)
OUTPUT
Results (Excel)
15


Number of nodes, links and O-D demands (Notepad)
Road capacities and Speed limits (Excel)
O-D demand data (Excel)
Construction project characteristics (Notepad)
Businesses characteristics (Notepad)
PURDUE UNIVERSITY.
INPUT.TXT
Set the links with construction projects
Sets
Constproj(i,j)
/90.91,
35.42,
91.48,
85.86,
30.35,
86.87,
14.15,
20.21
Fort Wayne Network: The Study Area
Legend
Links slated for road rehabilitation
Links slated for capacity expansion
Links not slated for roadwork
16

Number of nodes, links and O-D demands (Notepad) | Road capacities and Speed limits (Excel) | O-D demand data (Excel) | Construction project characteristics (Notepad) | Businesses characteristics (Notepad)

PURDUE UNIVERSITY

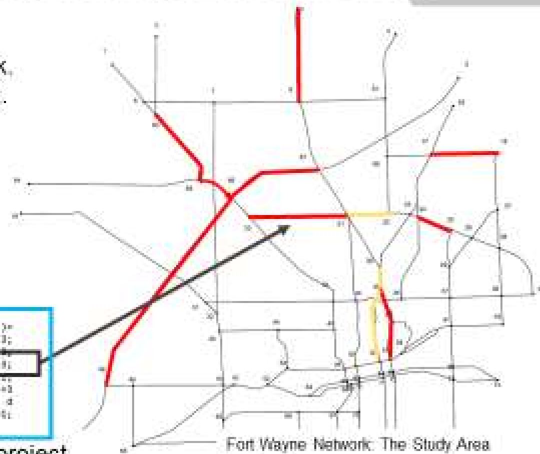
MODELANDPROJECTCHARACTERISTICS.TXT

$d(i, j, s)$

- i → start node of the link.
- j → end node of the link.
- s → gams set index.

```
parameter
d(i,j,s)
d('90','91','1')=4; d('91','90','1')=4; d('35','42','1')=
d('91','48','1')=3; d('48','91','1')=3; d('85','86','1')=3;
d('38','35','1')=2; d('35','38','1')=2 [illegible]
d('14','15','1')=2; d('15','14','1')=2 d('20','21','1')=3;
d('17','18','1')=1; d('18','17','1')=1 [illegible]
d('35','56','1')=3;                      d('83','85','1')=3
d('86','98','1')=3; d('98','86','1')=3; d('3','8','1')=1; d
d('42','57','1')=1; d('57','42','1')=1; d('21','22','1')=1;
```

The duration of construction project on link (20,21) is 3 periods (i.e., 12 months).



Fort Wayne Network: The Study Area

Legend

- Links slated for road rehabilitation
- Links slated for capacity expansion
- Links not slated for roadwork

Number of nodes, links and O-D demands (Notepad) | Road capacities and Speed limits (Excel) | O-D demand data (Excel) | Construction project characteristics (Notepad) | Businesses characteristics (Notepad)

PURDUE UNIVERSITY

MODELANDPROJECTCHARACTERISTICS.TXT

The impacts of construction projects on road capacities

$c(i, j, s, m)$

- i → start node of the link.
- j → end node of the link.
- s → gams set index.
- m → m-th period after starting the project on link (i, j).

Table

c(i,j,s,m)

	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9
90.91	0	0	0	0	1	1	1	1	1
35.42	0	0	0	1	1	1	1	1	1
91.48	0	0	0	1	1	1	1	1	1
85.86	0.5	0.5	0.5	1	1	1	1	1	1
38.35	0.5	0.5	1.25	1.25	1.25	1.25	1.25	1.25	1.25
86.87	0.5	0.5	1	1	1	1	1	1	1
14.15	0.5	0.5	1	1	1	1	1	1	1
20.21	0.5	0.5	0.5	1	1	1	1	1	1

Impact of construction after project implementation (first period, second period,….)

18

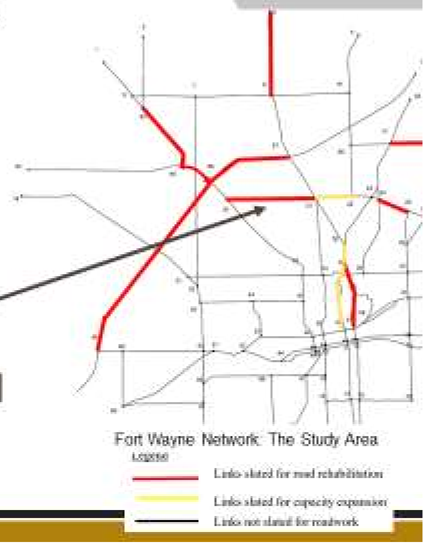
MODELANDPROJECTCHARACTERISTICS.TXT

The construction project on link (20,21) leads to capacity reduction by half on this link during project implementation (3 periods), and then capacity after 3 periods returns to the pre-construction level.

Table

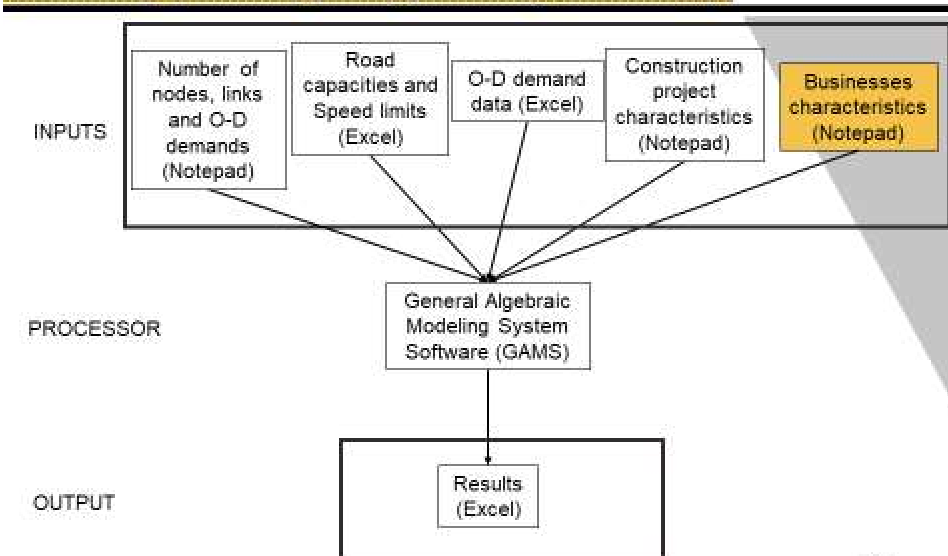
c(i,j,s,m)

	1.1	1.2	1.3	1.4	1.5
90.91	0	0	0	0	1
35.42	0	0	0	1	1
91.48	0	0	0	1	1
85.86	0.5	0.5	0.5	1	1
30.35	0.5	0.5	1.25	1.25	1.25
86.87	0.5	0.5	1	1	1
14.15	0.5	0.5	1	1	1
20.21	0.5	0.5	0.5	1	1

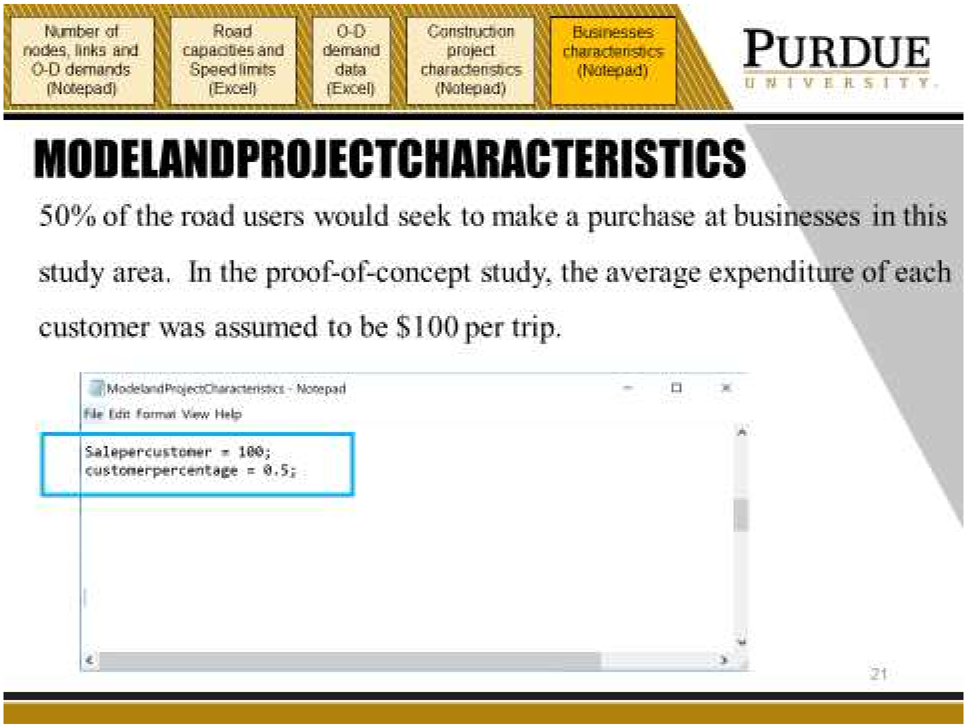


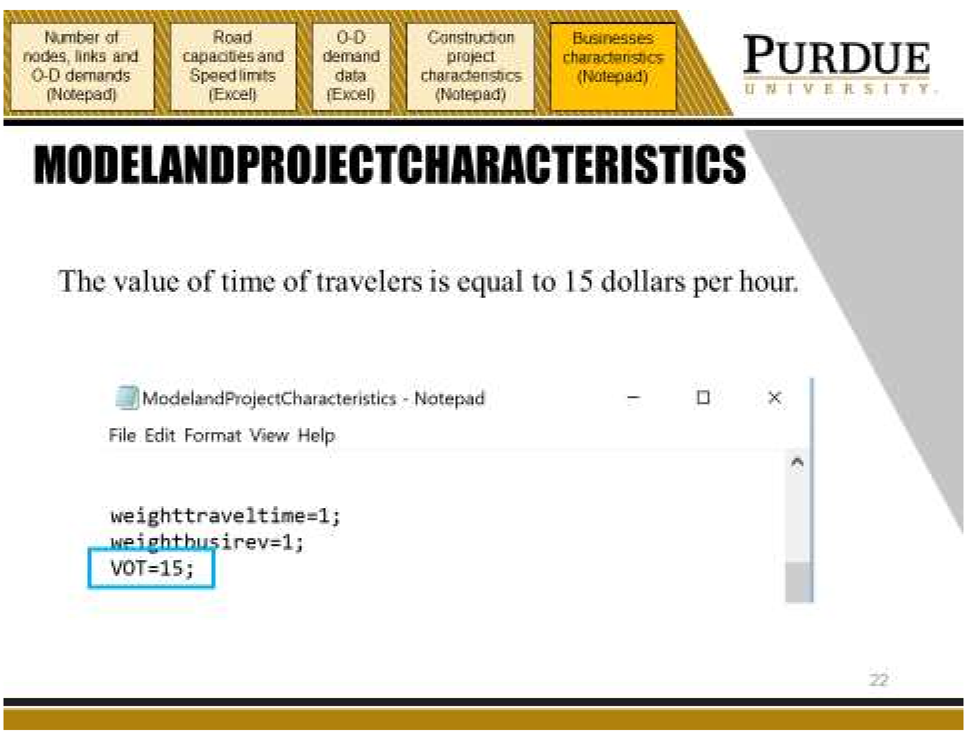
Fort Wayne Network: The Study Area

Number of nodes, links and O-D demands (Notepad) | Road capacities and Speed limits (Excel) | O-D demand data (Excel) | Construction project characteristics (Notepad) | Businesses characteristics (Notepad)
PURDUE UNIVERSITY.



20


Number of nodes, links and O-D demands (Notepad)
Road capacities and Speed limits (Excel)
O-D demand data (Excel)
Construction project characteristics (Notepad)
Businesses characteristics (Notepad)
PURDUE UNIVERSITY.
MODELANDPROJECTCHARACTERISTICS
50% of the road users would seek to make a purchase at businesses in this study area. In the proof-of-concept study, the average expenditure of each customer was assumed to be $100 per trip.
ModelandProjectCharacteristics - Notepad
File Edit Format View Help
Salepercustomer = 100;
customerpercentage = 0.5;
21


Number of nodes, links and O-D demands (Notepad)
Road capacities and Speed limits (Excel)
O-D demand data (Excel)
Construction project characteristics (Notepad)
Businesses characteristics (Notepad)
PURDUE UNIVERSITY.
MODELANDPROJECTCHARACTERISTICS
The value of time of travelers is equal to 15 dollars per hour.
ModelandProjectCharacteristics - Notepad
File Edit Format View Help
weighttraveltime=1;
weightbusirev=1;
VOT=15;
22

Number of nodes, links and O-D demands (Notepad) | Road capacities and Speed limits (Excel) | O-D demand data (Excel) | Construction project characteristics (Notepad) | **Businesses characteristics (Notepad)**

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MODELANDPROJECTCHARACTERISTICS

The weight of each system travel time dollar has been set to 1.

The weight of each business revenue dollar compared to system travel time is given by w. In this case study, w is set to be 1.

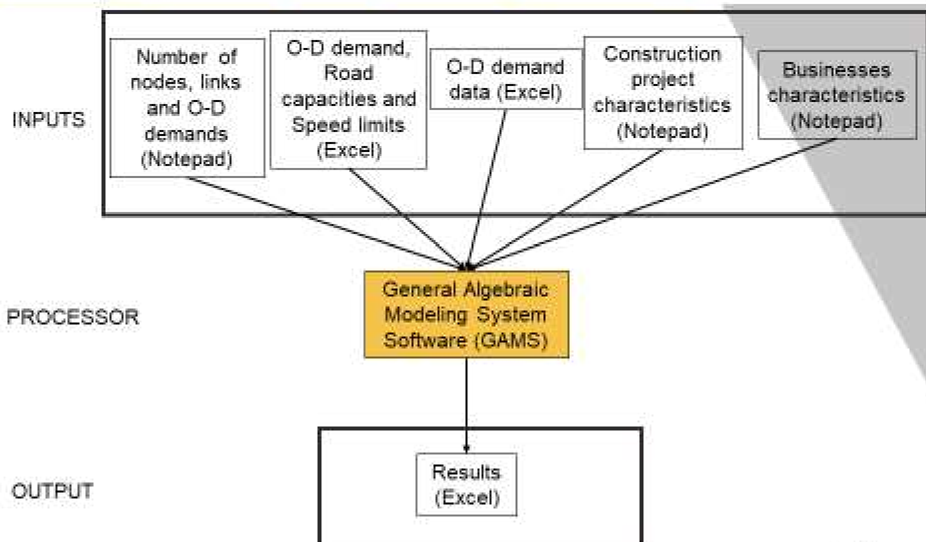
ModelandProjectCharacteristics - Notepad

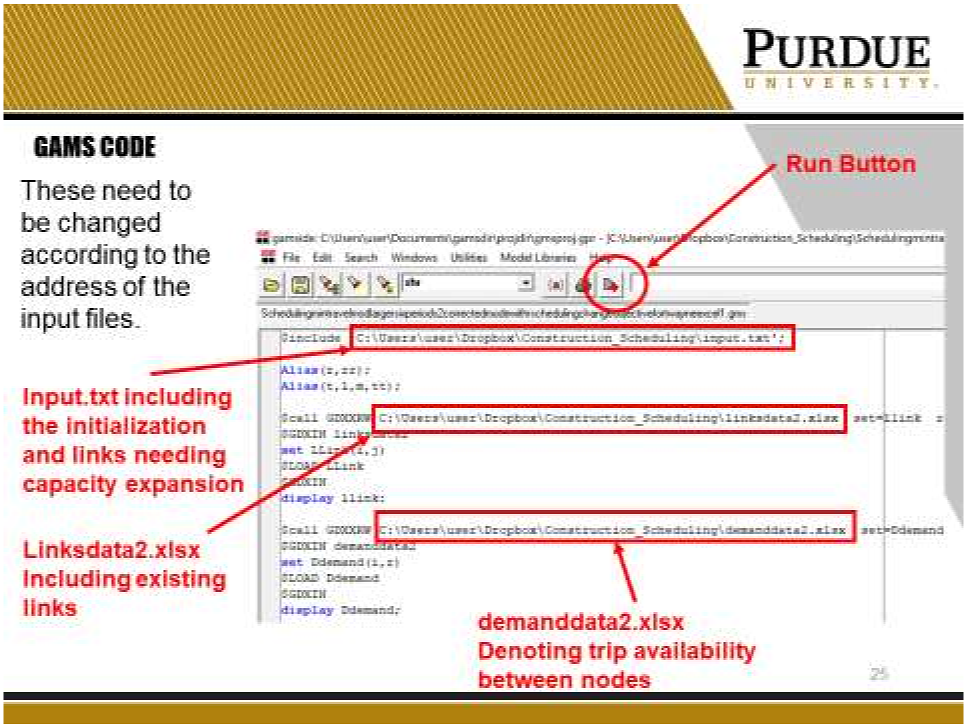
File Edit Format View Help

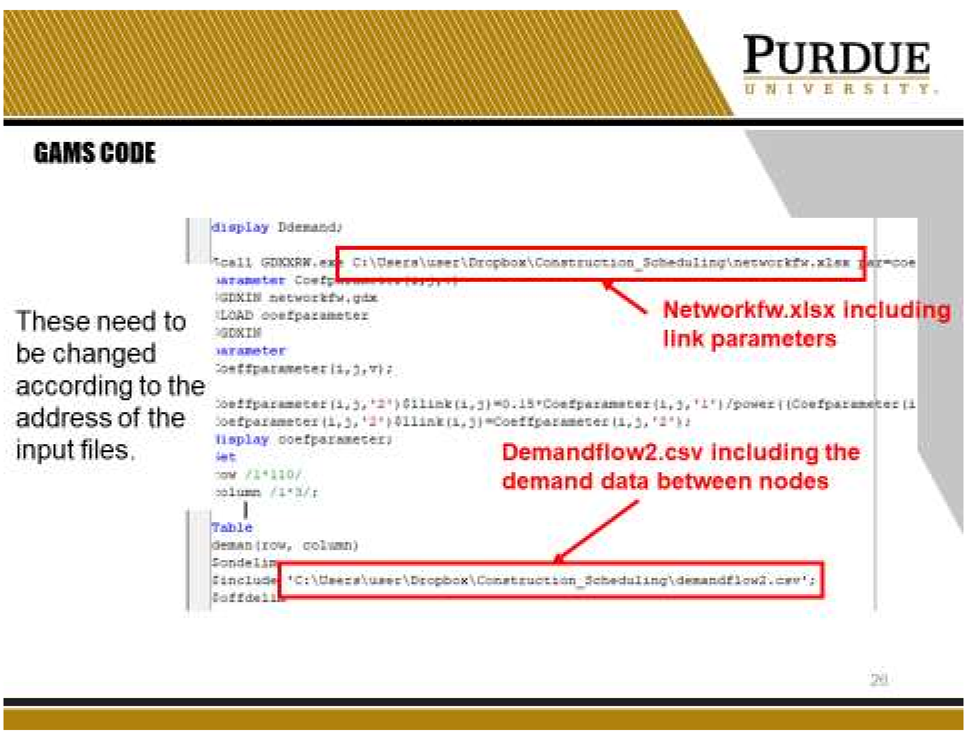
```
Parameter w;
weighttraveltime= 1;
weightbusirev= w ;
```

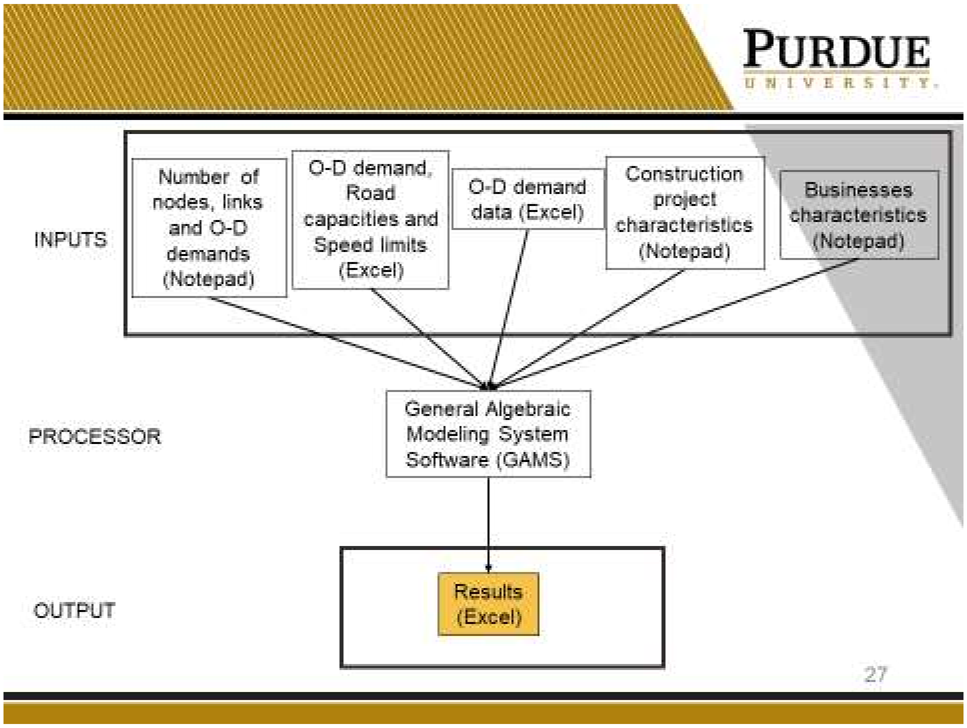

Number of nodes, links and O-D demands (Notepad) | Road capacities and Speed limits (Excel) | O-D demand data (Excel) | Construction project characteristics (Notepad) | Businesses characteristics (Notepad)

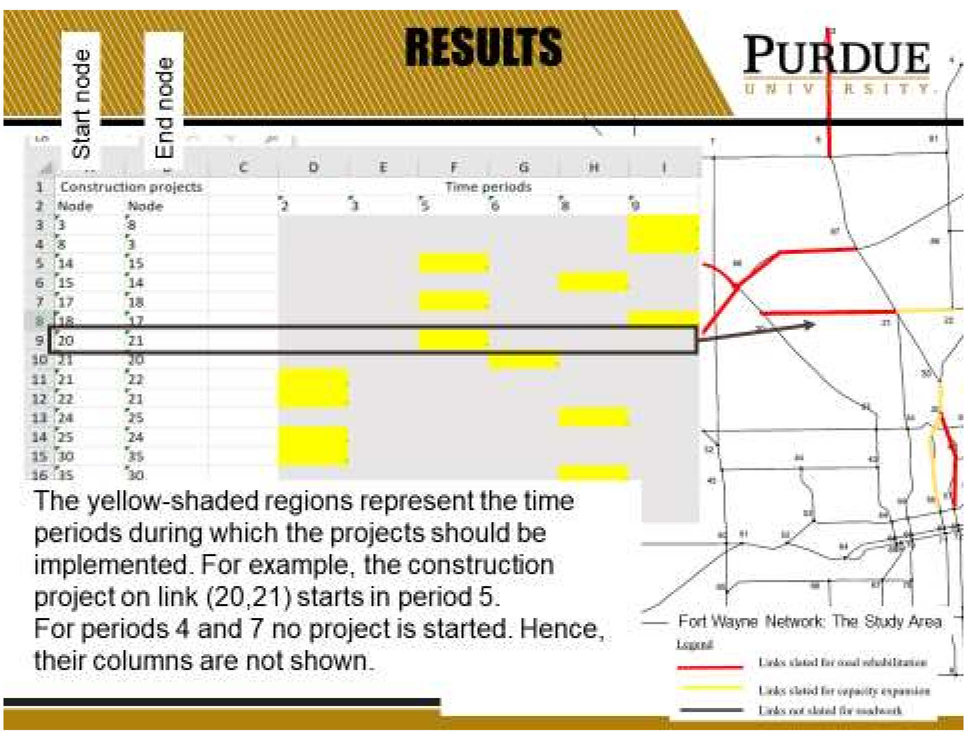
PURDUE UNIVERSITY

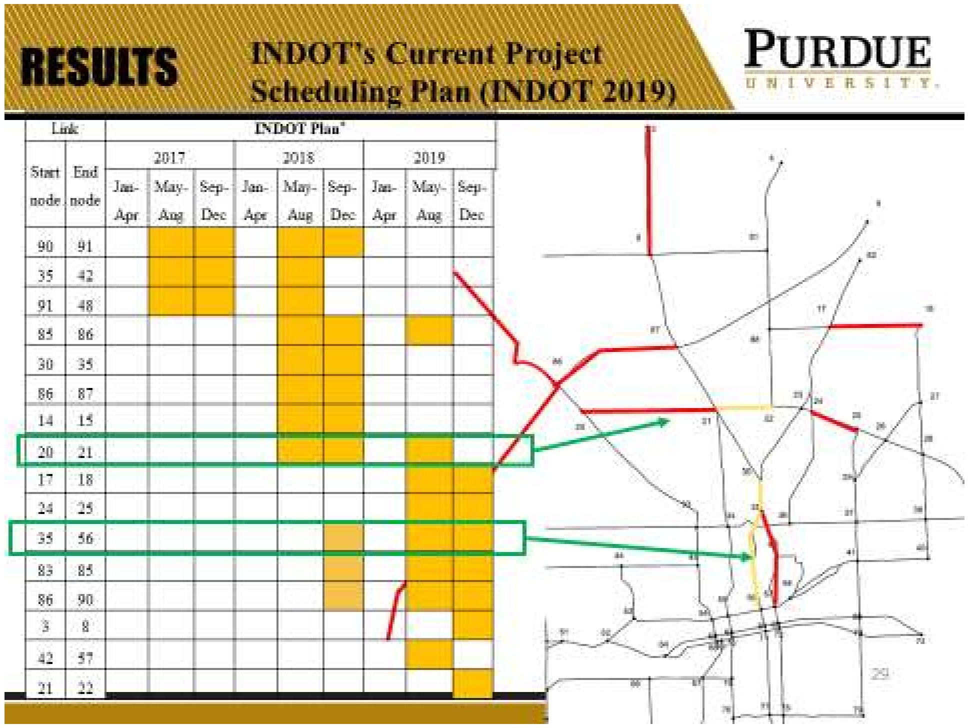



PURDUE
UNIVERSITY.
GAMS CODE
These need to be changed according to the address of the input files.
Run Button
$include 'C:\Users\user\Dropbox\Construction_Scheduling\input.txt';
Alias(r,rr);
Alias(t,l,m,tt);
$call GDXXRW C:\Users\user\Dropbox\Construction_Scheduling\linksdata2.xlsx
display llink;
$call GDXXRW C:\Users\user\Dropbox\Construction_Scheduling\demanddata2.xlsx
set Ddemand(i,r)
$LOAD Ddemand
$GDXIN
display Ddemand;
Input.txt including the initialization and links needing capacity expansion
Linksdata2.xlsx Including existing links
demanddata2.xlsx Denoting trip availability between nodes
25

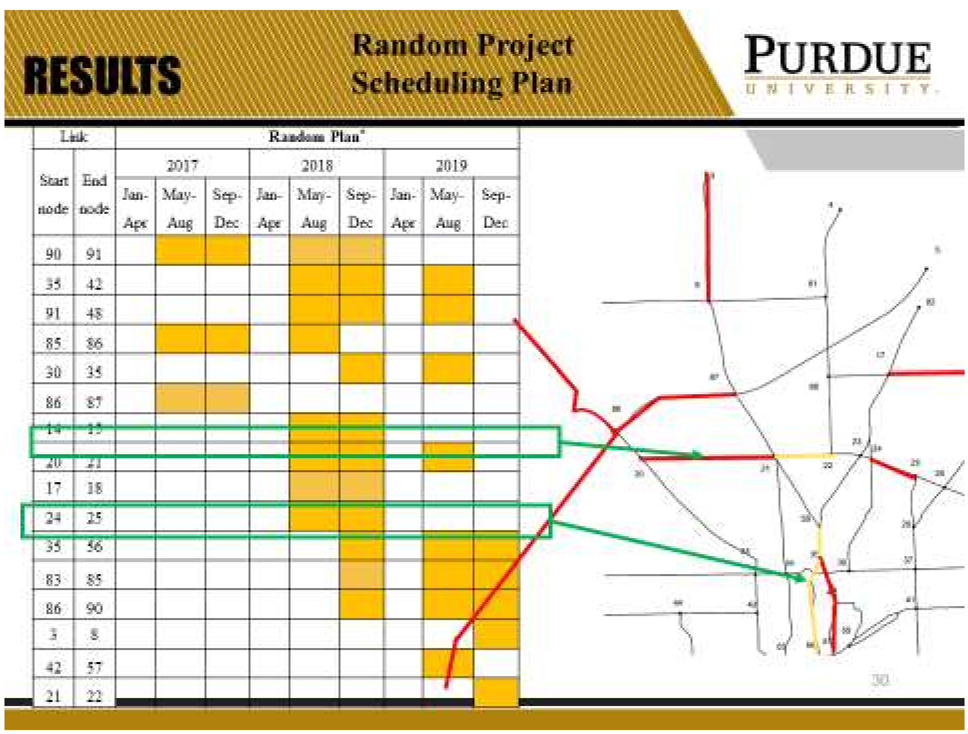

PURDUE
UNIVERSITY.
GAMS CODE
display Ddemand;
C:\Users\user\Dropbox\Construction_Scheduling\networkfw.xlsx
Networkfw.xlsx including link parameters
These need to be changed according to the address of the input files.
display coefparameter;
Demandflow2.csv including the demand data between nodes
Table
deman(row, column)
'C:\Users\user\Dropbox\Construction_Scheduling\demandflow2.csv';
26


PURDUE UNIVERSITY
INPUTS
Number of nodes, links and O-D demands (Notepad)
O-D demand, Road capacities and Speed limits (Excel)
O-D demand data (Excel)
Construction project characteristics (Notepad)
Businesses characteristics (Notepad)
PROCESSOR
General Algebraic Modeling System Software (GAMS)
OUTPUT
Results (Excel)
27


RESULTS
PURDUE UNIVERSITY
Start node
End node
Construction projects
Time periods
Node
Node
The yellow-shaded regions represent the time periods during which the projects should be implemented. For example, the construction project on link (20,21) starts in period 5.
For periods 4 and 7 no project is started. Hence, their columns are not shown.
Fort Wayne Network: The Study Area



Link		INDOT Plan*								
		2017			2018			2019		
Start node	End node	Jan-Apr	May-Aug	Sep-Dec	Jan-Apr	May-Aug	Sep-Dec	Jan-Apr	May-Aug	Sep-Dec
90	91									
35	42									
91	48									
85	86									
30	35									
86	87									
14	15									
20	21									
17	18									
24	25									
35	56									
83	85									
86	90									
3	8									
42	57									
21	22									



Link		Random Plan*								
		2017			2018			2019		
Start node	End node	Jan-Apr	May-Aug	Sep-Dec	Jan-Apr	May-Aug	Sep-Dec	Jan-Apr	May-Aug	Sep-Dec
90	91									
35	42									
91	48									
85	86									
30	35									
86	87									
14	15									
20	21									
17	18									
24	25									
35	56									
83	85									
86	90									
3	8									
42	57									
21	22									

RESULTS

Optimal Project Scheduling Plan

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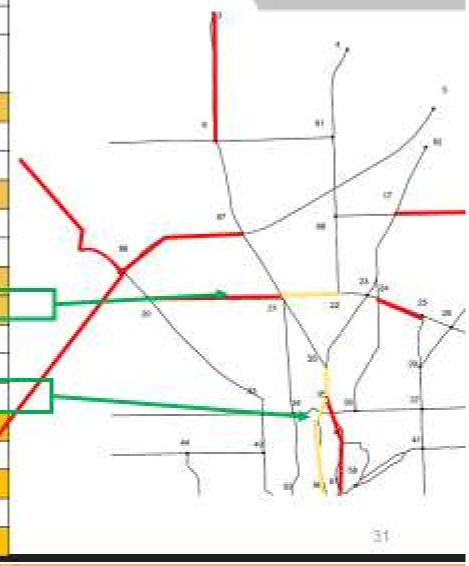
Link		Optimal Plan*								
Start node	End node	2017			2018			2019		
		Jan-Apr	May-Aug	Sep-Dec	Jan-Apr	May-Aug	Sep-Dec	Jan-Apr	May-Aug	Sep-Dec
90	91									
35	42									
91	48									
85	86									
30	35									
86	87									
14	15									
20	21									
17	18									
24	25									
35	56									
83	85									
86	90									
3	8									
42	57									
21	22									



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About the Joint Transportation Research Program (JTRP)

On March 11, 1937, the Indiana Legislature passed an act which authorized the Indiana State Highway Commission to cooperate with and assist Purdue University in developing the best methods of improving and maintaining the highways of the state and the respective counties thereof. That collaborative effort was called the Joint Highway Research Project (JHRP). In 1997 the collaborative venture was renamed as the Joint Transportation Research Program (JTRP) to reflect the state and national efforts to integrate the management and operation of various transportation modes.

The first studies of JHRP were concerned with Test Road No. 1—evaluation of the weathering characteristics of stabilized materials. After World War II, the JHRP program grew substantially and was regularly producing technical reports. Over 1,600 technical reports are now available, published as part of the JHRP and subsequently JTRP collaborative venture between Purdue University and what is now the Indiana Department of Transportation.

Free online access to all reports is provided through a unique collaboration between JTRP and Purdue Libraries. These are available at http://docs.lib.purdue.edu/jtrp.

Further information about JTRP and its current research program is available at http://www.purdue.edu/jtrp.

About This Report

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Recommended Citation

Woldemariam, W., Agyemang, A., Miralinaghi, M., Abraham, D. M., & Sinha, K. (2019). *Network-level scheduling of road projects during the construction season considering network connectivity* (Joint Transportation Research Program Publication No. FHWA/IN/JTRP-2019/25). West Lafayette, IN: Purdue University. https://doi.org/10.5703/1288284317105