



Accelerated Construction Decision-Making Process for Bridges

MRUTC Project 05 -04
April 2006

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Technical Report Documentation Page

1. Report No. MRUTC 05-04	2. Government Accession No.	3. Recipient's Catalog No. CFDA 20.701	
4. Title and Subtitle Accelerated Construction Decision-Making Process For Bridges		5. Report Date April 30, 2006	
		6. Performing Organization Code	
7. Author/s Sam Salem, PhD., P.E, CPC and Richard Miller, PhD., P.E Civil and Environmental Engineering Department, P.O. Box 210071, University of Cincinnati, Ohio 45221		8. Performing Organization Report No. MRUTC 05-04	
9. Performing Organization Name and Address Midwest Regional University Transportation Center University of Wisconsin-Madison 1415 Engineering Drive, Madison, WI 53706		10. Work Unit No. (TRAIS)	
		11. Contract or Grant No. 997 B 684	
12. Sponsoring Organization Name and Address U.S. Department of Transportation Research and Special Programs Administration 400 7th Street, SW Washington, DC 20590-0001		13. Type of Report and Period Covered May 2004 – April 2006	
		14. Sponsoring Agency Code	
15. Supplementary Notes Project completed for the Midwest Regional University Transportation Center with support from the Wisconsin Department of Transportation.			
16. Abstract <p>The decision making process for selecting appropriate construction plan for rehabilitation / reconstruction of bridges involves evaluating plans for their performance on qualitative and quantitative metrics. The decision maker has to decide the relative importance of various criteria in the decision making process. The qualitative nature of some of the criteria such as mitigation of impact on communities, businesses, environment, ensuring safety of stakeholders makes it difficult to establish a transparent decision making process. It is sometimes difficult for the decision-maker to justify extra expenditure for accelerating construction to achieve these non-quantifiable objectives.</p> <p>The decision making process developed in this research study is based on Analytical Hierarchy Process. It provides the decision maker with a tool to transparently extract quantitative weights which reflect the relative importance of both qualitative and quantitative criteria in the decision making process. It also enables the decision maker to evaluate various alternative construction strategies for their performance in meeting these qualitative and quantitative criteria.</p>			
17. Key Words Accelerated Construction, Bridges, Analytical Hierarchy Process, Decision Making System		18. Distribution Statement No restrictions. This report is available through the Transportation Research Information Services of the National Transportation Library.	
19. Security Classification (of this report) Unclassified	20. Security Classification (of this page) Unclassified	21. No. Of Pages 115	22. Price -0-

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This research was funded by the Midwest Regional University Transportation Center, Ohio Department of Transportation and the US Department of Transportation's Research and Innovative Technology Administration under Project MRUTC 05-04. The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the information presented herein. This document is disseminated under the sponsorship of the Department of Transportation, University Transportation Centers Program, in the interest of information exchange. The U.S. Government assumes no liability for the contents or use thereof. The contents do not necessarily reflect the official views of the Midwest Regional University Transportation Center, the University of Wisconsin, Wisconsin Department of Transportation or the US Department of Transportation's Research and Innovative Technology Administration at the time of publication.

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ACKNOWLEDGEMENTS

The authors would like to acknowledge the support provided by Midwest Regional University Transportation Center, Ohio Department of Transportation and the US Department of Transportation's Research and Innovative Technology Administration for this research study. The authors would also like to thank various state departments of transportation for their participation in questionnaire surveys and their valuable feedback.

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Executive Summary

The National Bridge Inventory shows that more than 480,000 bridges that serve the U.S highways are of a median age of more than 42 years and a design life of 50 years. According to statistics reported by the Federal Highway Administration (FHWA), approximately 14 and 16 percent of the bridge inventory falls into the functional and structural deficient categories, respectively. Not only must the public deal with the aging and deteriorating highway system but it also has to face a significant increase in traffic volumes and congestion. In a report to the Congress on the state of nation's infrastructure, the Department of Transportation, (DOT 2000) estimated the investment required to repair or replace all functionally obsolete or structurally deficient bridges at \$87.3 billion. More than half of the known bridge deficiencies are structural deficiencies. In 2002, the biennial report of the Secretary of Transportation to the U.S. Congress, pointed out that approximately 28% of the 590,000 bridges need to be rehabilitated or replaced. If the defects are not rectified in time, the expenses required to rectify the structural defects could increase substantially.

The need for upgrades and repair usually exceeds the funds available; decision makers must determine the best use of limited funds available. Unfortunately, the decision is more complicated than simply identifying those parts of the infrastructure most in need of repair, upgrade or replacement. In a mature infrastructure system, upgrade, repair, or replacement requires either restriction or closure of those parts of the

system. Traffic disruption during maintenance and construction activities frequently results in disruptions to local economies and communities; and raises issues of safety and congestion. The use of traditional technologies and techniques for infrastructure rehabilitation are not effective enough to mitigate these disruptive effects of rehabilitation work. A systems approach to accelerating infrastructure construction is required to mitigate the impact of the extensive rehabilitation activities that are likely to take place in immediate future.

FHWA is promoting the Accelerated Construction Technology Transfer (ACTT) as a new philosophy of project delivery which combines the use of innovative technologies such as Precast Components and Systems and innovative contracting methods such as A+B contracting. **The main objectives of ACTT are enhanced safety & mobility, reduced construction time and better quality of construction, lower life cycle costs, less traffic congestion, reduced environmental, socio-economical impacts.** The Ohio Department of Transportation has started the Strategic Initiative #9 (SI#9), “*Build Bridges Smarter, Faster, Cheaper*”, identifying bridges as a significant source of delays in the reconstruction process for roadways. This Strategic Initiative is exploring ways to minimize the down time of bridge structures by either constructing faster and/or improving quality to minimize future down time for repair or maintenance.

The decision making process for identifying an optimum strategy for construction of bridges requires careful evaluation of a number of factors such as construction costs, future rehabilitation costs, user costs, maintenance of traffic, quality of work, safety of motorists, safety of construction workers, safety of pedestrians, impact on surrounding communities and businesses, consideration of impact on sensitive ecosystems etc. In the

surveys of state DOTs conducted as a part of this study, it was found that all the DOTs evaluate these factors during the decision making process in a qualitative way. It was also found that factors such as impact of construction on local communities, local economy, impact on traffic flow have a significant impact on the eventual selection of a bridge construction plan.

Many of these benefits such as safety of motorists, construction workers, pedestrians, reduced impact on surrounding communities and businesses on account of accelerated construction can't be quantitatively evaluated. A decision maker may decide to choose accelerated construction of a bridge at a higher initial construction cost in order to achieve these tangible but non-quantifiable (in monetary terms) benefits. The current models proposed for decision making in such cases (viz. *Bridge Construction Plan* by El-Diariaby et. al and *Prefabricated Bridge & Element Systems* by Ralls) don't provide the decision maker a tool that transparently maps and synthesizes the trade-offs in required in the decision making system.

The decision making system proposed in this report uses Analytical Hierarchy Process (AHP) developed by Prof .Saaty at the Wharton business school in 1980. This methodology provides the decision maker with a tool to quantify the qualitative trade-offs between various objectives to extract a single set of weights which reflect the level of importance of each of the factors in the overall decision making process. The method uses pair wise comparisons to compare the relative importance of each factor with other factors using numerical / verbal scale. The Eigenvectors of the matrices obtained from the pair wise comparisons reflect the relative importance of each of the factor in the decision

making process. Finally the same **pair-wise** comparison method can be used to evaluate the proposed solutions for their efficacy in achieving the goals.

The most notable aspect of this decision making system is that it doesn't prescribe fixed arbitrary weights to various factors in the decision making system. This system provides the decision maker with a transparent, extensible, customizable method to derive weights. The decision makers can choose which factors will be addressed using the system and assign priorities to these factors and derive the weights using mathematically sound methods. This system will provide the decision makers an excellent and transparent tool to make decisions regarding choosing an optimal holistic strategy for decision making.

1 Introduction

1.1 Background of the Study:

After many years of gradually expanding and upgrading the vast highway network, the highway community is facing a big responsibility: to restore the aging highway system to good physical condition and make it perform more reliably, safely, and efficiently at minimum cost and with maximum benefit to tax payers, the environment, and the traveling public.

This mission is especially challenging because it must be achieved under heavy and escalating traffic conditions, on facilities that are aging and often in need of major repair and modernization, and under tightening budgetary constraints. In confronting these new challenges, many highway agencies are recognizing the need for greater flexibility in the way they develop and manage projects. Such flexibility is especially critical to ensuring the inflow of new products and processes. Many highway agencies are seeking to provide the innovative products and services necessary to meet the growing and changing demands being placed on the highway system.

While relatively little additional capacity is planned for the next two decades, significant growth in highway demand is expected to continue. The Vehicle Miles Traveled [VMT] is projected to increase 50 percent of the 520 by 2025. In the same time frame, truck volume is projected to double from 8.0 billion tons in 1998 to 16.8 billion tons (DOE 2004). The National Bridge Inventory shows that more than 480,000 bridges serve the U.S highways with a median age of more than 42 years and a design life of only 50 years. According to statistics reported by the Federal Highway Administration (FHWA), approximately 14 and 16 percent of the bridge inventory falls into the

functional and structural deficient categories, respectively. Not only must the public deal with the aging and deteriorating highway system but it also has to face a significant increase in traffic volumes and congestion (DOE, 2004).

In a report to the Congress on the state of nation's infrastructure, the Department of Transportation, (DOT 2000) estimated the capital investment required for ensuring satisfactory performance of the nation's highway and bridge infrastructure. It found that a total of \$166.7 billion of one time investment could be justified for maintenance of the 1997 condition and operational performance of the highway system. Approximately 72% of the investment backlog was found to be in the urban areas and the rest in rural areas. Forty two percent of the investment backlog was related to the capacity deficiency in the existing highway system whereas 58% backlog was found to be in pavement deficiencies. This figure does not contain any estimate for system enhancements or for the construction of new roads and bridges (DOT 2000).

This DOT report pegs the investment required to repair or replace all functionally obsolete or structurally deficient bridges at \$87.3 billion. In 2002, the biennial report of the Secretary of Transportation to the U.S. Congress, pointed out that approximately 28% of the 590,000 bridges need to be rehabilitated or replaced (DOT, 2002). Unless timely corrective action is taken, the social, environmental and economic costs associated with a declining system are likely to be enormous. The majority of the investment is likely to be in rehabilitation or expansion of the existing infrastructure. Texas Transportation Institute (TTI) conducted a study that found that in the 68 urban areas which were studied in 1997, Americans wasted 6.7 billion gallons of fuel and 4.3 billion hours of time annually because of congestion. TTI pegged the cost of these delays at \$ 72 billion annually. The

economic impact of continuation of traditional philosophy and techniques of project delivery over next two decades is too enormous to ignore. The concept of a systems approach to accelerating infrastructure construction was proposed to mitigate the impact of the extensive rehabilitation activities that are likely to take place in immediate future.

In 1997, nationwide bridge expenditures related to system preservation and construction of new highway bridges were US\$6.1 billion and US\$10.0 billion, respectively. Because the need for upgrades and repair usually exceeds the funds available, decision makers must determine the best use of limited funds available. Unfortunately, the decision is more complicated than simply identifying those parts of the infrastructure most in need of repair, upgrade or replacement. In a mature infrastructure system, upgrade, repair, or replacement requires either restriction or closure of those parts of the system. Traffic disruption during maintenance and construction activities frequently results in disruptions to local economies and commuters; and raises issues of safety and congestion.

Therefore, a decision maker must concentrate on more than just which parts of the systems are most in need of repair, upgrade or replacement. The decision maker must also consider issues such as:

- Should the affected part of the system be fully closed or partially restricted?
- Should the method of construction chosen be that which has the lowest initial cost (thus freeing up funds for other projects) or the one which has the lowest life-cycle costs?
- Should an accelerated construction method be used, even if it has higher initial cost, in order to reduce fatalities, injuries, congestion and overall user cost?
- Most decision models use short term (or initial) costs, long term costs and/or user

costs as factors in the decision, but as will be shown, these are not the only considerations.

In an effort to better manage highway infrastructure assets, the Ohio Department of Transportation (ODOT) started several initiatives aimed at reducing the problems associated with reconstruction of roadways. One initiative, Strategic Initiative #9 (SI#9), *Build Bridges Smarter, Faster, Cheaper*, identified bridges as a significant source of delays in the reconstruction process for roadways. This Strategic Initiative is exploring ways to minimize the down time of bridge structures by either constructing faster and/or improving quality to minimize future down time for repair or maintenance. The University of Cincinnati was given a contract to study various aspects of SI#9 through the use of pilot projects. One of the surprising results of the SI#9 study was that some of the barriers to minimizing down time are not technological. These barriers could be categorized as business, safety, political, environmental, and personal factors. The results of the pilot project studies show that if a contractor is given: a design which is both reasonable and capable of being built quickly; some latitude in construction materials and methods; a way of quickly resolving field problems; and a sufficient incentive, bridge down time can be decreased to a practical minimum. Thus, it appears that there are few technological barriers to minimizing bridge down time. However, it was discovered that there are significant other non-technical and policy barriers to minimizing bridge down time. Examples of these barriers are:

- Policies that require maintenance of the traffic (MOT) when closing a bridge.
- The presence of clearly identifiable business losers from bridge closures and traffic disruptions (e.g. being able to identify "Smith Industries" as being hurt

by the construction plans as opposed to business in general).

- Consideration of real, out-of-pocket costs and savings as opposed to theoretical soft costs and savings (e.g. user costs).
- Possible positive or negative impacts on the decision makers or policy makers themselves (e.g. personal incentives to decision-makers and fear from liability).

Implementation of accelerated construction initiatives should change from the traditional planning and construction approach to a systems approach that considers all possible impacts and contributing factors during the planning stage. This approach would not only consider traditional metrics such as safety, user costs, innovative financing, incentives/disincentives to contractors, and life cycle benefit/cost analysis but would also consider specific impacts on specific local businesses, impact of decisions on the decision-makers, policy makers, and DOT employees; environmental issues, political issues, and other less obvious metrics.

1.2 Objectives:

The factors which impact asset management decisions extend far beyond those which are considered in traditional asset management models. However, it would be impossible to examine these factors for the entire transportation infrastructure. It is proposed that factors affecting one particular area, bridge construction, be examined and identified. The goal of this project is to collect feedback from DOT and industry experts, through interviews and a national survey of the 50 US DOT's, as well as to use the existing SI#9 pilot projects and any future projects which may be added to identify these less obvious constraints and/or consideration in the accelerated bridge construction decision making process. The study focuses on the non-technical factors that affect the decision making

process but yet are not considered by policy makers and not reflected in policies (e.g., business, safety, environmental, social and economic factors). These factors can lead to the selection of a less favorable construction plan alternative that can lead to higher life cycle costs, higher user costs, more disruptions to traffic and local businesses, more accidents and less safe conditions, and more adverse environmental impacts. The factors are identified and a quantitative decision making model which has the capability to address all of these factors is developed. Thus this study will be used to:

- Facilitate removal of barriers to accelerated construction implementation and encourage development of strategies that generate beneficial accelerated construction policies and decisions.
- Provide decisions makers with a quantitative justification tool for their decisions.

2 Literature review:

2.1 State of infrastructure

As the Nation's system of highways and bridges ages, there is a necessity of repairing or replacing the infrastructure which translates into motorists experiencing "Work Zone" signs on a daily increasing basis. In 2000, Federal Highway Authority (FHWA) conducted a survey to measure the American public's satisfaction with the state of infrastructure (Keever, 2001). An increased dissatisfaction was found with highways that the member of public uses most often. The level of dissatisfaction grew from 17% in 1995 to 24% in 2000. It also found significant public dissatisfaction about work zone issues. 21% of public surveyed was dissatisfied with construction signage while 25% of public surveyed was dissatisfied with the safety features of work zones. The level of dissatisfaction in detour signs and directions was 26%. 56% of the public surveyed said that they were not satisfied with the speed of construction.

The survey also found that more than half of peak-hour urban interstate travel occurs under congested conditions. The delay has increased by 8.5% from 8.3 hours to 9 hours per 1000 vehicle miles traveled. The *Vehicle Miles Traveled* [VMT] on the nation's highways increased by 76 percent between 1980 and 1999 [FHWA 2001, Tables VM-202 (1980–1995) and VM-2 (1996–1999)], whereas the capacity of the system in lane-miles increased by only 3 percent [BTS 1999a, Table 1-5 (1908–1995); FHWA 2001, Table HM-60 (1996–1999)]. While relatively little additional capacity is planned for the next two decades, significant growth in highway demand is expected to continue. VMT is projected to increase 50 percent by 2025. In the same time frame, truck volume is projected to double from 8.0 billion tons in 1998 to 16.8 billion tons (DOE, 2004).

In the 2002 biennial report of the Secretary of Transportation to the U.S. Congress (DOT, 2002) pointed out that the number of people injured annually in motor vehicle crashes remained virtually unchanged from 1997- 2000, at just under 42,000 and fatalities have been around 1000 annually for last few years. Motor vehicle crashes are estimated to cost the American economy \$230 billion a year in lost productivity, medical expenses and property damage.

Year	Fatalities in US	Fatalities in Ohio
2000	1026	27
2001	989	34
2002	1186	28
2003	1028	13

Table 1: Work Zone Fatalities

(Fatality Analysis Reporting System, National Center for Statistics and Analysis)

2.1.1 Capital Investment Requirements

In a report to the Congress on the state of nations infrastructure, the US Department of Transportation (DOT, 2000) estimated the capital investment required for ensuring satisfactory performance of the nation’s highway and bridge infrastructure. It found that a total of \$166.7 billion of one time investment could be justified for maintenance of the 1997 condition and operational performance of the highway system. This figure does not include rural minor collectors, or rural and urban local roads and streets. The states and city authorities can hardly afford to neglect the maintenance of the collectors, urban and rural roads. Hence, the actual investment backlog in transportation infrastructure is likely to be much higher. Approximately 72% of the investment backlog was found to be in the

urban areas and the rest in rural areas. 42% of the investment backlog was related to the capacity deficiency in the existing highway system whereas 58% backlog was found to be in pavement deficiencies. This figure does not contain any estimate for system enhancements or for the construction of new roads and bridges. The report pegs the investment required to repair or replace all functionally obsolete or structurally deficient bridges at \$87.3 billion. More than half of the known bridge deficiencies are structural deficiencies. These deficiencies will require timely attention. If the defects are not rectified in time, the expenses required to rectify the structural defects could increase substantially. The following table shows the total investment required from 1998-2017 to maintain the current condition of the highway infrastructure. In 2002, the biennial report of the Secretary of Transportation to the U.S. Congress, pointed out that approximately 28% of the 590,000 bridges need to be rehabilitated or replaced (DOT, 2002). Unless timely corrective action is taken, the social, environmental and economic costs associated with a declining system are likely to be enormous.

The majority of the investment detailed below is likely to be in rehabilitation or expansion of the existing infrastructure. Thus, a significant amount of work will have to be carried out adjacent to the traffic. The use of traditional construction techniques and philosophy in such conditions will not only expose the motorists and construction workers to unsafe conditions but also cause a significant long term environmental and economic impact on account of lost time due to congestion. The Texas Transportation Institute estimated, in 68 urban areas it studied in 1997, Americans wasted 6.7 billion gallons of fuel and 4.3 billion hours of time annually because of congestion. TTI pegged the cost of these delays at \$ 72 billion annually. The economic impact of continuation of

traditional philosophy and techniques of project delivery over next two decades is too enormous to ignore. The concept of a systems approach to accelerating infrastructure construction was proposed to mitigate the impact of the extensive rehabilitation activities that are likely to take place in immediate future.

<i>Rural Arterials & Collectors</i>	<i>20 year Investment</i>	<i>Average Annual</i>
<i>Rural Arterials & Collectors</i>		
<i>Interstate</i>	\$73.7	\$3.7
<i>Other Principal Arterial</i>	\$ 115.8	\$5.8
<i>Minor Arterial</i>	\$61.5	\$3.1
<i>Major Collector</i>	\$81.8	\$4.1
<i>Minor Collector</i>	\$17.9	\$0.9
<i>Subtotal</i>	\$350.6	\$17.5
<i>Urban Arterials & Collectors</i>		
<i>Interstate</i>	\$161.5	\$8.1
<i>Other freeway & Expressway</i>	\$59.4	\$3.0
<i>Other Principal Arterial</i>	\$133.3	\$6.7
<i>Minor Arterial</i>	\$76.1	\$3.8
<i>Collector</i>	\$35.2	\$1.8
<i>Subtotal</i>	\$465.2	\$23.3
<i>Subtotal Rural and urban</i>	\$815.8	\$40.8
<i>Rural and Urban Local</i>	\$200.4	\$10.0
<i>Total Investment</i>	\$1016.2	\$50.8

Table 2: Highway Investment requirements 1998-2017 (\$ Billion)

2.2 Accelerated Construction

In 1996, Transportation Research Board published the Special Report 249, titled “Building Momentum for Change”, (TRB, 1996) which called for the creation of a strategic forum to promote accelerated construction techniques and concepts. Based on this recommendation, TRB Task Force A5T60 was formed in 1999 with the following objectives:

- Remove barriers to innovation;
- Advocate continuous quality improvement and positive change;
- Enhance safety and mobility;
- Encourage the development of beneficial strategies; and
- Create a framework for evaluating proposed innovations.

The Federal Highway Administration (FHWA) and the Technology Implementation Group (TIG) of the American Associations of State Transportation Officials (AASHTO) joined the task force’s efforts. This led to the development of Accelerated Construction Technology Transfer (ACTT) program. In the Spring 2003 meeting of ACCT in Lexington, KY, Dan Sanayi, of the Office of Management and Budget defined ACCT as *“ACTT is a strategic process, which uses various innovative techniques, strategies, and innovative techniques, strategies, and technologies to minimize actual construction time while maintaining quality and enhancing safety on today’s complex, multi-phase highway projects.”*

The main objectives of Accelerated Construction are:

1. Enhanced Safety & Mobility
2. Reduced Construction Time and Better Quality of Construction
3. Lower Life Cycle Costs
4. Minimized Traffic Congestion
5. Minimized Environmental impacts
6. Minimized Socio-Economical impacts

Thus, accelerated construction doesn't imply only new construction technique but a new philosophy of project delivery. Its salient features are:

1. Innovative technology and new materials.
2. Innovative Contracting Techniques.
3. Emphasis on work zone safety.
4. Emphasis on life cycle cost as opposed to up-front cost
5. Better Customer Orientation
6. Environment Friendly design and construction
7. Innovative financing.

Hence, to prevent gridlock and preserve and maintain the highway system with the least impact on the motoring public, accelerated construction techniques are gaining in popularity across the country. Examples of accelerated construction of bridges using various techniques are discussed in the next section.

The I-40 Bridge over Arkansas River:

In May 2002, the Interstate 40 Bridge on the Arkansas River in Oklahoma was struck by a barge. This bridge was of vital urgency to both the State and the entire south-central region of the country as I 40 is a major artery in the nation's highway system. The vehicles had to be rerouted to a crossing 20 miles away. This urgency led to an unprecedented accelerated construction schedule that had the bridge reopened to traffic in 47 days. The Oklahoma Department of Transportation employed several innovative measures to speed up the project, including A+B (cost + time) bidding. The project was completed 10 days ahead of schedule and the contractor earned a bonus of \$1.5 million as an incentive for early completion (Oklahoma State Senate 2002).

The Pelican Creek Bridge:

A small fishing community on Chicagof Island in southeast Alaska needed a new bridge quickly after buying a fire truck that was too heavy for their old timber bridge. Construction requirements included staying out of the sensitive creek bed and completing work within a short time defined by the Department of Fish and Game. The Alaska Department of Transportation & Public Facilities hence chose to accelerate the construction of the bridge by constructing a totally prefabricated bridge with all material, including rock for the approach fill, barged to the work site. The contractor floated in barges at high tide and anchored them in the creek. Crews drove steel piles from barges, drove a large wheeled crane onto the barges, and then used the crane to help construct the bridge. No heavy equipment was lodged in the creek bed. All construction completed in approximately 5 weeks.(FHWA 2006).

The Guernsey 513 bridge located in Quaker City, OH on State Route 513 is the only north-south thoroughfare through the town. A complete closure of the bridge for rehabilitation would have caused a 20 mile detour for automobiles and a 40 mile detour for trucks and buses. Because this route is used by school buses, local officials had concerns about the long detour and were also concerned about possible safety issues if the bridge were constructed with a part-width construction. Hence, to address these concerns, Ohio DOT decided to accelerate construction and use a 16 day window which coincided with the school vacation between the end of the regular year and the beginning of summer classes. It was imperative that the bridge be completed within this period as the annual Ohio Hills Folk Festival, a major source of income for the residents and the city was scheduled to follow soon after the completion date. An incentive/penalty of \$5000 was set up for early/late completion respectively. Although the bridge was completed in 19 days (3 days more than the schedule), it was completed within a reasonable enough time that the project's objective of having the bridge open for the school bus and the festival traffic to be accomplished (Basu 2005).

Accelerated construction is not a traditional technology but rather an approach to highway construction that draws on everything from using innovative contracting procedures and new materials and practices to building extended life pavements and bridges to cut down on construction time. Media and publicity campaigns that keep area residents and businesses informed about reconstruction plans and let motorists know about alternate routes are critical to the success of accelerated construction projects.

2.3 Prefabrication

“For highway agencies, the use of prefabricated bridge elements and systems, ranging from substructures to entire bridges, is proving to be not only a best practice but good business” (Focus, 2000).

A significant number of bridges in the United States require rehabilitation or replacement. While rehabilitating these bridges, increased emphasis has to be placed on improving work zone safety and minimizing traffic disruption while maintaining construction quality and reducing life-cycle costs and environmental impact. The use of innovative prefabricated systems can be an efficient solution, one which would address many of the challenges along with the most important factor “time” in the acceleration of bridges.

Prefabricated bridge elements may be manufactured on-site or off-site, under controlled conditions, and brought to the job location ready to install. Using prefabricated bridge elements and systems facilitates meeting key public needs as follows:

- Minimizes traffic impacts of bridge construction projects.
- Improves construction zone safety.
- Makes construction less disruptive for the environment.
- Makes bridge designs more constructible.
- Increases quality and lowers life-cycle costs.

Bridge engineers are increasingly turning to prefabrication of the bridge elements and systems to save money, to solve project-specific challenges, and to increase the quality of bridges by conducting fabrication in a controlled environment.

In the report: “Prefabricated bridges 2004: Good Business – Best Practice”, AASHTO Technology Implementation Group (2004) which was formed to champion the implementation of innovative prefabrication of bridges highlights the best-practice applications in Bridge prefabrication. This report documents the successful implementation of prefabrication technologies in various components of bridges such as totally prefabricated bridges, bridges with totally prefabricated superstructures, bridges with prefabricated superstructure full-depth decks, bridge with prefabricated substructure caps (AASHTO 2004):

2.3.1 Totally Prefabricated Bridges:

Total prefabricated bridge systems offer maximum advantages for rapid construction and depend on a range of prefabricated bridge elements (most of the elements of the sub structure as well as the super structure) that are transported to the work site and assembled in a rapid-construction process. Following are some of the examples of totally prefabricated bridges (FHWA 2006 a).

Mississippi River Bridge

To provide safer and more efficient access to downtown La Crosse and into Minnesota, the Wisconsin Department of Transportation decided to build a new bridge across the Mississippi River, changing US 14/61/WIS 16 from a two-lane to a four-lane facility.

This bridge is 2,573 feet in length and 50 feet in width and includes a 475-ft steel arch center span with a totally prefabricated superstructure system. The bridge elements were fabricated 90 miles from the site in pieces manageable for shipping and erection. They were then assembled entirely off site on barges. The prefabrication allowed the Wisconsin Department of Transportation to keep the main channel of the Mississippi river open to all river traffic during construction as per Coast Guard requirements. It also allowed the contractor to work on both the river piers and the arch simultaneously, thus speeding the construction schedule. Contract specification did not allow temporary false work structures in the Mississippi River during navigation season. The tied arch which was erected on barges allowed the construction company crews to work during favorable weather without interference with river navigation. The use of prefabrication thus minimized impact on the community, speeding construction of the bridge and limiting disruption of river traffic.

2.3.2 Total Super Structure Systems:

In this system, the entire superstructure including the girders and deck are fabricated offsite and transported to the site and lifted to place on the site in one operation. This system improves the quality of the superstructure, reduces the down-time of the bridge, and reduces the on site activity to the bare minimum. Following are some of the examples of total super structure bridges (FHWA 2006 b).

Church Street Bridge:

The Church Street Bridge located at New Haven in Connecticut directly linking downtown New Haven and the Long Wharf and waterfront areas. To minimize disruption in the rail yard located around it, and to improve work-zone safety for a crew working over active rail lines, Connecticut Department of Transportation required that this portion of the bridge be completed in a single weekend night. The 320-ft long, 850 ton prefabricated truss center span was constructed over several months next to the active rail lines and then lifted into place by a single high-capacity crane. The crane, which required more than four weeks to assemble, lifted the entire truss span more the 65 ft. and moved it more than 100 ft. to its final position. Specifying prefabrication saved Connecticut Department of Transportation about a year on its overall contract time and at least \$1.1 million. (AASHTO-TIG, 2004) Prefabrication of the center span greatly improved constructability; the center span could not have been built during the limited working hours allowed by the rail yard. Also, the use of prefabrication on this project avoided closure of 4 tracks during bridge construction.

Richville Road Bridge:

The Richville Road Bridge located in the town of Manchester in Vermont is a single-span bridge 69 ft. long and 32 ft. 8 in. wide and has a concrete deck on steel girders. The superstructure of the bridge was in poor condition, but the existing abutments were good enough to be reused with only minimal repairs. The Town limited bridge closure time to 14 days and then decided to choose bridge prefabrication after comparing costs. Bridge designers chose total superstructure prefabrication with the Inverset System constructed off-site and transported to the site on trucks and lifted into place by a crane. Each of three

prefabricated units consisted of two rolled beams with a precast reinforced concrete bridge deck. In place, the three units provided a complete superstructure except for the sheet membrane, paving, curb, and railing. Richville Road was closed for only the specified 14 days. Use of total superstructure prefabrication saved the Town of Manchester approximately \$20,000 over conventional construction plus a temporary bridge. (AASHTO-TIG, 2004) Because of the prefabrication, bridge users avoided a lengthy detour with its resulting traffic disruption, travel costs, and time delays.

2.3.3 Superstructure-Prefabricated Decks:

Prefabrication offers numerous advantages for deck construction, particularly for removing deck placement from the critical path of bridge construction schedules, for cost to place the deck, and for quality of the deck. *Partial-depth prefabricated deck panels* act as stay-in-place forms to not only speed construction but also allow more controlled construction for a more durable deck than fully cast-in-place decks. *Full-depth prefabricated bridge decks* facilitate and speed construction. Following are some of the examples of superstructure prefabricated deck bridges (FHWA 2006 c).

Dead Run and Turkey Run Bridges:

The bridges located at the George Washington Memorial Parkway experience heavy commuter usage from workers traveling from Virginia and Maryland into Washington D.C. The 1996 average daily traffic for the Parkway was 42,800 vehicles, with 53,500 vehicles/day projected for 2016. Because of its heavy commuter use, the bridges over Dead Run and Turkey Run needed to be kept open to traffic on weekdays during

replacement of bridge decks. Both the bridges consist of two structures that carry two lanes of traffic; both bridges have an 8-inch concrete deck supported on steel beams with non-composite action. The non-composite aspect of the original design, along with the use of precast concrete post-tensioned full-depth deck panels, facilitated quick deck replacement and allowed the structures to be kept open during weekday traffic. The construction sequence closed the bridge on Friday evening, saw cut the existing deck into transverse sections that included curb and rail, removed the saw cut sections of the deck, set new precast panels, stressed the longitudinal tendons after all panels in a span were erected, grouted the area beneath the panel and above the steel beam, and opened the bridge to traffic by Monday morning with one span replaced every week end. The advantages of this method were observed from the minimized traffic disruption and the maintenance of traffic during weekdays which minimized the effect on commuters traveling between Virginia, Maryland and Washington D.C.

IH70/Lake St. Louis Boulevard Bridge

This bridge which takes the Interstate 70 over the lake St. Louis is situated in the St. Charles County in Missouri. To reduce congestion on the bridge, the Missouri Department of Transportation opted for widening it and then accepted a contractor's value-engineering proposal to rebuild the bridge using prefabrication, replacing the four-span bridge with two spans. Although costs increased, the proposal offered both short- and long-term benefits. The new bridges used precast deck and beam sections and puzzle wall abutments, which allowed a design with fewer spans. With the prefabrication redesign, the Missouri Department of Transportation reduced construction time by

several months. By reducing the number of spans, geometrics of the interchange improved, increasing its safety and efficiency. Fewer spans would also result in lower maintenance costs. By eliminating the need for formwork, the value-engineering proposal using prefabrication greatly improved work zone safety. With prefabrication facilitating faster construction, bridge users were spared several months of inconvenience. Motorist safety increased because false work towers were not needed in the outside shoulders.

2.3.4 Prefabricated Sub Structure Systems- Bent caps and Columns:

The sub-structure can also be prefabricated off-site and erected in place using crane. The footing, piers, bent caps have been prefabricated and erected in place. The bent cap is a horizontal member at the top of column which supports the superstructure. If the bent caps are cast in place, they require extensive formwork and curing time. If the bent caps are prefabricated, the problem of formwork and curing time is eliminated. The prefabricated bent caps are very useful in case of over water bridges. In case if the bridge is over an existing roadway, the prefabricated bent cap ensures that traffic is not disrupted by formwork. In some cases, the precast columns can be used on cast-in situ footings. Columns can be segmental, post tensioned, and either hollow or concrete filled. Use of these precast columns can considerably reduce bridge construction times. Following are some projects where prefabricated Bent caps and columns were used (FHWA 2006 d).

I-45/ Pierce Elevated:

The bridge is located in the busy Houston downtown in Texas. When a 113-span section of I-45 in Houston's central business district needed replacing, designers estimated that a

conventional bridge system would require more than a year and a half of construction. Estimating user delay costs at \$100,000 a day, Texas Department of Transportation opted to speed construction by using precast bent caps on the existing columns. The bridge consists of twin structures, one northbound and the other southbound. Each structure was completed in 95 days with a total of 226 spans replaced in 190 days. To connect the precast caps to the existing columns, the precast caps were anchored with post-tensioning bars and hardware. Thus the prefabrication on this project not only accelerated the bridge rehabilitation by reducing the construction time from 547 days to 190 days but also saved \$ 100,000 per day in terms of road user-costs.

From the analysis of the survey (Shahawy 2003) “Prefabricated Bridge Elements and Systems to Limit Traffic Disruption during Construction – NCHRP Synthesis 324”, it is found that:

- The aspects of prefabrication of bridges that stand out as causes of concern:
 - High Initial Cost
 - Insufficient number of experienced contractors
 - Difficulty in design / specification due to proprietary nature of prefab systems.
- Parts of superstructure are considered to be the most suitable for prefabrication. Decks [22%], Girders [17%], Total Superstructure [17%] are found to be the most commonly prefabricated bridge components. This could be due to the extensive experience gained over last two decades in superstructure prefabrication.

- Of the cases studied, the elements were prefabricated at site in only 11% of the cases thus making the prefabrication process less disruptive to the site environment.
- A majority of reasons ascribed to the choice of prefabricated systems related to the concerns about user costs associated with the project. These reasons include Lane Closure (17%), Safety (10%), Environmental Impact (4%), and Construction Delay (28%).

Prefabrication of the bridge elements facilitates in the reduction of traffic and environmental impacts, improved constructability, and safety is improved because work is moved out of the right-of-way to a remote site, minimizing the need for lane closures, detours, and use of narrow lanes. Also, prefabrication of bridge elements and systems can be accomplished in a controlled environment without concern for job-site limitations, which increases quality and can lower the life cycle costs.

2.4 Review of Existing Decision Making Models

2.4.1 Framework for Prefabricated Bridge Elements and Systems Decision Making:

(Ralls, 2005)

Prefabrication offers significant advantage over cast-in-place construction in terms of life cycle costs, time saved and overall quality of the structure. The reduction in the on-site time required to construct or rehabilitate a bridge using prefabrication would in-turn reduce the impact of construction on the traffic, environment, businesses and community around the site. Ralls (2005) developed the Prefabricated Bridge Elements and Systems (PBES) framework which is a decision-making tool for the objective consideration of

prefabrication to achieve accelerated bridge construction. In other words, it helps answer the important question as to whether a prefabricated bridge is achievable and effective for a specific site. This frame work has been made for decision makers (including owners, designers and project managers) and is divided into three important sections.

1. A flow chart for high level decision making.
2. A matrix for detailed analysis of various factors.
3. An in-depth discussion of various factors.

The flowchart shown in Figure 1 assists the users in making high-level decisions on whether a prefabricated bridge might be an economical and effective choice for the specific bridge under consideration.

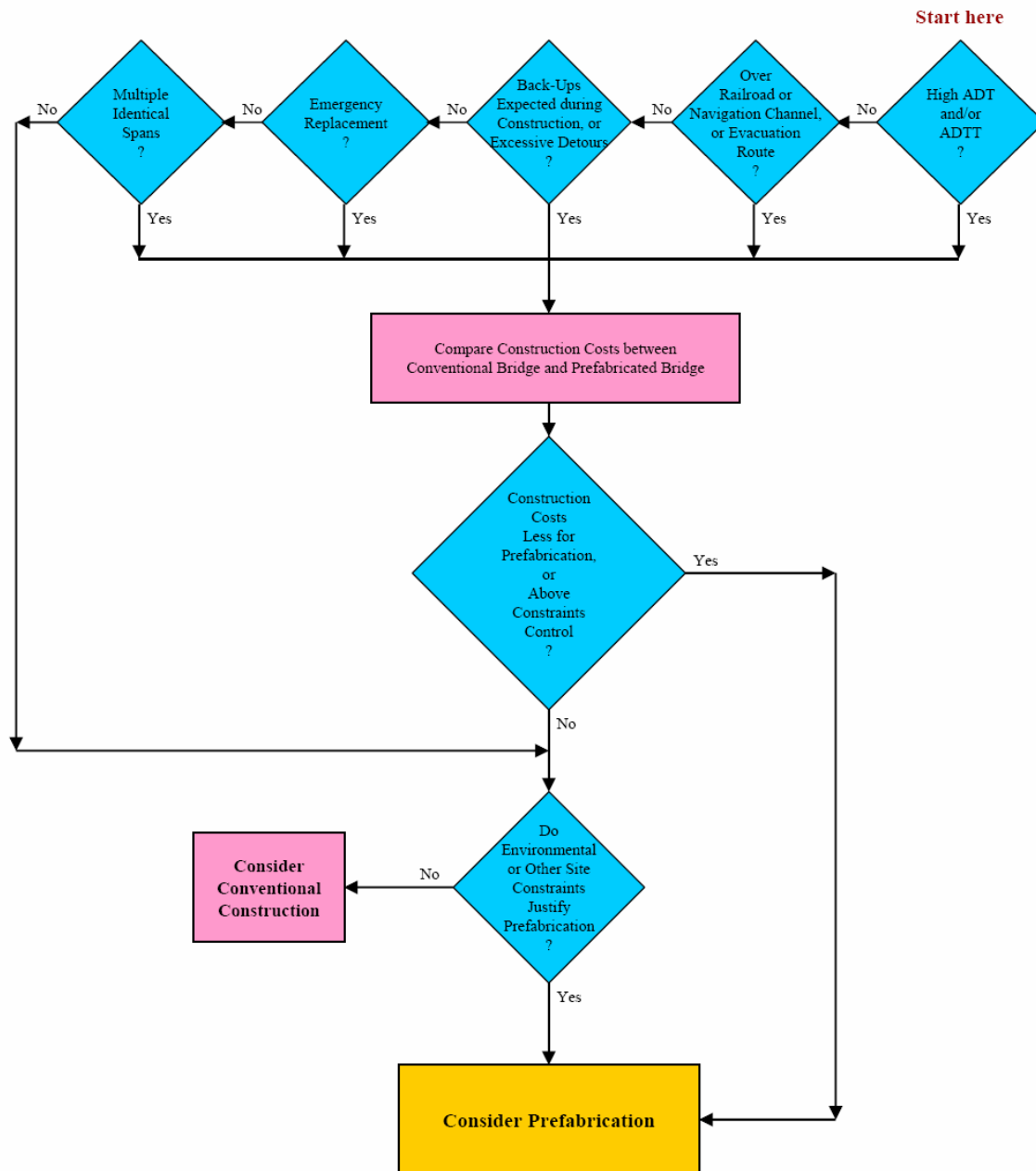


Fig 1: Flowchart for High Level Decision-Making Process (Ralls, 2005)

The matrix (Table 3) which also helps in making high-level decision making process can be used in conjunction with or as an alternative to the flowchart. The matrix consists of a set of Yes/No/Maybe questions. If the majority of the responses to the

questions are “Yes”, it can be concluded from the matrix that prefabrication offers advantages for the particular project.

Question	Yes	Maybe	No
Does the bridge have high average daily traffic (ADT) or average daily truck traffic (ADTT), or is it over an existing high-traffic-volume highway?			
Is the bridge over a railroad or navigable waterway, or is it on an emergency evacuation route?			
Will traffic be subject to back-ups when using the bridge during construction, or be subject to excessive detours during construction of the bridge?			
Is this project an emergency bridge replacement?			
Must traffic flow be maintained on the bridge during construction?			
Can the bridge be closed during off-peak traffic periods, e.g., nights and weekends?			
Does the bridge have multiple identical spans?			
Can the bridge be grouped with other bridges for economy of scale?			
Will roadway construction activities away from the bridge be completed quickly enough to make rapid installation of a prefabricated bridge a cost-effective solution?			
Can adequate time be allocated from project award to site installation to allow for prefabrication of components to occur concurrently with site preparation?			
Do worker safety concerns at the site limit conventional methods, e.g., adjacent power lines or over water?			
Is the site in an environmentally sensitive area requiring minimum disruption (e.g., wetlands, air quality, noise, etc.)?			
Is the bridge location subject to construction time restrictions due to adverse economic impact?			
Are there natural or endangered species at the bridge site that necessitate short construction time windows or suspension of work for a significant time period, e.g., fish passage or peregrine falcon nesting?			
If the bridge is on or eligible for the National Register of Historic Places, is prefabrication feasible for replacement/rehabilitation per the Memorandum of Agreement?			
Is the bridge site accessible for delivery of prefabricated components or use of heavy lifting equipment?			
Does the location of the bridge site create problems for delivery of ready-mix concrete?			
Does the local weather limit the time of year when cast-in-place construction is practical?			
Does the height of substructures make use of formwork to construct them inconvenient or impractical?			
Are fabricators available to economically manufacture and deliver the required prefabricated components?			
Are there contractors available in the area with sufficient skill and experience to perform prefabricated bridge construction?			
Does the height of the bridge above ground make false work uneconomical or impractical?			
Totals:			

Table 3: PBES Matrix for High-Level Decision Making

The questions and discussions are divided on the basis of costs, environmental issues, prefabrication availability, site conditions and design considerations.

In this decision making system, the decision to use prefabricated bridge elements is based on the number of “Yes” / “No” answers to the questions in the matrix. Although the flow chart also helps in arriving at the decision, the relative importance of different factors is not considered. The decision-making process for selecting a construction strategy from a number of possible alternatives, each having its implications for cost, flow of traffic, disruption to local businesses, communities and environment requires a series of trade-offs between the priorities. This decision making process allows the user to assign weights to various factors but doesn’t provide a clear cut methodology to achieve the same. In absence of a transparent system, the process of assigning weights to various qualitative factors such as safety, environment, impact on local businesses and communities can prove to be a contentious process.

2.4.2 Model for evaluating Bridge Construction Plans: (El-Diarabi et. al, 2001)

This model presents a method for evaluating bridge construction plans (BCP) during the design phase of a project. It is intended to help designers balance impact of bridge construction plans on project performance, traffic flow and business activity. The model includes five major factors: safety, accessibility, carrying capacity, schedule performance and budget performance. To assist these five major factors, an additional set of 22 factors was developed. These factors were identified on the basis of observation of actual construction sites and through input from industry experts. It was then validated through input from another set of industry experts and application to an actual bridge

construction planning case. The weights for the five major factors deduced from responses by experts are:

- Safety (24%)
- Accessibility (19%)
- Carrying capacity (19%)
- Schedule performance (19%)
- Budget performance (19%)

These weights are used in an objective matrix for decision making. A prototype objective matrix is shown in figure 2.

	Safety	Accessibility	Carrying capacity	Schedule	Budget	Project specific factor(s)	Total
Weights	W_s	W_a	W_c	W_t	W_b	W_q	100%
BCP #1	S_1	A_1	C_1	T_1	B_1	Q_1	F_1
BCP #2	S_2	A_2	C_2	T_2	B_2	Q_2	F_2
BCP #3	S_3	A_3	C_3	T_3	B_3	Q_3	F_3
BCP #n	S_n	A_n	C_n	T_n	B_n	Q_n	F_n

Fig. 2: BCP Objective Matrix (El-Diarabi et. al, 2001)

The final score for each plan is arrived at using the following formula.

$$F_i = (W_s \times S_i) + (W_a \times A_i) + (W_c \times C_i) + (W_t \times T_i) + (W_b \times B_i) + (W_q \times Q_i)$$

Where $S_i, A_i, C_i, T_i, B_i, Q_i$ are scores of i^{th} bridge construction plan for safety,

Accessibility, Carrying Capacity, Schedule, Budget and Project Specific Factors rated on a scale of 1 to 10 with 10 being the best score. The construction plan with the highest score is considered to be the best amongst alternatives.

The basic drawback of this model is that it is not customizable. Every project is unique in nature and will have its own set of priorities and constraints. The weights prescribed in this model may not objectively represent the priorities and constraints. Decision makers have to derive weights for every project. Further, this model doesn't identify any method for deriving weights for factors which need to be considered in the decision making system.

2.4.3 Analytical Hierarchy Process for Bridge Construction Decision Making

From the discussion of bridge construction decision making systems discussed earlier, we find that both the systems identify the problem accurately but they are not able to provide justifiable methodology to reach the solution. The decision making process for identifying an optimum strategy for construction of bridges requires careful evaluation of a number of factors such as construction costs, future rehabilitation costs, user costs, maintenance of traffic, quality of work, safety of motorists, safety of construction workers, safety of pedestrians, impact on surrounding communities and businesses, consideration of impact on sensitive ecosystems, etc. The decision making process involves a trade off between the requirements imposed by these factors. Every project is unique and has its own specific requirements. Hence, a decision making system that issues specific numerical values to the importance of various factors can't be universally applied.

Both the decision making systems discussed earlier identify the requirement of assigning weights to various factors but don't provide us with a justifiable method. While Bridge Construction Plan (El-Dairiaby, 2001) provides us with numerical values for weights, PBES includes a cursory discussion about the weights. The difficulty in assigning weights to various factors stems from the fact that the factors involved in the decision making system are qualitative (e.g. safety, impact on surrounding communities and businesses, environmental impact) as well as quantitative (costs, impact on traffic flow). The trade off between these factors reflects the priorities placed by the decision makers on various factors. The challenge is to convert these qualitative analyses of priorities into quantitative weights of importance.

The Analytical Hierarchy Process (AHP) (Saaty, 1980) provides us with a tool to quantify these qualitative trade-offs between various objectives to extract a single set of weights which reflect the level of importance of each of the factors in the overall decision making system. The method uses pair wise comparisons to compare the relative importance of each factor with other factors using numerical / verbal scale. The Eigenvectors of the matrices obtained from the pair wise comparisons reflect the relative importance of each of the factor in the decision making process. Finally the same pair-wise comparison method can be used to evaluate the proposed solutions for their efficacy in achieving the goals.

Analytical Hierarchy Process has strong theoretical foundations in mathematics. The method has been validated through significant body of research over last two decades. The method has been used for many wide ranging application such as Comparing technologies (AbouRizk et. al, 1994), forest management (Mendoza, Sprouse,

1989), setting priorities (Reynolds, 1997), resource management (Peterson et. al, 1994), resource allocation (Saaty, Bennett, 1977), risk assessment (kangas, 1993), transportation infrastructure management studies (Saaty, 1977a), personnel selection (McIntyre et.al 1999) (ASCE paper) etc.

The model proposed in this research uses the AHP for developing a model that can be used to quantify the relative importance of various criteria in achieving the goal of selecting an optimum bridge construction plan from a number of alternatives. In the near future, a large number of bridges will have to be rehabilitated. The traditional decision making process which relies on comparison of costs alone, will not be able to address the requirements imposed by the need to maintain traffic flow, to ensure minimum impact on local businesses and communities, less disruption of environment and ecosystems. The proposed decision making system will give the decision makers a tool to occasionally justify a decision to accelerate construction even if the initial construction costs are higher than traditional alternatives based on non-quantifiable benefits. The proposed decision making system is explained in detail in one of the following sections.

3 Surveys of State Departments of Transportation

The primary objective of this study “Accelerated Construction: A Decision Making Process for Bridges” is to identify the non technical factors affecting the decision making process of the bridges and formulate a decision making model which would incorporate these factors into the decision making process along with the traditional factors such as costs. Based on the input from the literature search, informal interviews with key DOT bridge planning, design & construction personnel and industry bridge experts, a questionnaire survey (Appendix 2) was prepared and mailed to the 50 U.S. and 5 Canadian Department of Transportation officials. The main objective of this Questionnaire-Survey was to identify the above mentioned non technical factors and their relative importance. Determining these factors and their effects on the decision making process would help the policy makers in making more informed decisions regarding accelerating the construction of bridges.

From the 55 surveys that were sent out to the Department of Transportation executives, 30 replies were obtained. Out of the 30 replies that were received, 5 agencies had never used any kind of accelerated construction techniques. Of the 25 DOTs which used acceleration of rehabilitation/construction of bridges, a majority (21) used it in more than 10 percent of the projects. Of these DOTs 4 used accelerated construction in 30% of the projects.

% Of Total Projects Executed Using Accelerated Construction	No. of agencies
(<10)	3
10	16
20	1
30	4
40	0
50	1

Table 4: Percentage of Bridge Projects executed using Accelerated Construction

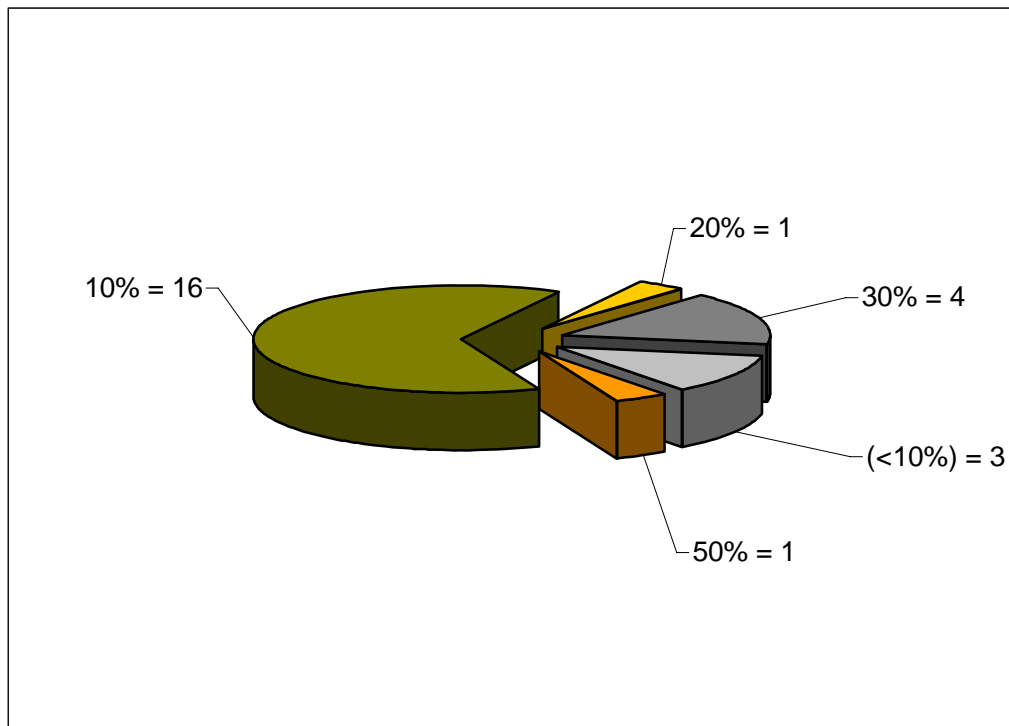


Figure 3: Percentage of Bridge Projects executed using Accelerated Construction

Herbsman (1995), Herbsman, Chen (1995), Herbsman (1995a) reported the findings of a research studies conducted to evaluate the performance of projects executed using innovative contracting techniques such as A+B, lane rental etc. The analysis of the projects showed that the states which were more experienced at using A+B methodology experienced substantial time savings as compared to states which were implementing the technique in fewer projects. The study also found that various Departments of Transportation preferred the use of the Incentives / Disincentives clause in conjunction with A+B contract. In majority of the cases studied, the contractors were able to get the incentives fee and in many cases they also could get the maximum allowable incentives. In the projects under study, it was also found that reduction in time was achieved with no increase in cost as compared to projects executed using conventional bidding methods.

The Manual of Innovative Contracting by the Department of Transportation (ODOT, 2003) describes various non traditional contracting methods available for use of Ohio Department of Transportation. Strategic Initiative # 9 evaluated various non traditional contracting methods to evaluate their effect on Maintenance of Traffic, safety/congestion, construction cost, construction administration and project development. After the evaluation, the committee selected Work Day Contract, Incentive/Disincentive Contract, Lump Sum Incentive Contract, Liquidated Savings Contract, Design-Build, A+B Contract and Warranties as some of the best alternatives for efficient construction to be used in ODOT projects.

The DOT official's response to the question on innovative contracting procedures in the survey validates the importance of the innovative contracts used in accelerated construction projects. Only 8% of the respondents use I/D contracts on a frequent basis.

A+B contract with Incentive/Disincentive (I/D) followed by the two used individually were found to be the most used type of contracts depending on the importance of the different factors involved in the projects. The following graphs depict the use of the contracts by the responding agencies depending on the type of projects, cost of projects and on the location of the project.

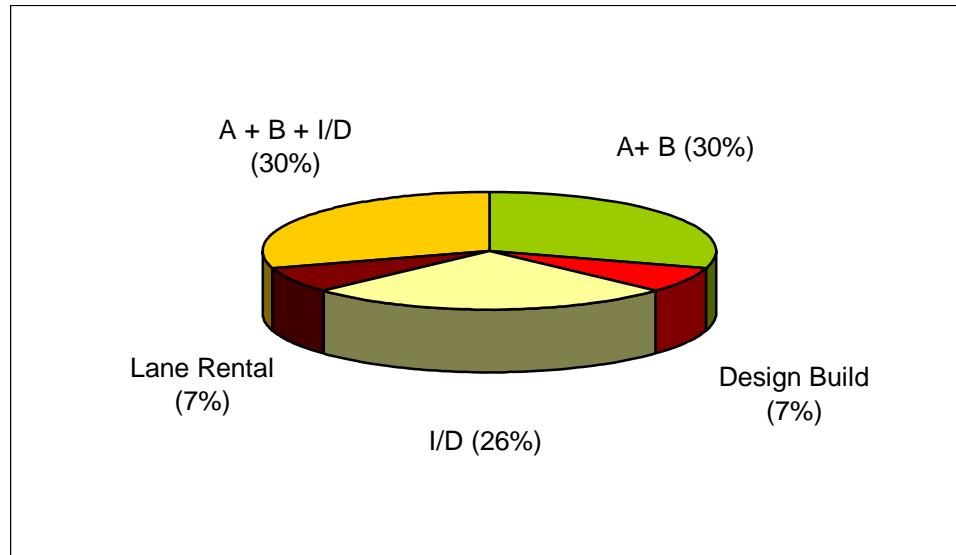


Figure 4: Innovative Contracts: Use Depending on the Type of Job

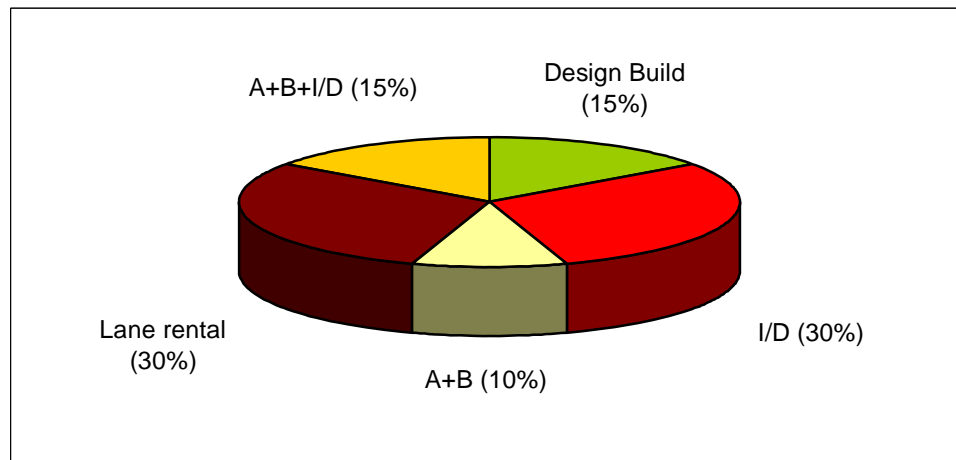


Figure 5: Innovative Contracts: Use depending on the Location

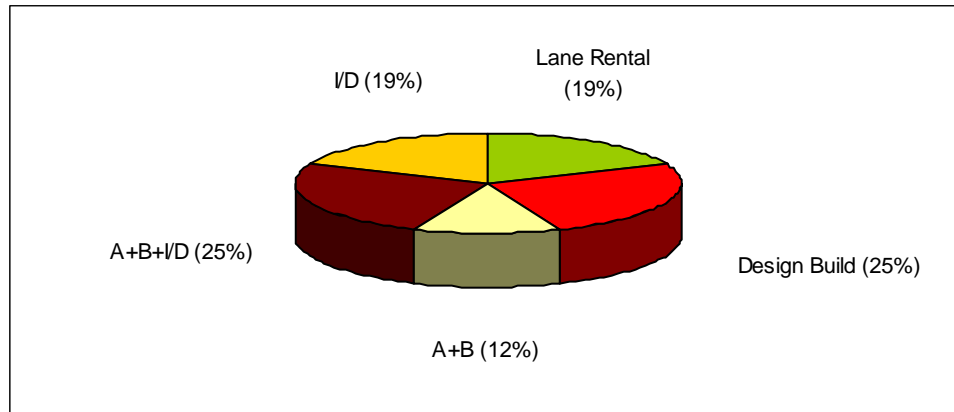


Figure 6: Innovative Contracts: Use depending on the Size of Project (Cost).

The responses in the survey show an increasing trend towards accelerated construction strategies. Most of the agencies that have never worked with acceleration techniques before are working towards introducing these strategies in their agencies, whereas the agencies that are already using these strategies are looking to use them on a more frequent basis.

The respondents rated the impact of different factors on the decision to accelerate the construction of bridges. A list of these factors (Q # 4- survey # 1 in Appendix C) was obtained from the literature search and after informal interviews with bridge experts at the Transportation Research Board Conference (January 2005). The criticality of the infrastructure element was found to be the most important factor in influencing the decision to accelerate the construction of bridges. Another surprising observation was that respondents reported that political influence was the fourth most important factor influencing the decision to accelerate construction. A DOT official from a state which has not implemented Accelerated Construction Strategies commented that *“The Decision making process is based on initial construction costs coupled with “Political*

Considerations”” The bar chart in the following figure shows the influence of various factors on the decision to accelerate the construction of bridges.

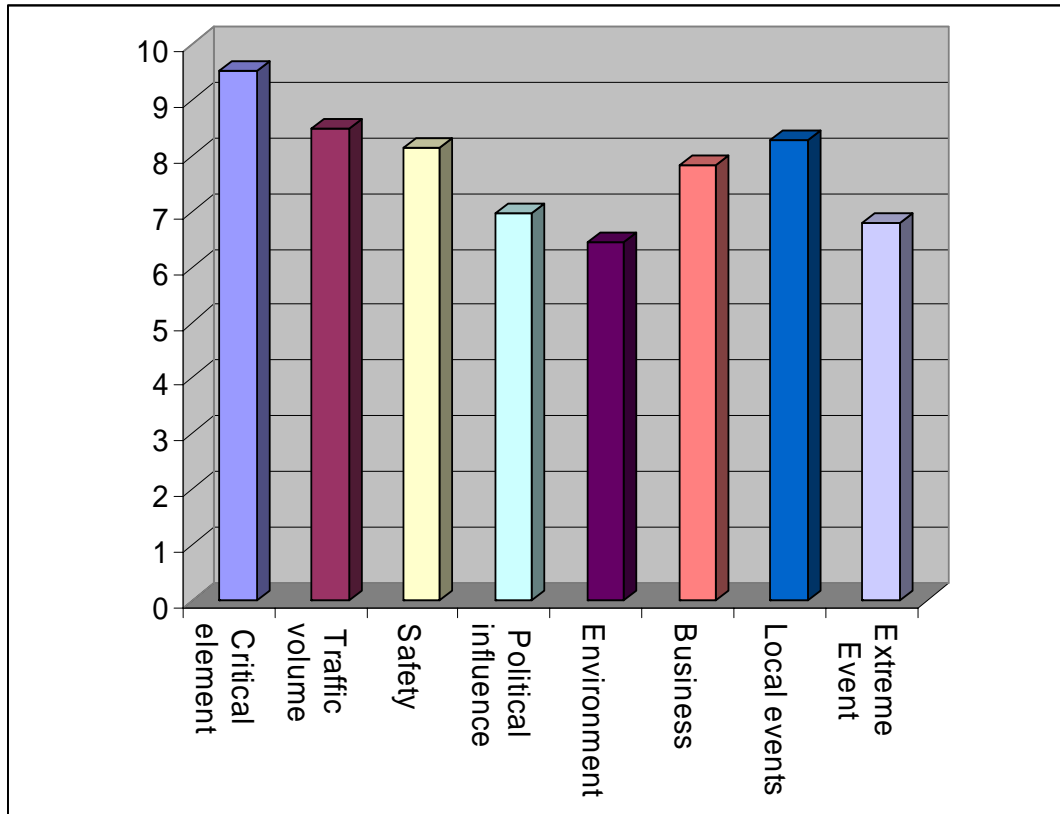


Figure 7 Factors influencing the decision to accelerate Construction.

The scatter plots of extent of influence of these factors on the decision to accelerate (Figures 31 - 38 in appendix 4) show a consensus among decision makers in state DOTs on impact of these factors on the decision making process.

In many instances, bridges are the only comfortable link between any two points A and B. If such bridges have to be shut down for repair or replacement, the traveling public has to take detours to reach their destination. These detours would re-route the traffic thus causing an inconvenience to the communities through which the detour occurs, the communities around the site, a loss of revenue to the business owners around

the rehabilitation site, etc. Hence it is very important to consider the views of the communities and businesses that get affected due to the rehabilitation. Only one agency among those who had responded to the survey said that they do not consider or consult business owners. All others consult and inform the community and the businesses at some point of time during the construction or before construction starts. Nine agencies involve both businesses as well as the communities in the decision making process before the planning phase, during the planning phase and during the construction phase whereas 11 agencies involve the businesses and communities only during the planning phase. The rest of the agencies consider them in any one of the other two phases.

Bridges constitute a unique class of structures that are influenced by continuously changing loads. Due to the nature of the load imposed on the structures and field conditions, bridges are subject to a more rapid deterioration process than most other structures (Basu 2005). With the increasing volume of truck traffic and rapid deterioration of bridge elements, most highway bridges are rapidly approaching a stage that requires some type of rehabilitation or replacement. This makes Life Cycle Cost Analysis of bridges an important issue during the decision making process. Almost half of the agencies that responded to the survey consider the Life Cycle Costs during their decision making processes. Also, user costs which play a major role in any decision making process, are considered by 70% of the total survey respondents.

As discussed earlier, analysis of the 1st Survey gave us a key insight into some of the factors which are subjectively considered while making the decision to accelerate, but are not included quantitatively in the decision making models. Safety, Social, Economic and Environmental factors along with traffic flow and costs were identified as some of

the main factors which should be quantitatively addressed in the decision making models. Hence, another questionnaire survey (Appendix 3) containing the above six factors and their related sub factors were sent out to the 25 agencies which had positively replied to the initial survey. The survey was to gauge the weights to be assigned to the different factors and sub-factors that would be generic to most bridge construction projects.

Out of the surveys sent out to the 25 Department of Transportation officials, 17 favorable responses were obtained. The main factors viz.: Costs, Traffic flow, Safety, Economy, Social factors and Environment were to be weighed such that they would total to 100. Some of these factors as listed below had sub factors which were to be individually weighed such that they would total to 100.

- Safety
 1. Motorist safety
 2. Construction worker safety
 3. Pedestrian safety.
- Impact on Local Economy
 1. Reduced access to businesses
 2. Detour acceptability to businesses
 3. Congestion
 4. Parking isolation
 5. Effect on supply routes.
- Impact on affected communities
 1. Reduced access to communities
 2. Detour acceptability to the community

3. Access to emergency services
 4. Local events of Importance
- Impact on Environment
 1. Air pollution
 2. Noise pollution
 3. Effect on Sensitive Ecosystems.

A t-test was run on the responses obtained from the 17 Departments of Transportation. The scatter plots (Appendix 4, figures 39-58) depict the responses and confidence intervals at 95% confidence level.

The tables shown below depict the weights for the different factors and sub-factors obtained from the above analysis. These weights do not correspond to a particular project but are generic in nature and are to be used just as guidelines. The weights do not reflect the current decision making processes of DOTs but they reflect the opinion of decision makers on how much importance should be given to various factors. In an ideal situation, all the factors should have equal weights but agencies have to execute projects using a strict budget, costs are given an higher weight age as compared to the other factors.

Factor	95 % Confidence interval	Recommended (Mean) weight
Cost	16-31	25
Traffic flow	11-29	20
Safety	11-31	20
Economy	8-18	15
Social	7-16	10
Environment	7-13	10
Total		100

Table 5: Recommended weights: Overall

Safety	95 % Confidence interval	Recommended (Mean) weight
Motorist Safety	33-47	40
Worker Safety	24-44	30
Pedestrian Safety	13-39	30
Total		100

Table 6: Recommended weights: Safety

Local Economy	95 % Confidence interval	Recommended weight
Reduced Access to businesses	22-39	30
Detour acceptability	16-28	20
Parking for customers	8-20	20
Congestion in front of businesses	12-26	15
Supply routes to manufacturing units	9-22	15
Total		100

Table 7: Recommended weights: Local Economy

Local Communities	95 % Confidence interval	Recommended weight
Reduced Access to the community	13-29	20
Detour acceptability	14-32	25
Access to emergency services	21-48	35
Local events	10-24	20
Total		100

Table 8: Recommended weights for the factors: Local Communities

Environment	95 % Confidence interval	Recommended weight
Sensitive Ecosystems	36-67	50
Noise pollution	13-32	25
Air pollution	16-34	25
Total		100

Table 9: Recommended weights for the factors: Environment

4 The Accelerated Construction Decision-Making Model

4.1 Analytical Hierarchy Process

The accelerated construction decision making model in this report is based on the Analytical Hierarchy Process (AHP). The Analytical Hierarchy process, being used in more than 57 countries (as of 1995) all over the world, was developed by Prof. Thomas Saaty at the Wharton School of Business. This process allows the decision makers to model complex problems into a hierarchical structure showing the relationship between the ultimate goal, the objectives (factors), sub-objectives (sub-factors) and alternatives. In allowing the decision makers to derive ratio scale properties (opposed to arbitrarily assigning them), AHP not only supports decision makers by enabling them to structure complexity and exercise judgment, but also allows them to incorporate both objective and subjective considerations in the decision process (Saaty, 1980). This method is a compensatory decision methodology as alternatives that are deficient with respect to one or more objectives (factors) can compensate by their performance with respect to other objectives. AHP is composed of several previously existing but unassociated concepts and techniques such as hierarchical structuring of complexity, pairwise comparisons, redundant judgments, eigenvector method for deriving weights, consistency considerations, etc. which have been combined to form a process which is far superior to its individual constituents. AHP has a variety of applications such as:

- Setting priorities.
- Generating a set of alternatives.
- Choosing the best policy alternative.
- Determining requirements.

- Allocating resources.
- Risk assessment.
- Performance measurement.
- System design.
- Ensuring system stability.
- Optimizing.
- Planning.
- Conflict resolution, etc.

The Analytical Hierarchy Process overcomes the problems with weights and scores by structuring complexity as a hierarchy and by deriving ratio scale measures through pairwise relative comparisons. The pairwise comparison process can be performed using words, numbers, or graphical bars, and typically incorporates redundancy, which results in a reduction of measurement error as well as producing a measure of consistency of the comparison judgments. The use of redundancy permits accurate priorities to be derived from verbal judgments even though the words themselves are not very accurate. Thus, words can be used to compare qualitative factors and derive ratio scale priorities that can be combined with quantitative factors hence allowing the user to make a qualitative as well as a quantitative evaluation. By using AHP pairwise comparison process, weights or priorities are derived from a set of judgments (expressed verbally, numerically or graphically). While it is difficult to justify weights that are arbitrarily assigned, judgments and the basis for these judgments (e.g.: hard data, knowledge, experience, etc.) can be relatively easy to justify.

AHP is thus built on a solid yet simple theoretical foundation. The basic model can be compared to a pie chart. If a pie chart is drawn, it would represent the goal of the decision problem as a whole. The pie consists of wedges where each wedge represents the factors that contribute to the ultimate goal. AHP helps determine the relative importance of each wedge of the pie. Each wedge (factor) can then be further decomposed into smaller wedges which represent the sub-factors which can in turn be further sub divided. The wedges corresponding to the lowest level of sub-factors are broken down into alternative wedges, where each alternative wedge represents how much the alternative contributes to that sub-factor. By adding up the priority for the wedges for the alternatives, we can determine how much the alternatives contribute to the organization's objectives.

In this study, the goal (the pie) is: to develop a decision making process which helps to complete the construction/rehabilitation of the bridge in the most cost effective and safe manner with least disruption to the flow of traffic, surrounding communities and businesses. The factors (wedges of the pie) on which the successful completion of this goal depends can hence be classified as Costs, Traffic flow, Safety, Communities, Economy, and Environmental concerns that are associated with the bridge project. These factors have been determined in consultation with industry experts and confirmed by an extensive survey of the officials from the State Department of Transportation in USA and Canada.

The decision making process using AHP essentially consists of the following six steps:

STEP 1: Develop Decision Hierarchy.

STEP 2: Construct Comparison Matrices.

STEP 3: Calculate Eigenvector and Eigen values.

STEP 4: Check Consistency of Matrices.

STEP 5: Evaluate and Compare Alternatives for Criteria and Decision making.

STEP 6: Conduct a sensitivity analysis of the model

4.2 Methodology

4.2.1 Develop Decision Hierarchy:

- *Identify the Objective of the Process*

This process begins with defining the overall objective or goal of the process. In a typical bridge construction project, the goal is to complete the construction /rehabilitation of the bridge in the most economical and safe conditions, with the least disruption to traffic, community, businesses and the environment around the site.

- *Identify the Criteria to achieve Objectives*

Criteria that contribute to the successful realization of this goal are then identified. These criteria can be divided into factors like *Costs, Impact on Traffic flow, Safety, Social Impact, Impact on local Economy and Environmental Impact.*

- *Identify the sub-criteria*

Specific sub criteria (sub factors) related to each criterion (factors) can then be identified and included in the hierarchy. These criteria and sub criteria may be either qualitative or quantitative based on the preferences and experience of the decision makers. The sub-criteria should be organized in such a way that the comparison between the sub-criteria is intuitive. For example, if the main criterion is “Optimize safety for all the stakeholders”,

the sub-criteria could be “Maximize Motorist Safety”, “Maximize Construction Worker Safety” and in some cases “Maximize Pedestrian Safety”.

- *Identify the alternatives*

The solutions or alternatives that satisfy the overall objective are then identified.

All of these elements are then arranged in a descending order, starting with the overall objective or goal, followed by the factors (criteria), the sub-factors (sub-criteria) and finally the alternatives. Figure 8 shows a schematic representation of a decision hierarchy. In decomposing the problem, the factors comprising the hierarchical structure at a given level are related to the factors in the level directly above and the next level.

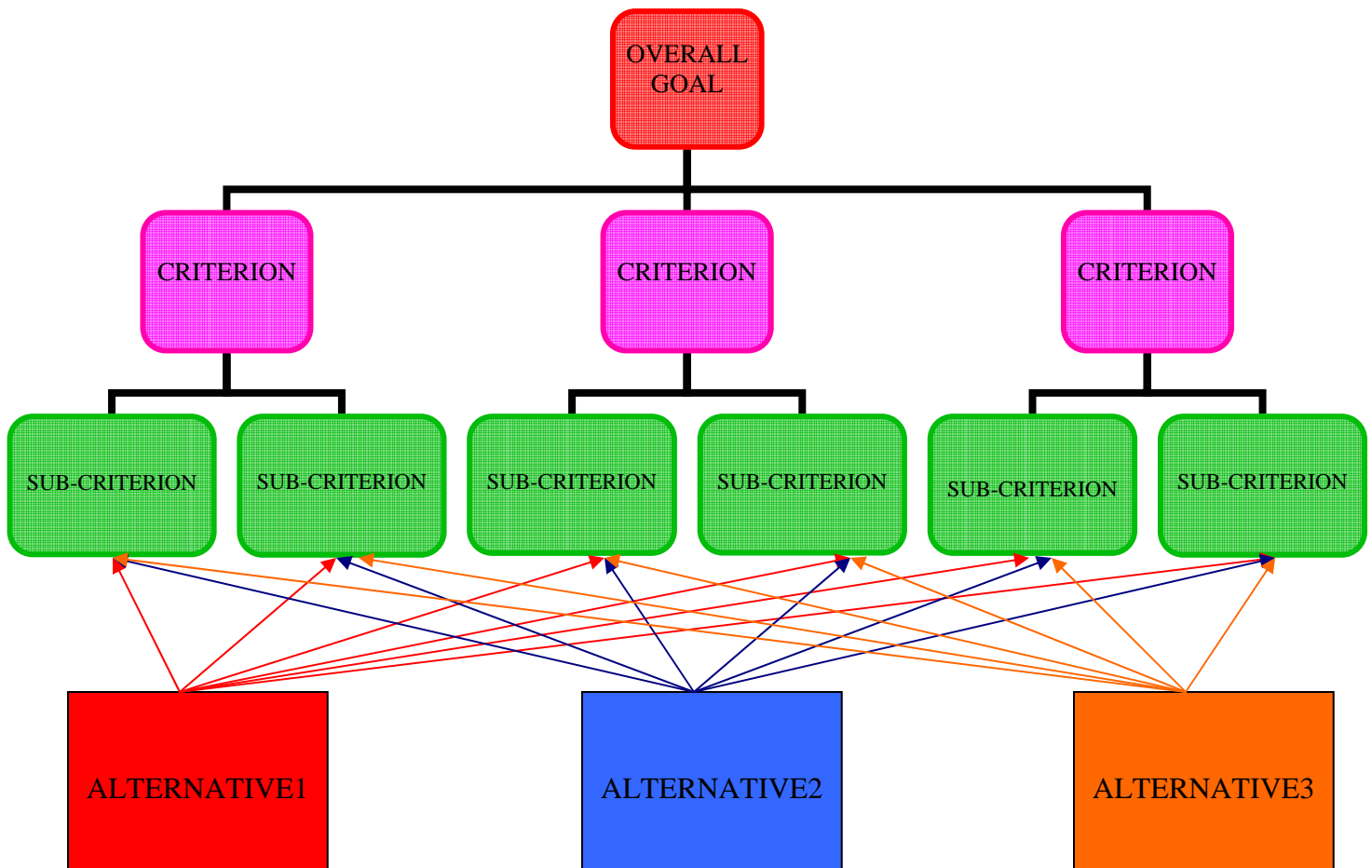


Figure 8: Schematic Representation of Decision Hierarchy

There are several advantages of using the hierarchical form of system representation (Saaty, 1980):

- Hierarchical representation of a system can be used to describe how changes in priority at upper levels affect the priority of elements in lower levels.
- They give detail of information on the structure and function of a system in the lower levels and provide an overview of the factors and their purposes in the upper levels.
- Natural systems assembled hierarchically i.e.: through modular construction and final assembly of modules, evolve more efficiently than those assembled as a whole.
- They are stable and flexible; stable in that small changes have small effect and flexible in that additions to a well-structured hierarchy do not disrupt the performance.

4.2.2 Construct Comparison Matrices:

Comparison matrices are constructed to determine the potency with which the various elements in one level influence the elements on the next higher level, so as to compute the relative strengths of the impacts of the elements of the lowest level on the overall objective. Each element is then evaluated against each of its peers in relation to its impact on achieving the objective of the parent element. These evaluations are termed as pairwise comparisons and take the form of matrices.

The pair-wise comparisons of the elements at each level are made in terms of:

- i. Importance: when comparing objectives with respect to their relative importance.
- ii. Preference: when comparing the preference for alternatives with respect to an objective.
- iii. Likelihood: when comparing uncertain events or scenarios with respect to the probability of their occurrence.

The values for comparing the elements using the technique of pair-wise comparisons are assigned from a pre-determined scale of relative importance (Saaty 1980), viz. the ratio-scale shown in table 4.

Intensity of Importance	Definition	Explanation
1	Equal Importance	Two Activities Contribute equally to the Objective
3	Weak Importance of one over another	Experience and judgment slightly favor one activity over another
5	Essential or Strong Importance	Experience and judgment strongly favor one activity over another
7	Demonstrated Importance	An activity is strongly favored and its dominance demonstrated in Practice
9	Absolute Importance	The evidence favoring one activity over another is of the highest possible order of affirmation
2,4,6,8	Intermediate Values between two Judgments	Used to facilitate compromise between slightly differing judgments.

Table 10: The Ratio Scale for Pair-wise Comparison. (Saaty 1980)

For example, in a typical bridge construction project, the overall objective is to “To complete the construction / rehabilitation of a bridge in the most cost effective & safe

manner with least disruption to flow of traffic surrounding communities and businesses.”

The ability of each construction strategy (alternative) in achieving this objective can be evaluated with respect to the following criteria:

1. Cost Effectiveness of strategy (C)
2. Minimum Disruption to Flow of Traffic (T)
3. Mitigate the impact of construction on Surrounding Communities (P)
4. Mitigate the impact of construction on Local Businesses (B)
5. Safety of all stakeholders (S)
6. Minimum disruption to environment & ecosystems. (E)

The pair-wise comparison matrix for main factors is shown in figure 9. For example W_C/W_T represents the pair-wise comparison of Cost criterion C with Traffic criterion (T). If the cost criterion is considered slightly more important than the traffic criterion, the pair wise comparison of cost criterion with traffic criterion will be: $W_C/W_T = 1 / 3$. This also means that the pair wise comparison of traffic criterion with cost criterion will be $W_T / W_C = 3 / 1$.

The elements on the diagonal of this matrix represent the pair-wise comparison of each criterion with itself. Thus, all the elements on the diagonal are equal to 1/1. From Figure 9 it also follows that the elements below the diagonals are the reciprocals of the corresponding elements above the diagonal. (e.g. an element on the first row, second column will be a reciprocal of the element on the second row in the first column.)

W_C / W_C	W_C / W_T	W_C / W_S	W_C / W_B	W_C / W_P	W_C / W_E
W_T / W_C	W_T / W_T	W_T / W_S	W_T / W_B	W_T / W_P	W_T / W_E
W_S / W_C	W_S / W_T	W_S / W_S	W_S / W_B	W_S / W_P	W_S / W_E
W_B / W_C	W_B / W_T	W_B / W_S	W_B / W_B	W_B / W_P	W_B / W_E
W_P / W_C	W_P / W_T	W_P / W_S	W_P / W_B	W_P / W_P	W_P / W_E
W_E / W_C	W_E / W_T	W_E / W_S	W_E / W_B	W_E / W_P	W_E / W_E

Where:

W_i / W_j represents the pair wise comparison of factor I with factor J

I, J = C, T, P, B, S, E

C = Cost Effectiveness of strategy

T = Disruption to Flow of Traffic

P = Impact of construction on Surrounding Communities

B = Impact of construction on Local Businesses

S = Safety of all stakeholders

E = Disruption to environment & ecosystems.

Figure 9: Pair-wise Comparison: Highest Level

The pair-wise comparison for these factors is likely to be unique to the project and priorities placed by decision makers on these factors. The second survey conducted as a part of this research study extracted relative importance of various factors in the decision making process. The figure 9a is an interpretation of the responses obtained from DOT officials. It can be used as a guideline for conducting pair wise comparisons.

PAIR WISE COMPARISONS	C	T	S	B	P	E
C	1	3 / 1	3 / 1	4 / 1	4 / 1	5 / 1
T	1 / 3	1	1	3 / 1	4 / 1	4 / 1
S	1 / 3	1	1	3 / 1	4 / 1	4 / 1
B	1 / 4	1 / 3	1 / 3	1	3 / 1	3 / 1
P	1 / 4	1 / 4	1 / 4	1 / 3	1	1
E	1 / 5	1 / 4	1 / 4	1 / 3	1	1

Figure 9a: Guidelines for Pair Wise Comparisons

The six main criteria in the above matrix can further be sub-divided into sub criteria which form their own matrices using pair-wise comparisons. The pair wise comparison matrices for sub criteria discussed here are for demonstration of the technique. Each bridge construction project is unique and the factors discussed may or may not be used. This model, based on the AHP, is flexible because the user can customize these matrices according to unique project requirements.

The criterion related to Safety of all stakeholders can be divided into sub criteria such as:

1. Ensuring Motorist safety (M)
2. Ensuring safety of Construction Workers (S)
3. Ensuring safety of Pedestrians.(P)

w_M / w_M	w_M / w_S	w_M / w_P
w_S / w_M	w_S / w_S	w_S / w_P
w_P / w_M	w_P / w_S	w_P / w_P

w_i / w_j represents the pair wise comparison of factor I with factor J

$I, J = M, S, P$

Fig 10: Pair Wise Comparison: Safety

From the responses of DOT officials in survey 2, the guidelines for pair-wise comparisons for this matrix are shown in figure 11.

PAIR WISE COMPARISONS	M	S	P
M	1	3 / 1	3 / 1
S	1 / 3	1	1
P	1 / 3	1	1

Figure 11: Guidelines for Pair Wise Comparisons: Safety

The criterion related to impact of construction on Local Businesses can be divided into sub-criteria such as:

1. Ensuring access to local businesses, (A)
2. Acceptability of the detour (if required) (D)
3. Availability of Parking Space, (P)
4. Congestion (C)
5. Supply routes to local manufacturing facilities. (S)

w_A / w_A	w_A / w_D	w_A / w_P	w_A / w_C	w_A / w_S
w_D / w_A	w_D / w_D	w_D / w_P	w_D / w_C	w_D / w_S
w_P / w_A	w_P / w_D	w_P / w_P	w_P / w_C	w_P / w_S
w_C / w_A	w_C / w_D	w_C / w_P	w_C / w_C	w_C / w_S
w_S / w_A	w_S / w_D	w_S / w_P	w_S / w_C	w_S / w_S

w_i / w_j represents the pair wise comparison of factor I with factor J

I, J = A, D, P, C, S

Fig 12: Pair Wise Comparison: Business

From the responses of DOT officials in survey 2, the guidelines for pair-wise comparisons for this matrix are shown in figure 13.

PAIR WISE COMPARISONS	A	D	P	C	S
A	1	3 / 1	3 / 1	5 / 1	5 / 1
D	1 / 3	1	1	3 / 1	3 / 1
P	1 / 3	1	1	3 / 1	3 / 1
C	1 / 5	1 / 3	1 / 3	1	1
S	1 / 5	1 / 3	1 / 3	1	1

Figure 13: Guidelines for Pair Wise Comparisons: Local Economic Impact

The criterion related to impact of construction on surrounding communities can be divided into sub-criteria such as:

1. Impact on access to community (A)
2. Acceptability of the detour (if required) (D)
3. Access to Emergency services (E)
4. Scheduled Local events (L)

$$\begin{bmatrix}
 W_A / W_A & W_A / W_D & W_A / W_E & W_A / W_L \\
 W_D / W_A & W_D / W_D & W_D / W_E & W_D / W_L \\
 W_E / W_A & W_E / W_D & W_E / W_E & W_E / W_L \\
 W_L / W_A & W_L / W_D & W_L / W_E & W_L / W_L
 \end{bmatrix}$$

W_i / W_j represents the pair wise comparison of factor I with factor J

$I, J = A, D, P, C, S$

Fig 14: Pair Wise Comparison: Community

From the responses of DOT officials in survey 2, the guidelines for pair-wise comparisons for this matrix are shown in figure 15.

PAIR WISE COMPARISONS	A	D	E	L
A	1	1 / 3	1 / 5	1
D	3 / 1	1	1 / 4	3 / 1
E	5 / 1	4 / 1	1	5 / 1
L	1	1 / 3	1 / 5	1

Figure 15: Guidelines for Pair Wise Comparisons: Impact on Communities

The criterion related to impact of construction on environment and ecosystems can be divided into sub-criteria such as:

1. Air pollution due to construction and congestion (A)
2. Noise pollution due to construction and congestion (N)
3. Ecosystems. (E)

$$\begin{bmatrix}
 w_A / w_A & w_A / w_N & w_A / w_E \\
 w_N / w_A & w_N / w_N & w_N / w_E \\
 w_E / w_A & w_E / w_N & w_E / w_E
 \end{bmatrix}$$

w_i / w_j represents the pair wise comparison of factor I with factor J

$I, J = A, N, E$

Fig 16: Pair Wise Comparison: Environment

From the responses of DOT officials in survey 2, the guidelines for pair-wise comparisons for this matrix are shown in figure 17.

PAIR WISE COMPARISONS	A	N	E
A	1	1	1 / 5
N	1	1	1 / 5
E	5 / 1	5 / 1	1

Fig 17: Guidelines for Pair Wise Comparisons: Environment

From the table, we can see that the relative importance of impact of air and noise pollution is almost the same in the decision making process whereas the importance of impact on ecosystems is significantly high. This could be on account of laws that protect ecosystems whereas the laws concerning air and noise pollution can't be easily applied to a specific project.

4.2.3 Calculate Eigen values and Eigenvectors:

The relative importance (weight) of sub-criteria with respect to the criterion at one level above can be determined by calculating the eigenvector of the matrix. For a comprehensive theoretical discussion of this concept, please refer to appendix 1.

The Eigenvector associated with the principal Eigen value of a Matrix 'A' can be calculated as:

$$\lim_{k \rightarrow \infty} \frac{A^k e}{e^T A^k e} = Cw \quad (\text{Saaty, 1980}) \dots \dots \dots (1)$$

Where:

1. E is the column vector unity and e^T its transpose
2. C is a constant.
3. w is the Eigen vector.

The eigenvector solution can be found out by either using computer programs like MATLAB or by manual calculations. Saaty (1980) developed approximate methods for calculating eigenvectors. These methods are discussed below:

1. Normalization of Row Averages:

The elements in each row are added and then normalized by dividing each sum by the total of all the sums. The results now add up to unity. The first entry of the resulting vector is the priority of the first activity; the second of the second and so on.

$$w_i = \frac{\sum_{j=1}^n a_{ij}}{\sum_{i,j=1}^n a_{ij}} \dots\dots\dots (2)$$

2. Geometric mean of the rows:

This method involves the following four steps:

- a. Multiply the n elements in a row.
- b. Take their n^{th} root.
- c. Normalize the resulting numbers by dividing the sum of the product of all the numbers in every row.

$$w_i = \frac{\left(\prod_{j=1}^n a_{ij}\right)^{1/n}}{\sum_{k=1}^n \left(\prod_{j=1}^n a_{kj}\right)^{1/n}} \dots\dots (3)$$

3. ***Average of normalized columns:***

This is the most commonly used method. It involves the following steps:

- i. Convert the fraction pairwise comparisons to decimal equivalents.
- ii. Add the elements of each column.
- iii. Create a normalized matrix by dividing each element by its column total.
- iv. Add the elements of the rows of the resulting normalized matrix.
- v. Average the normalized columns by dividing the row sum by the number of elements in the row.

The resulting column of values is an approximation of the eigenvector, which is actually the weight assigned to each of the factors. The following equation 4 summarizes the process explained above.

$$w_i = \frac{1}{n} \sum_{j=1}^n \frac{a_{ij}}{\sum_{k=1}^n a_{kj}} \dots\dots\dots (4)$$

Saaty (1980) recommends the use of average of Normalized Columns for calculating the Eigen vector for the matrices because of its ease of use and it approximates the values of Eigen vector to a satisfactory level.

4.2.4. Check consistency of Matrices:

At various stages in the analysis, the consistency of the matrices must be checked to verify the reliability of the judgments of the decision maker. For a consistent positive

reciprocal matrix, the largest Eigen value is equal to the order of the matrix (n) and for an inconsistent positive reciprocal matrix; the Eigen value is greater than the order of the matrix. Saaty (1980) defined a measure of consistency of matrix called the consistency index (CI). The Consistency Index can be defined as:

$$\text{Consistency Index} = (\lambda_{\max} - n) / (n - 1) \dots\dots\dots (5)$$

For a perfectly consistent matrix of pairwise comparisons, the CI would be zero, because the Eigen value is equal to the order of the matrix (Saaty 1982). Pairwise comparison based on quantitative judgments results in a consistent matrix. However, it is difficult to maintain this consistency when the judgments are qualitative in nature. E.g.: If we say that criteria A is slightly more important than criteria B for achieving the goal(1:3), and criteria A is strongly more important than criteria C for achieving the goal (1:5), then it can be deduced that criteria B is slightly important as compared to criteria C in achieving the goal (1:3). This analogy might not hold true in all cases. Hence, as a general rule, perfect consistency cannot be expected and is not required by AHP; thus, the computed CI will be greater than zero.

The maximum Eigen value, required to calculate the consistency index may be estimated using the following method (McIntyre, 1996)

1. Multiply each column in the original matrix by the weight vector value associated with the column number (e.g., the third column would be multiplied by the third value in the weight vector);
2. Sum the rows of this new matrix;

3. Divide the each of the sum of the rows by the corresponding value from the weight vector; and
4. Sum and average the column containing the summed rows. The resulting value is an approximation of the maximum Eigen value (McIntyre 1996).

The Consistency of judgments in the pair wise comparisons can be calculated by finding the consistency ratio. The Consistency Ratio can be defined as the ratio of Consistency Index and Random Index (Saaty 1982).

$$\text{Consistency Ratio} = \text{Consistency Index} / \text{Random Index} \dots\dots (6)$$

The Random Index (RI), for the different order random matrices was calculated by Saaty by randomly creating 500 positive reciprocal matrices of various sizes (1 X 1 to 15 X 15) and calculating the Consistency Index of each matrix. The probability distributions of the CIs were then studied and values for Random Index were recommended. These values are listed in table11.

Size of Matrix	Random Index
1	0
2	0
3	0.58
4	0.9
5	1.12
6	1.24
7	1.32
8	1.41
9	1.45
10	1.49
11	1.51
12	1.48
13	1.56
14	1.57
15	1.59

Table 11: Random Index Table

When making judgments concerning a large number of comparisons, it is important to emphasize that the objective in making good decisions is not to minimize the consistency ratio. Good decisions are most often based on consistent judgments, but the reverse is not necessarily true. AHP allows a margin of inconsistency. If the calculated CR for a given matrix is 0.10 or less, the inconsistency is generally considered to be acceptable for the evaluation of the decision hierarchy (Saaty 1982). If the CR is above 0.10, then the values assigned to the pairwise comparison in the given matrix should be re-examined. The whole procedure starting with the pairwise comparisons, matrix calculations, and consistency checks throughout the entire hierarchy should then be repeated.

4.2.5 Evaluate and Compare Alternatives for Criteria and Decision making:

Each project would have a number of activities that need to be evaluated in order to determine the best alternative that would suit the project. The final weights for sub-criteria can be obtained by multiplying the weight (from the Eigen-vector) with the weight of the corresponding criteria one level up higher in the hierarchy. For Example: If the weight (from the Eigen Vector at the top level) of the Safety criterion = 0.2 and the weights of corresponding sub-criteria

Motorist safety = 0.5,

Construction worker safety = 0.25,

Pedestrian safety = 0.25;

The final weights are:

Motorist safety = $(0.5 * 0.2) = 0.1$

$$\text{Worker safety} = (0.25 * 0.2) = 0.05$$

$$\text{Pedestrian safety} = (0.25 * 0.2) = 0.05$$

In the next step each alternative is evaluated for its effectiveness in achieving the objective stated in each sub-criterion using pair-wise comparison similar to step 2 using the pair-wise comparison scale. The consistency of these pair-wise matrices is checked and Eigen vectors are calculated. These Eigen vectors represent the performance of each alternative on the particular criteria for which they are evaluated.

Finally, a matrix of Eigen values obtained from the previous stage is created and it is multiplied with the transpose of the final sub-criterion weights. The alternative with the largest value is the most favorable.

$$\begin{array}{l}
 \text{Alternative x} \\
 \text{Alternative y} \\
 \text{Alternative z}
 \end{array}
 \begin{bmatrix}
 e_{1x} & e_{2x} & e_{3x} & e_{4x} & e_{5x} \\
 e_{1y} & e_{2y} & e_{3y} & e_{4y} & e_{5y} \\
 e_{1z} & e_{2z} & e_{3z} & e_{4z} & e_{6z}
 \end{bmatrix}
 \begin{bmatrix}
 w_1 \\
 w_2 \\
 w_3 \\
 w_4 \\
 w_5
 \end{bmatrix}$$

Where: w_1, w_2, w_3, w_4, w_5 are the final weights for sub-criteria 1, 2, 3, 4, 5
 e_{1x} = Effectiveness of alternative x for sub-criteria 1

Fig 18: Final Evaluation of Alternatives

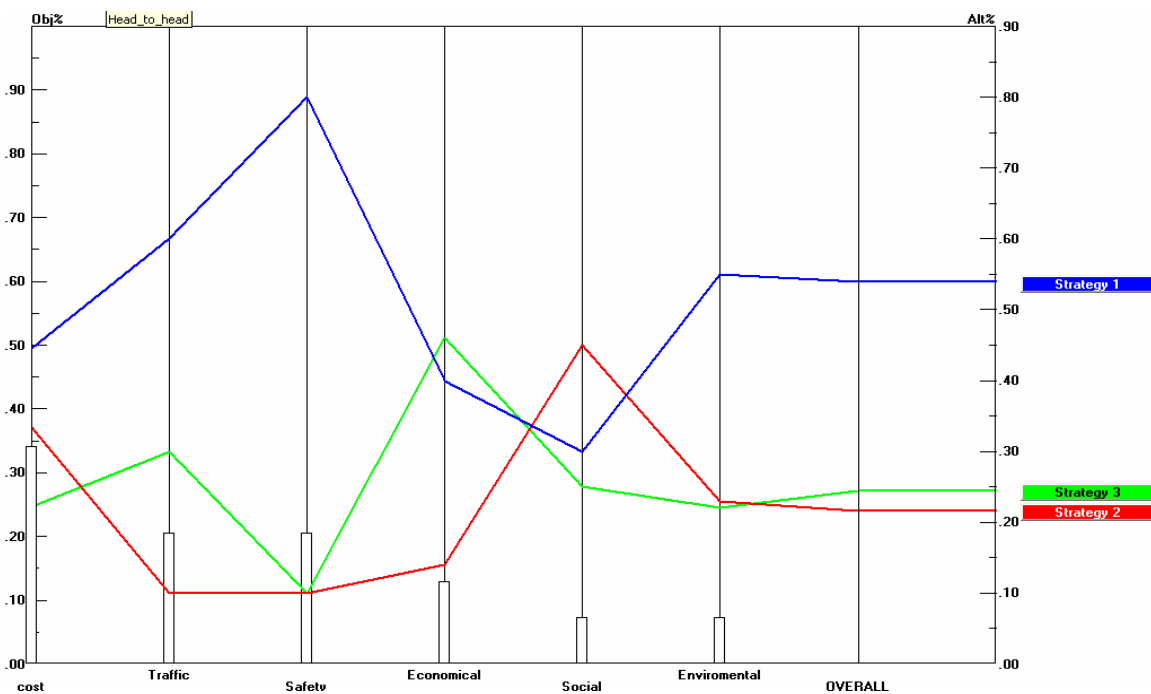
4.2.6 Sensitivity analysis:

Sensitivity analysis is the study of how the variation in the output of a model can be apportioned qualitatively or quantitatively to different sources of variation and of how the

given model depends upon the information fed into it (Saltelli, 2000). Sensitivity analysis can be performed to see how well the alternatives perform with respect to each of the criteria as well as how sensitive the alternatives are to changes in the importance of the criteria.

Sensitivity analysis of the decision making model which uses AHP requires checking the change in output for small change in the input. This would entail changing the pair wise comparison values for every factor and conducting the entire analysis. This will have to be done for every factor at many different levels. This process is computationally intensive and it can take a significant amount of time. Many commercially available software programs such as Expert Choice can be utilized to conduct sensitivity analysis. With small changes in the weight of a single factor, the software changes the weights of the other input variables and changes the values of the resulting outputs. A typical sensitivity analysis graph is shown in figure 19.

Fig 19: Typical Performance Sensitivity Graph



The "left y-axis" can be used to read each objective's priority. The "right y-axis" can be used to read the alternative priorities with respect to each objective. The lines connecting the alternatives from one objective to another have no meaning; they are included to help the user find where a particular alternative lies as the user moves from one objective to another. The decision making process is encapsulated in the following flow chart.

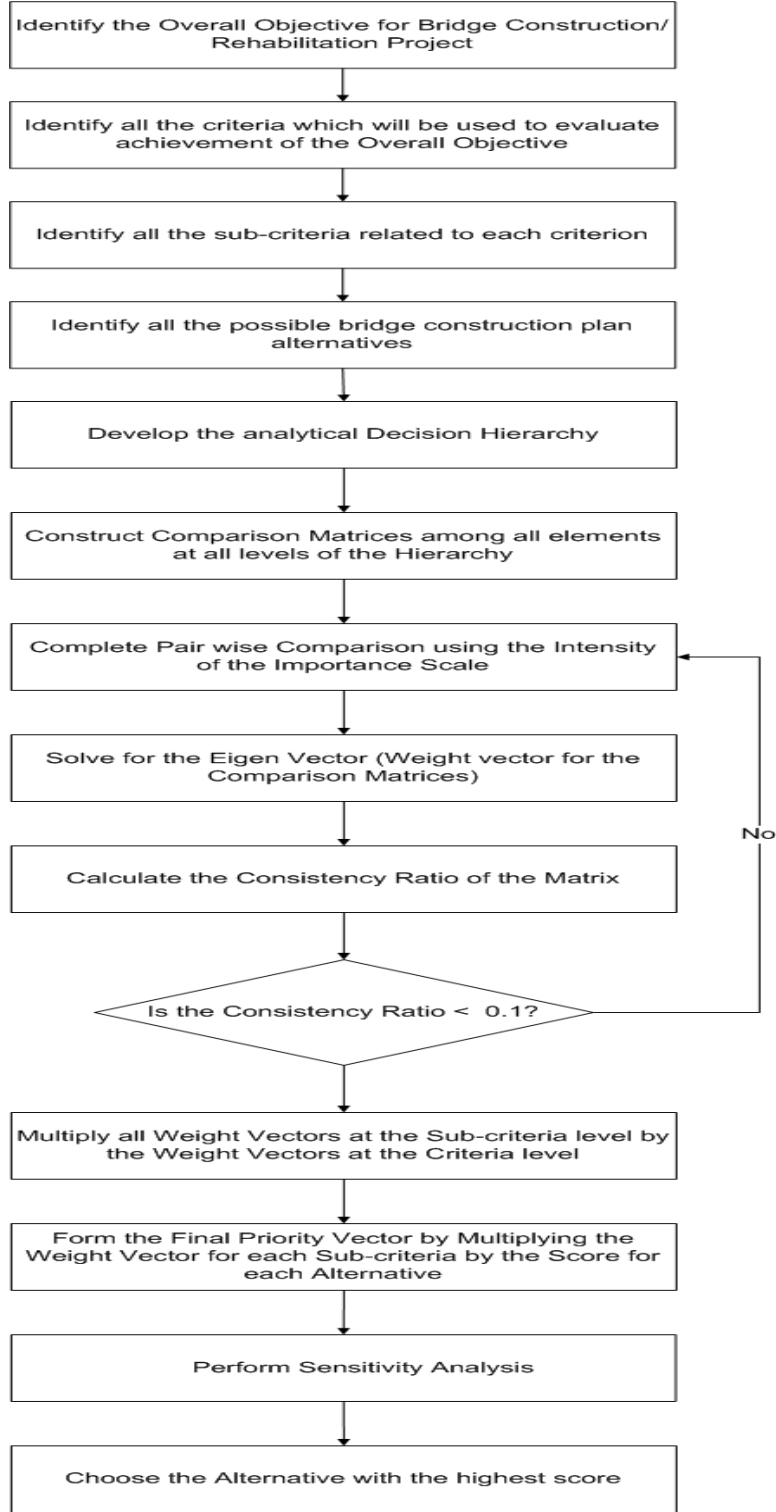


Fig. 20: Flowchart of Decision Making Process

5 The Accelerated Construction Decision-Making Model:

Illustrations from SI #9 Projects

5.1 Introduction

In an effort to better manage highway infrastructure assets, the Ohio Department of Transportation started several initiatives aimed at reducing the problems associated with the reconstruction of roadways. One initiative, Strategic Initiative # 9, “*Build Bridges Faster, Smarter and Better*” identified bridges as a significant source of delays in the rehabilitation process of roadways. This Strategic Initiative explores ways to minimize the down time of bridge structures by either constructing faster and/or improving quality to minimize future downtime for repair or maintenance. The University of Cincinnati has been studying the various aspects of Strategic Initiative # 9 through various pilot projects. The Analytical Hierarchy Process based model developed in this study has been applied and tested on two SI # 9 pilot projects for illustrating the use of this decision making model.

5.2 The Guernsey 513:

This Bridge which was one of the pilot projects in the Strategic Initiative # 9 study is located in Quaker City, Ohio; a rural town located approximately fifty miles west of Columbus. This structure over the Leatherwood Creek on the State Route 513, is the only north-south thoroughfare through the town. Closure of the bridge would have resulted in a 20 mile detour for automobiles and a 40 mile detour for trucks and buses. As this route is used by school buses, local officials had concerns about this long detour. Also, safety issues would have arisen had the bridge been rehabilitated using part-width

construction which would have reduced the bridge into a one-lane, signal controlled bridge.

Also, Quaker City holds an annual Ohio Hills Folk Festival. The festival is a major revenue generator for the people and Quaker City as a whole and hence it was imperative that the bridge be complete and operative before the festival started. These were some of the main factors that prompted the acceleration of this bridge rehabilitation project. To address these concerns, Ohio Department of Construction decided to use a 16 day window in late June to reconstruct the bridge. This window period corresponded to the end of the regular school year and the beginning of the summer school classes. There was also a funeral home near the bridge construction site which required noise levels to be maintained to a minimum had there been a death that occurred in the area during the rehabilitation period. This was one of the concerns while accelerating as a few hours of delay would have hampered the whole schedule.

The following construction of the model with the use of the data obtained from the project compares the different alternatives of construction that were considered and the reasons as to why acceleration was preferred over the other alternatives. The six-step Analytical Hierarchy Process explained in the previous chapters was used to develop the model for this project. The factors and their related sub-factors that were considered in this project according to the hierarchical structure are as listed below.

- Costs (C)
- Traffic flow (T)
- Safety (S): Motorist safety (M_S), Construction worker safety (C_S),
Pedestrian safety (P_S).

- Social (P): Access to community (A_P), Detour acceptability (D_P), Access to Emergency services (E_P), Local events (L_P).
- Economic (B): Access to businesses (A_B), Detour acceptability (D_B), Congestion (C_B), Supply route to manufacturing units (S_B).
- Environment (E): Air pollution (A_E), Noise pollution (N_E).

The three alternative construction options considered were:

- Accelerated construction with complete closure
- Partial width construction
- Traditional construction

The goal was to find the best possible alternative to serve the purpose of early completion with a high safety level and minimum disturbance to the community and the environment surrounding the project site. The second step after forming the hierarchical structure was the construction of the Comparison matrices which were constructed to help determine the potency with which the various elements in one level would influence the elements on the next higher level. By constructing the comparison matrices using pair wise comparison, we could now compute the relative strengths of the impacts of the elements of the lowest level on the overall objective. The ratio scale depicted in the table 10 in the previous chapters was used as a guideline for the pair wise comparisons. The following are the Comparison Matrices for the main factors and the sub factors:

C	T	S	B	P	E	
1.00	2.00	2.00	4.00	1.00	2.00	C
0.50	1.00	1.00	2.00	0.50	1.00	T
0.50	1.00	1.00	2.00	0.50	1.00	S
0.25	0.50	0.50	1.00	0.25	0.50	B
1.00	2.00	2.00	4.00	1.00	2.00	P
0.50	1.00	1.00	2.00	0.50	1.00	E

Figure 21: Pair-wise comparison of the factors of the Main Matrix

M	W	P	
1.00	2.00	2.00	M
0.50	1.00	1.00	W
0.50	1.00	1.00	P

Figure 22: Pair-wise comparison for the Safety Sub Matrix

A _B	D _B	C _B	S _B	
1.00	2.00	3.00	3.00	A _B
0.50	1.00	2.00	2.00	D _B
0.33	0.50	1.00	1.00	C _B
0.33	0.50	1.00	1.00	S _B

Figure 23: Pair-wise comparison for the Economy Sub Matrix

$$\begin{array}{cc}
 A_E & N_E \\
 \left(\begin{array}{cc}
 1.00 & 0.50 \\
 2.00 & 1.00
 \end{array} \right) & \begin{array}{l} A_E \\ N_E \end{array}
 \end{array}$$

Figure 24: Pair-wise comparison for the Environment factor Sub Matrix

$$\begin{array}{cccc}
 A_P & D_P & E_P & L_P \\
 \left(\begin{array}{cccc}
 1.00 & 0.50 & 0.25 & 0.14 \\
 2.00 & 1.00 & 0.50 & 0.33 \\
 4.00 & 2.00 & 1.00 & 0.50 \\
 7.00 & 3.00 & 2.00 & 1.00
 \end{array} \right) & \begin{array}{l} A_P \\ D_P \\ E_P \\ L_P \end{array}
 \end{array}$$

Figure 25: Pair-wise comparison for the Social factor Sub Matrix

The third step was to calculate the Eigen values for all the matrices. The five step “Average of normalized columns” method described previously in the report was followed to calculate the Eigen values. The following table 11 summarizes the Eigen values that were obtained from the calculations.

Criterion	Sub-Criteria	Eigen Value
Cost		0.2700
Traffic flow		0.1300
Safety	Motorist safety	0.0650
	Construction worker safety	0.0325
	Pedestrian safety	0.0325
Economic factor	Access to businesses	0.0315
	Detour acceptability	0.0182
	Congestion	0.0098
	Supply routes to manufacturing units	0.0098
Social factor	Access to the community	0.0189
	Detour acceptability	0.0405
	Access to emergency services	0.0756
	Local events	0.1350
Environmental factor	Air pollution	0.0429
	Noise pollution	0.0871

Table 12 Eigen values obtained from pair wise comparison of matrix elements.

To check the reliability of the judgments of the decision maker, the next step is to check the consistency of the matrices. The consistency of the matrices can be calculated by following the procedure described in chapter 4. The value of the maximum Eigen value gives us the Consistency Index (CI). The ratio of the Consistency Index and the Random Index (RI) gives us the corresponding Consistency Ratios (CR). If the Consistency Ratio is less than 0.10, then the Matrix is said to be consistent. The following table 12 lists the

Consistency Indices, Random Indices and the Consistency Ratios for the Guernsey 513 bridge project model.

Matrix	Consistency Index (CI)	Random Index (RI)	Consistency Ratio (CR)
Main Matrix	0.0000	1.2500	0.0000
Safety factors Matrix	0.0000	0.5200	0.0000
Economy factors Matrix	0.0200	1.1100	0.0180
Social factors Matrix	0.0200	0.8900	0.0230
Environmental factors Matrix	0.2000	0.5200	0.0390

Table 13: Consistency Values for Matrices for the Guernsey 513 Project

It can be seen from the above Consistency table 12, that all the matrices are consistent as their Consistency Ratio is less than 0.10. The next step in the model development procedure was to compare the available alternatives to find out as to which alternative would be the best choice for the project. In order to determine this, each alternative was evaluated for impact on each sub-factor using the pair wise comparison method. An example of the pair-wise comparison matrix for the cost factor is as shown in the Figure 26 below.

The Eigen values obtained from these pair wise comparisons (shown in the figure 26 below) were then multiplied with the transpose of the final factor weights calculated in table 12 above. The alternative with the largest weight would be the most favorable alternative. The following figure 27 shows the matrix multiplication of the weights obtained from the pair wise comparison of the different alternatives with the weights of the different factors.

	Alt 1	Alt 2	Alt 3	
(1.00	0.20	0.14	Alt 1
	5.00	1.00	0.20	Alt 2
	7.00	5.00	1.00	Alt 3

Figure 26 Pair wise Comparison of the Alternatives with respect to the Cost factor.

Alt 1	Alt 2	Alt 3	Weights	Factors	
(0.07	0.23	0.70	0.2700	Costs
	0.70	0.23	0.07	0.1300	Traffic flow
	0.71	0.10	0.19	0.0650	Motorist Safety
	0.71	0.14	0.14	0.0325	Worker Safety
	0.78	0.11	0.11	0.0325	Pedestrian Safety
	0.63	0.26	0.11	0.0315	Access to businesses
	0.63	0.26	0.11	0.0182	Detour Acceptability (Businesses)
	0.67	0.23	0.10	0.0098	Congestion
	0.67	0.24	0.09	0.0098	Supply Route
	0.70	0.23	0.07	0.0189	Access to community
	0.74	0.19	0.08	0.0405	Detour Acceptability (Community)
	0.70	0.23	0.07	0.0756	Emergency service access
	0.72	0.22	0.06	0.1350	Local events
	0.60	0.20	0.20	0.0429	Air Pollution
	0.60	0.20	0.20	0.0871	Noise Pollution

Figure 27: Final Evaluation of Alternatives – Guernsey

$$\text{Alt 1 (Acceleration)} = [(0.07*0.27) + (0.70*0.13) + \dots + (0.6*0.0871)] = 0.52$$

$$\text{Alt 2 (Partial lane closure)} = [(0.23*0.27) + (0.23*0.23) + \dots + (0.2*0.0871)] = 0.21$$

$$\text{Alt 3 (Traditional method)} = [(0.70*0.27) + (0.07*0.13) + \dots + (0.2*0.0871)] = 0.27$$

As we can see from the results above, acceleration was a clear winner as the most efficient construction technique in comparison with the other construction strategies.

Sensitivity Analysis

The “Expert Choice” software was used to perform sensitivity analysis on the model that was developed. We use the performance sensitivity analysis in which we dynamically change the priorities of the factors to determine how these changes affect the priorities of the alternative choices. The graph in the Figure 29 below shows the relation between the different factors and the alternatives.

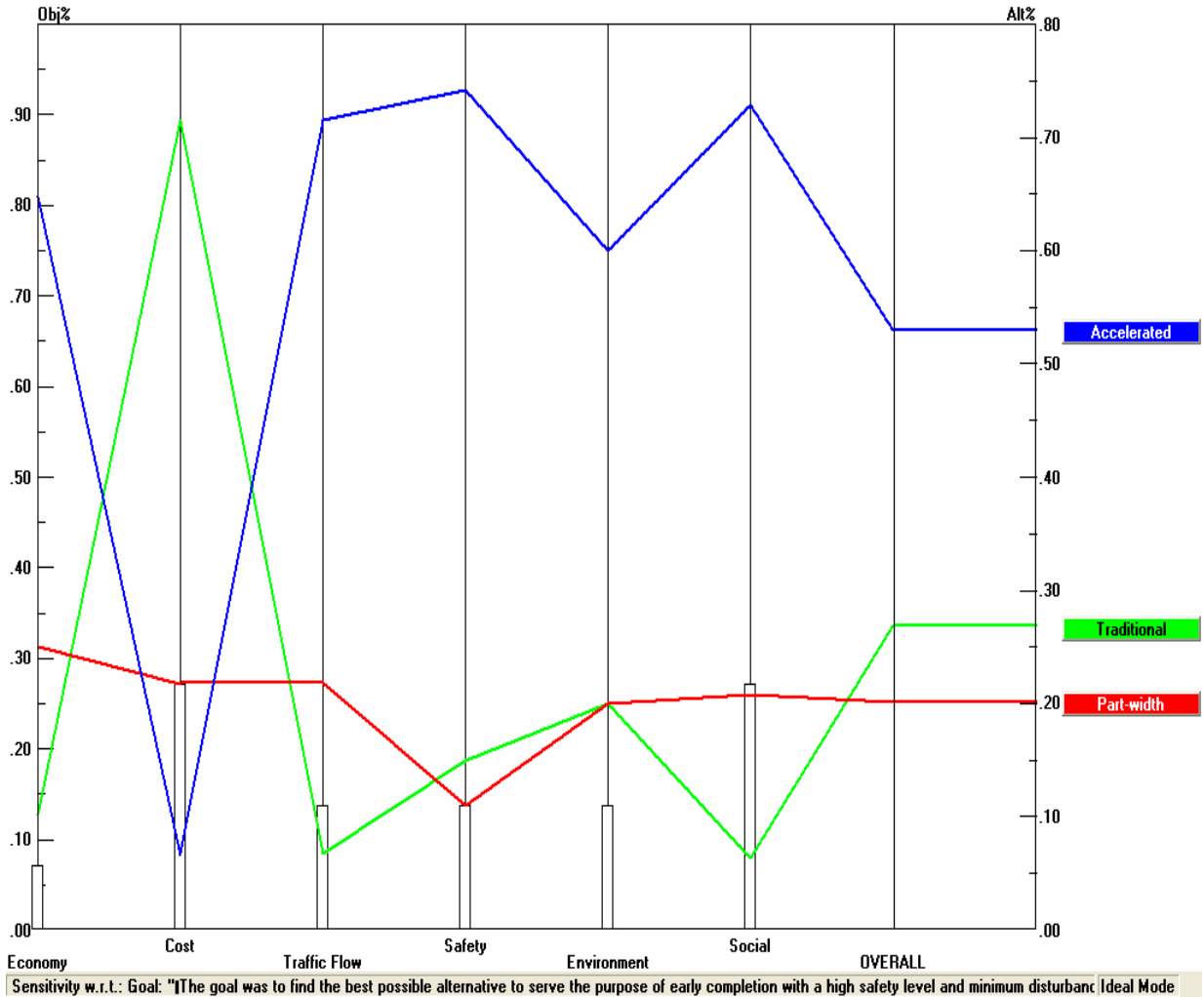


Figure 28: Performance Sensitivity Graph - Guernsey

The graph is dynamic in nature, viz.: the software allows the user to dynamically change values of the factors one at a time. The software changes the values of the other factors accordingly and hence the final output can be evaluated. This graph which depicts accelerated construction to be the best alternative with a weight of 0.53 or 53% followed by traditional construction (27%) and Part-width construction (20%) which is similar to the results obtained by the AHP process as shown in our calculations in figure 28 above.

5.3 The PIC 22 Bridge:

The PIC 22 Bridge is a part of the State Route US 22 where it passes over the Scioto River in Circleville, Ohio. This bridge located in the Pickaway County was to be replaced in 60 days. This route is used by more than 9000 vehicles in a day. The bridge could not close to the traffic before the end of the school year in June, and had to be re-opened no later than the beginning of the fall harvest in August. A replacement structure could not be built adjacent to the existing structure without impacting traffic, since a railroad passes over Route 22 east of the bridge, and there is significant earthwork west of the bridge (Swanson 2004). A design/build contract along with daily incentive/liquidated damages of \$50,000 was offered to complete the bridge in 60 days. There were some environmental problems faced as the US Army Corps of Engineers needed the plans with regards to the effect of the trestles on the waterway. Delays were also caused due to delays caused by a mistake in the permits for the trucks transporting the prefabricated components. However, the bridge was completed in 48 days, which was 12 days ahead of schedule for which the contractor earned the maximum incentive of \$500,000 due to the effective acceleration techniques used for construction.

The factors considered while deciding the method of construction to be selected were: Cost, Traffic flow, Safety, and Environment. The Analytical Hierarchy Process based model was used for the decision making procedure. The goal was to find the best possible alternative to serve the purpose of project completion within 60 days with a high level of safety and minimum disturbance to the environment surrounding the project site. Traditional construction and accelerated construction were the two alternatives to be considered for the AHP decision making process. The decision hierarchy consisted of 2

tiers with the Cost (C), Traffic flow (T), Safety (S) and Environmental (E) factors being followed by the two alternatives.

The Eigen values for decision making were derived by developing a pair wise comparison matrix for the factors mentioned above. The ratio scale depicted in Table 11 was used for comparing the factors with each other. The following figure 29 shows the pair wise comparison matrix.

$$\begin{array}{cccc}
 & \text{C} & \text{T} & \text{S} & \text{E} \\
 \left(\begin{array}{cccc}
 1 & 2 & 2 & 4 \\
 0.5 & 1 & 1 & 2 \\
 0.5 & 1 & 1 & 2 \\
 0.25 & 0.5 & 0.5 & 1
 \end{array} \right) & \text{C} \\
 & & & & \text{T} \\
 & & & & \text{S} \\
 & & & & \text{E}
 \end{array}$$

Figure 29: Pair wise comparison Matrix – PIC 22 Bridge

The Eigen vectors were then calculated using the Normalization of row averages method. The Eigen values are shown in the table 13 below. To verify the reliability of the decision-makers judgments, the consistency of the matrix was checked by deriving the Consistency Ratio by using the consistency Indices and the Random Index table. The Consistency Index, Consistency Ratios and Random indices are shown in the table 14 below. The table shows the judgments to be consistent enough as the consistency ratios are less than 0.10.

Factor	Eigen Value
Cost	0.44
Traffic flow	0.22
Safety	0.22
Environment	0.11

Table 13: Eigen Vector – PIC 22

Consistency Index (CI)	Random Index (RI)	Consistency Ratio (CR)
0	0.9	0

Table 14 Consistency Values of the Matrix for the PIC 22 Bridge Project

The next step in the model development procedure was to compare the available alternatives to find out as to which alternative would be the best choice for the project. In order to determine this, the two alternatives were evaluated for impact on each factor using the pair wise comparison method. The Eigen values obtained from these pair wise comparisons (shown in the figure 30 below) were then multiplied with the transpose of the final factor weights calculated in table 13.

$$\begin{array}{ccc}
 \text{Alt 1} & \text{Alt 2} & \text{Weight} \\
 \left(\begin{array}{cc} 0.20 & 0.80 \\ 0.86 & 0.14 \\ 0.86 & 0.14 \\ 0.80 & 0.20 \end{array} \right) & & \left(\begin{array}{c} 0.44 \\ 0.22 \\ 0.22 \\ 0.11 \end{array} \right)
 \end{array}
 \begin{array}{l}
 \text{Costs} \\
 \text{Traffic flow} \\
 \text{Safety} \\
 \text{Environment}
 \end{array}$$

$$\text{Alt 1 (Accelerated construction)} = [(0.44*0.20) + (0.22*0.86) + \dots + (0.11*0.8)] = 0.56$$

$$\text{Alt 2 (Traditional construction)} = [(0.44*0.80) + (0.22*0.14) + \dots + (0.11*0.20)] = 0.44$$

Figure 30: Final Evaluation of Alternatives - PIC 22

The above figure 30 shows the matrix multiplication of the weights obtained from the pair wise comparison of the different alternatives with the weights of the different factors.

As the Accelerated Construction strategy (0.56) weighed more than the traditional strategy (0.44), acceleration was to be the most favorable construction technique to be used for the construction of PIC 22 Bridge.

6 Conclusions & Recommendations

6.1 Conclusions

The decision making process for identifying an optimum strategy for construction of bridges involves careful evaluation of a number of factors such as construction costs, future rehabilitation costs, user costs, maintenance of traffic, quality of work, safety of motorists, safety of construction workers, safety of pedestrians, impact on surrounding communities and businesses, consideration of impact on sensitive ecosystems etc. In the surveys of state DOTs conducted as a part of this study, it was found that all the DOTs evaluate these factors during the decision making process in a qualitative and quantitative way. It was also found that factors such as impact of construction on local communities, local economy, impact on traffic flow have a significant impact on the eventual selection of a bridge construction plan.

Many of these factors such as safety of motorists, construction workers, pedestrians, reduced impact on surrounding communities and businesses on account of accelerated construction can't be quantitatively evaluated. A decision maker may decide to choose accelerated construction of a bridge at a higher initial construction cost in order to achieve these tangible but non-quantifiable (in monetary terms) benefits. The current models proposed for decision making in such cases (viz. *Bridge Construction Plan* by El-Diariaby et. al and *Prefabricated Bridge & Element Systems* by Ralls) correctly identify the need to assign weights to these factors to reflect the trade-offs that a decision maker has to make. They don't provide the decision maker a tool that transparently maps and synthesizes the trade-offs in required in the decision making system.

The decision making system proposed in this report provides the decision maker with a tool to quantify the qualitative trade-offs between various factors to extract a single set of weights which reflect the level of importance of each of these factors in the overall decision making process. The method uses pair wise comparisons to compare the relative importance of each factor with other factors using numerical / verbal scale. **The Eigenvectors of the matrices obtained from the pair wise comparisons reflect the relative importance of each of the factor in the decision making process.** Finally the same pair-wise comparison method can be used to evaluate the proposed solutions for their efficacy in achieving the goals.

The most notable aspect of this decision making system is that it doesn't prescribe fixed arbitrary weights to various factors in the decision making system. This system provides the decision maker with a transparent, extensible, customizable method to derive weights. **The decision makers can choose which factors will be addressed using the system and assign priorities to these factors and derive the weights using mathematically sound method.** This system will provide the decision makers an excellent and transparent tool to make decisions regarding choosing an optimal holistic strategy for decision making.

6.2 Recommendations

The problems related to the implementation of this decision making model needs to be studied in a real decision making environment on a bridge project. The unique problems faced while conducting pair wise comparisons of factors in a group decision making environment need to be diagnosed. Based on this experience, tools need to be identified for synthesizing opinions of a group of decision makers. The authors will work in co-operation with officials from the Ohio Department of Transportation to formulate a plan for implementing this decision making system.

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APPENDIX 1: Analytical Hierarchy Process

Eigenvector & Priorities (Weights)

Why is the eigenvector associated with the principal Eigen-value used to set priorities? (Saaty, 1980)

Let us consider the elements $C_1, C_2, C_3, \dots, C_n$ be of some level in a hierarchy.

Let $w_1, w_2, w_3, \dots, w_n$ be the weights of influence of these elements on the element in the higher level in the hierarchy.

Let a_{ij} be the number indicating the strength of C_i when compared with C_j

Let the matrix of these a_{ij} numbers be represented by A .

$$A = (a_{ij})$$

Since matrix A is reciprocal, $a_{ij} = a_{ji}$

The matrix A will be perfectly consistent if and only if

$$a_{ik} = a_{ij} * a_{jk} \text{ for all } i, j, k \quad \dots\dots(1)$$

We can say that: $a_{ij} = w_i / w_j$ where $i, j = 1, 2, \dots, n$

Thus, $a_{ij} * a_{jk} = (w_i / w_j) * (w_j / w_k) = w_i / w_k = a_{ik}$

Also, $a_{ji} = (w_j / w_i) = 1 / ((w_i / w_j)) = 1 / a_{ij}$

We can denote a set of linear equations in the matrix form:

$$A * x = y$$

Where $x = (x_1, x_2, x_3, \dots, x_n)$ and $y = (y_1, y_2, y_3, \dots, y_n)$

$$\sum_{j=1}^n a_{ij} x_j = y_i \quad \text{for all } i = 1, 2, 3, \dots, n$$

$$a_{ij} * (w_j / w_i) = 1 \quad \text{for all } i, j = 1, 2, 3, \dots, n$$

Consequently,

$$\sum_{j=1}^n a_{ij} * w_j / w_i = n \quad \text{for all } i, j = 1, 2, 3, \dots, n$$

$$\sum_{j=1}^n a_{ij} * w_j = n * w_i \quad \text{for all } i, j = 1, 2, 3, \dots, n$$

This equation is equivalent to:

$$A * w = n * w$$

This equation can be written as:

$$A * w - n * w = 0$$

$$\text{Or } (A - nI) * w = 0$$

This is a system of homogeneous equations which has a non trivial solution if and only if the determinant of $(A - nI) = 0$ viz. n is an Eigen value of A .

However, A has a unit rank because all the rows are a constant multiple of the first row.

Thus, all the Eigen values except one are zero and the sum of Eigen values of the matrix is equal to its trace, which is equal to n .

APPENDIX 2: Survey Instrument 1

Accelerated Construction Decision-Making Process for Bridges
Mid-West Regional University Transportation Center and Ohio DOT Research Project

QUESTIONNAIRE

General Information

Name: _____ Title: _____

Agency: _____ email: _____

Phone Number: _____

May we contact you with follow-up questions? Yes No

Accelerated construction of transportation infrastructure is actively being implemented under the aegis of the Accelerated Construction Technology Transfer [ACTT] program promoted by FHWA. This questionnaire is a part of a research study being conducted by the University of Cincinnati on behalf of the Ohio DOT and MRUTC to identify the factors which affect the decision making process of accelerating the construction of Bridges.

In the context of the survey, we would like to define an Accelerated Construction Project as any infrastructure project which was recently completed / is planned to be completed in substantially less time as compared to the traditional methods of project delivery in order to mitigate the impact of construction on the users of the infrastructure.

If you have additional comments please feel free to add them in the space provided at the end of the survey indicating the question number referred to.

We would like to thank you for your participation in this survey.

1. In the recent past, has your organization used the acceleration of construction as a strategy to dramatically reduce project delivery time?

- a. Yes b. No.

If: "Yes", please indicate below the percentage of accelerated projects to the overall projects executed:

10 20 30 40 50 60 70 80 90 100

If: "No", explain why it has not been used so far and please stop at question 1.

2. While making the decision to accelerate the speed of a construction / rehabilitation project, do you currently consider life cycle costs ___ and/or user costs___ (please check) associated with various possible alternatives and use these costs as a part of the decision making process?

- a. Yes b. No.

If you answered “Yes” to the above question, can you direct us to the information on how these costs are calculated?

3. Do you consider the impact on local Businesses, Environment, etc. while calculating user costs with reference to

- | | | |
|---|-----|----|
| a. Loss of revenue | Yes | No |
| b. Increased traffic | Yes | No |
| c. Loss of parking access. | Yes | No |
| d. Isolation of a business from traffic
due to closures/detours. | Yes | No |
| e. Others | Yes | No |

Please specify:

4. How would you rate the impact of the following factors on the decision to accelerate the speed of construction / rehabilitation projects?

[On a scale of 0 to 10 where 0 represents no impact and 10 represents the maximum impact]

- | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|----|
| a. Critical infrastructure element (e.g.: the only bridge or access to a particular area) | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| b. Current Traffic Volume | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| c. Road User Safety | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| d. Political influence | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| e. Impact on Environment | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| f. Impact on local businesses | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| g. Local events (e.g.: project to be completed before school begins) | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| h. Storm or earthquake damage | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |

5. While executing a project which is likely to have a substantial impact on local businesses that depend on the part of transportation infrastructure under rehabilitation, at which stage do you involve the local businesses in the decision making process?
 - a. Not involved in the process.
 - b. Before the project planning phase, so as to consider their views on the project.
 - c. During the planning phase so as to address their concerns.
 - d. During the execution phase to make them aware of the detours / closures.

6. While executing a project that is likely to have substantial impact on the communities in its surrounding area, at which stage do you involve them in the decision making process?
 - a. Not involved in the process.
 - b. Before the project planning phase, so as to consider their views on the project.
 - c. During the planning phase so as to address their concerns.
 - d. During the execution phase to make them aware of the detours / closures.

7. Which of the following innovative contracting techniques (impacting the timely completion of a project with minimum impact on flow of traffic) did you use in the accelerated construction project(s)?
 [1-Used frequently; 2-Use depends on type of job; 3-Use depends on size (cost) of job; 4-Use depends on location; 5-Used occasionally; 6- Not used]

a. A + B	1	2	3	4	5	6
b. A + B + Incentive / Disincentive	1	2	3	4	5	6
c. Incentive / Disincentive	1	2	3	4	5	6
d. Lane Rental	1	2	3	4	5	6
e. Design Build	1	2	3	4	5	6
f. Other (Please Specify)	1	2	3	4	5	6

Please make use of this space to identify factors which affect the decision making process in accelerated construction projects (you can use the space overleaf for additional comments).

Glossary:

- **A+B:** The cost plus time bidding process, commonly known as the A+B method, involves time (B) along with the associated cost (A). Here, the winning bid is decided on the basis of both the cost and time components (Construction cost + Time * Road user cost per day).

- **Design Build:** In this type of contracts, the owner specifies end result parameters and establishes design criteria and the bidders develop proposals which optimize their design and construction capabilities. The work is awarded on the basis of design quality, timeliness and cost etc.

- **Incentive/Disincentive:** These provisions are aimed at motivating the contractor to finish the work before scheduled completion time. The contractors receive an incentive for an early finish and have to suffer losses if they go over the time limit. In many cases incentives don't exceed 5% of the contract value. These provisions are often used in conjunction with A+B contracts. The incentive is usually based on the Road user costs determined at the beginning of the project.

- **Lane Rental:** In Lane rental concept, the contractor is charged a fee (usually based on the Road User Costs) for occupying the lanes during construction. This type of contract is targeted at motivating the contractor to reduce the road user impacts to a minimum during construction.

APPENDIX 3: Survey Instrument 2

Accelerated Construction Decision-Making Process for Bridges
Midwest Regional University Transportation Center and Ohio DOT Research Project

General Information:

Name:

Title:

*We would like to thank you for your participation in the previous questionnaire survey. As you must be aware, we are conducting a research study at the University of Cincinnati on behalf of the Ohio DOT and MRUTC to identify the factors which affect the decision making process of accelerating the construction of Bridges. Through the questionnaire survey and review of literature we **have identified a number of factors** which impact the decision to accelerate the construction / rehabilitation of bridges. We are formulating a holistic decision making tool which will help decision makers address more than just the traditional metrics (initial costs, life cycle costs, user costs) while making the decision to accelerate the construction in a bridge project. This tool will explicitly address the socio-economic factors, safety factors, Local conditions etc.*

We would like your opinion on the relative importance that should be given to these factors while making the decision to accelerate the speed of construction. This may not reflect your current decision making process.

We would like to thank you for your participation.

What is the **relative importance that should be given** to the following factors while making the decision to accelerate the construction of bridges? (Please note that all the factors add-up to 100%)

Factor	Percent Weight
Cost <i>(How much importance should be given to the initial construction costs, road user costs, maintenance costs while deciding the construction strategy?) (Traditional /Accelerated)</i>	___%
Traffic flow <i>(How much importance should be given to the impact of construction strategy on the flow of traffic in that section of the network during construction while deciding the construction strategy?) (Traditional /Accelerated)</i>	___%
Safety <i>(How much importance should be given to motorist safety, construction worker safety, and pedestrian safety while deciding the construction strategy?) (Traditional /Accelerated)</i>	___%
Impact on local Economy <i>(How much importance should be given to the impact of the construction strategy on the local businesses on account of loss of access, business parking space isolation etc. while deciding the construction strategy?) (Traditional /Accelerated)</i>	___%
Impact on local Community <i>(How much importance should be given to the impact of the construction strategy on affected communities while deciding the construction strategy?) (Traditional /Accelerated)</i>	___%
Environmental Impact <i>(How much importance should be given to the impact of the construction strategy on local ecosystems, pollution, noise etc. while deciding the construction strategy?) (Traditional /Accelerated)</i>	___%
Total	100%

We have identified the following sub factors within each of the above factors. Please rate the relative importance of each of the sub factors?

Safety Factors:

<i>Factor</i>	<i>Percent Weight</i>
Motorist Safety	__%
Construction Worker Safety	__%
Pedestrian Safety	__%
Total	100%

Impact on local Economy:

<i>Factor</i>	<i>Percent Weight</i>
Reduced Access to Local Businesses	__%
Reduction in Business Parking Space	__%
Construction / Traffic Congestion In Front of Businesses	__%
Acceptability of Detours to Local Businesses	__%
Material supply routes to local manufacturing facilities	__%
Total	100%

Impact on local community:

<i>Factor</i>	<i>Percent Weight</i>
Reduced Access to Local Communities	__%
Acceptability of Detours to affected Community	__%
Access to emergency services	__%
Local Events (major sports event, etc.)	__%
Total	100%

Environmental Factors:

<i>Factor</i>	<i>Percent Weight</i>
Ecosystems (e.g.: Wetlands, etc.)	__%
Air Pollution	__%
Noise Pollution	__%
Total	100%

APPENDIX 4: Scatter Plots of data from Survey Responses

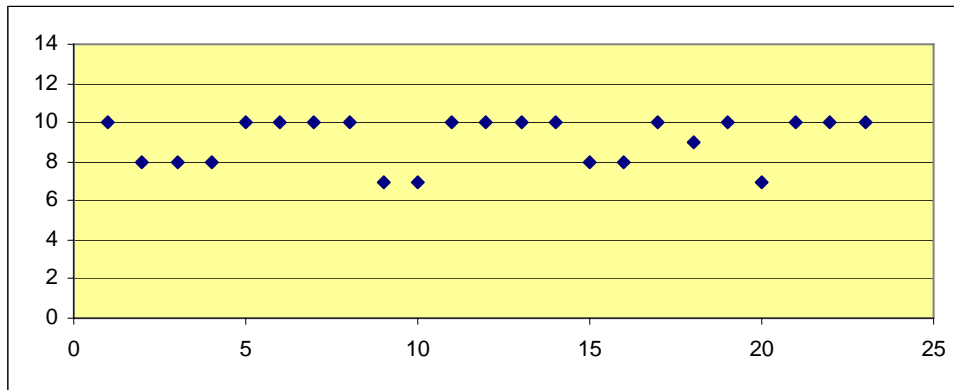


Figure 31. Critical Infrastructure Elements

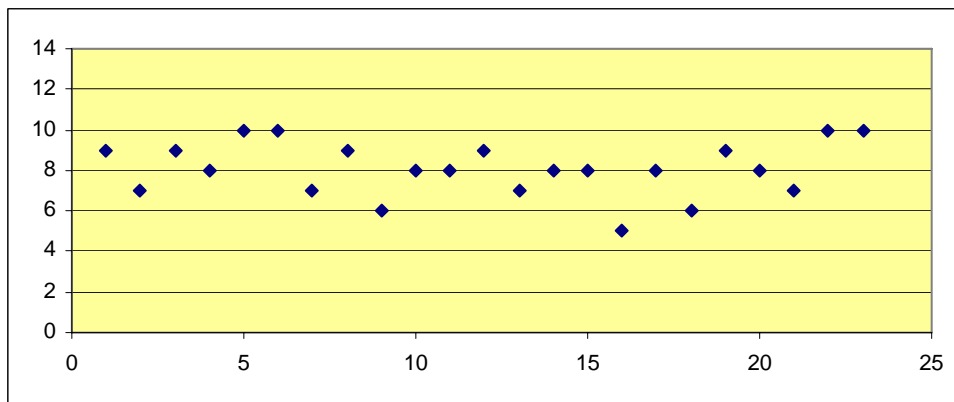


Figure 32: Current Traffic volume: Scatter Plot

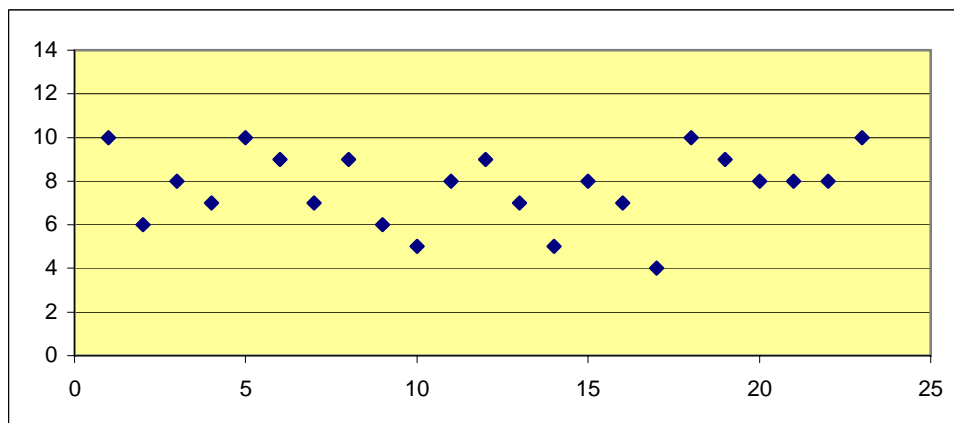


Figure 33: Road User Safety: Scatter Plot

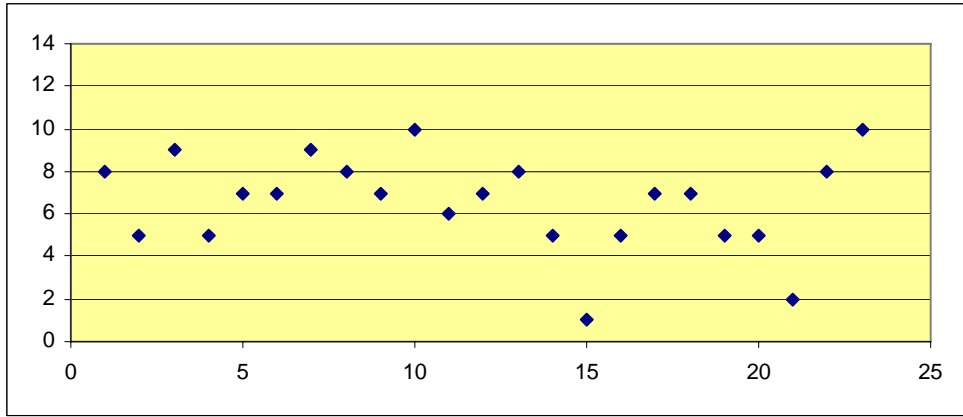


Figure 34: Political Influence: Scatter Plot

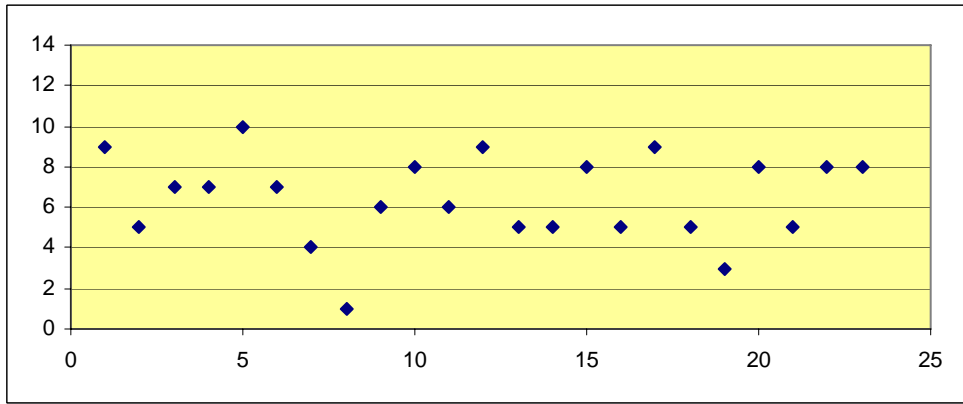


Figure 35: Impact on Environment: Scatter Plot

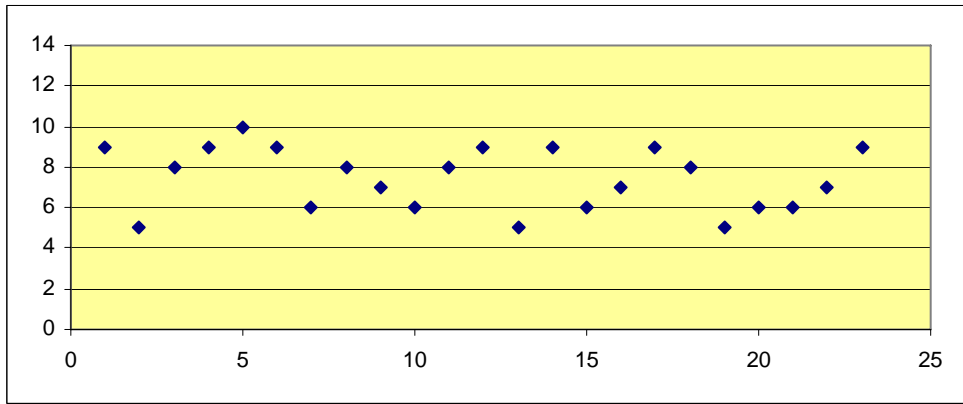


Figure 36: Impact on Local Businesses: Scatter Plot

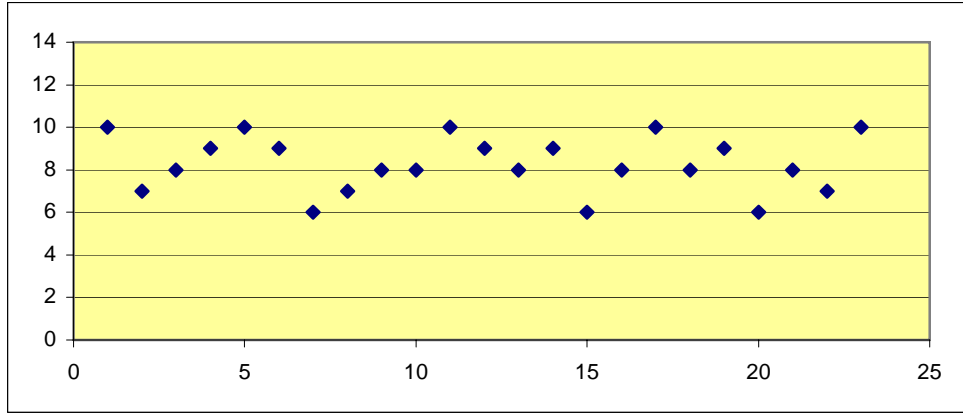


Figure 37: Local Events: Scatter Plot

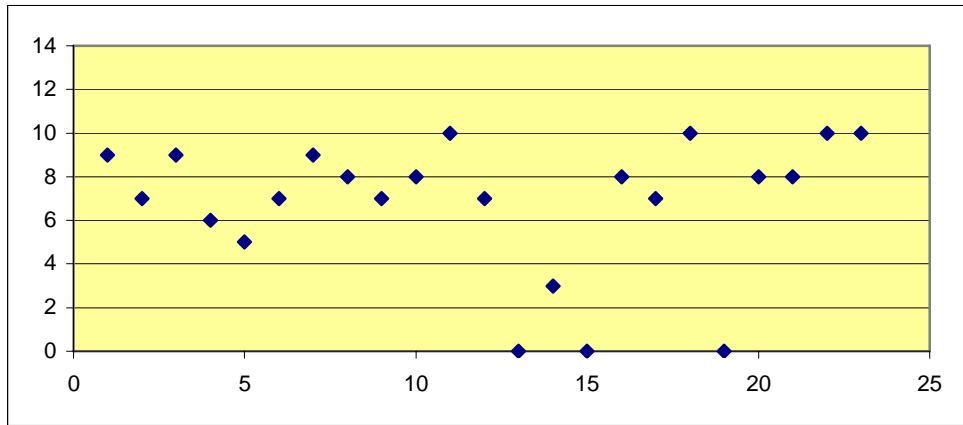


Figure 38: Emergency Situations: Scatter Plot

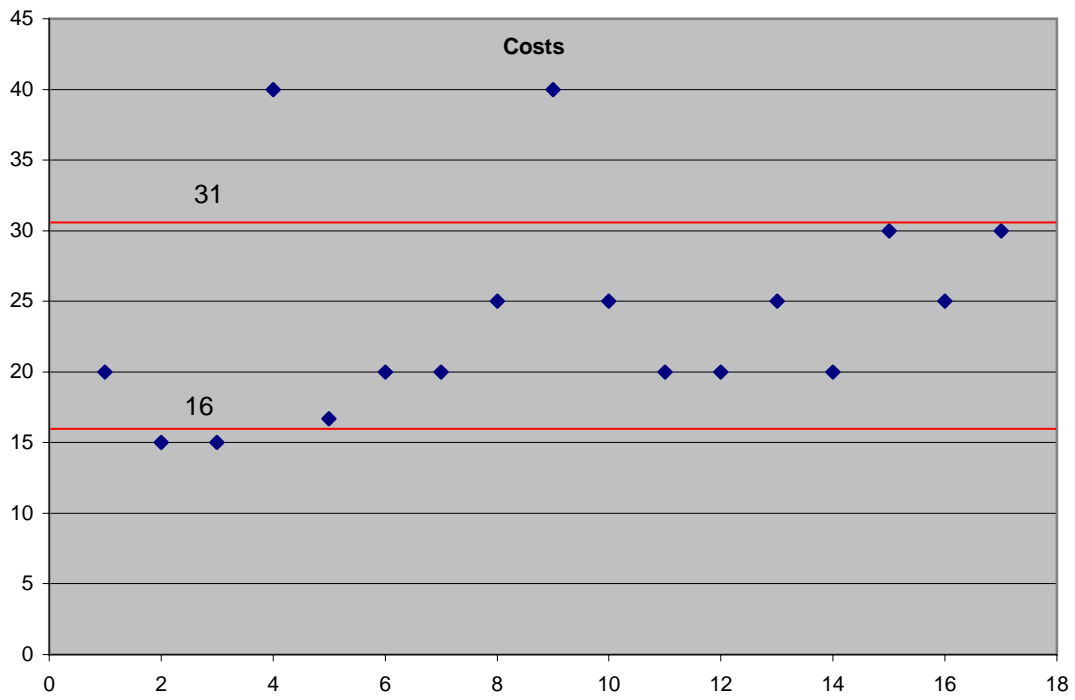


Figure 39: Scatter plot for Cost factor.

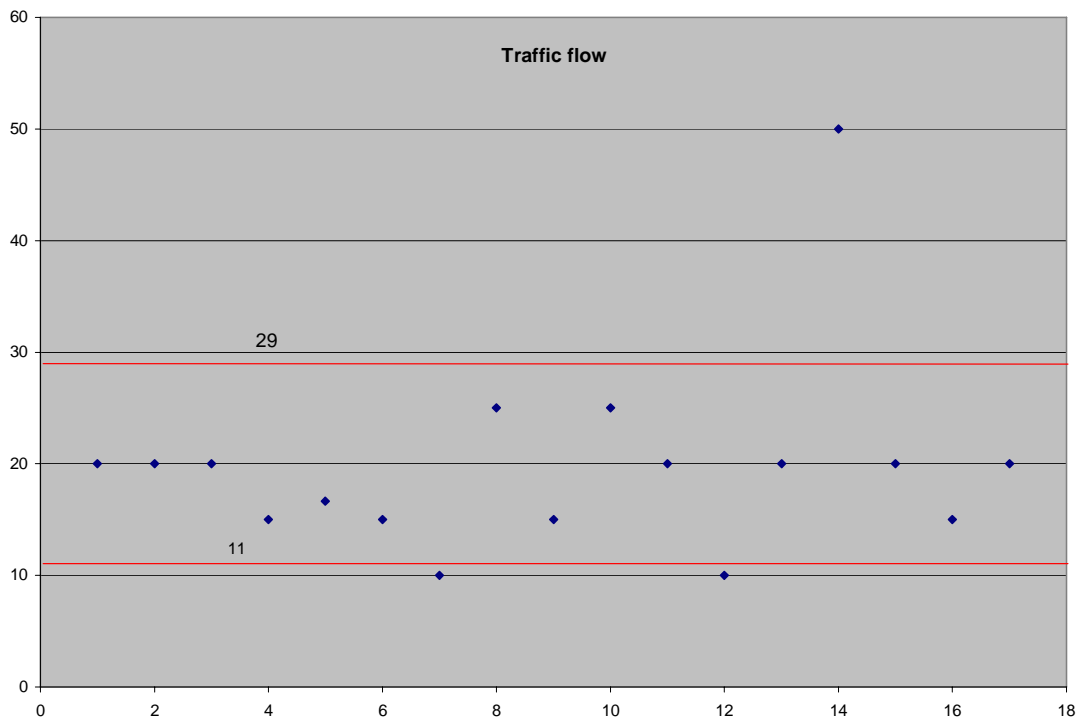


Figure 40: Scatter plot for Traffic flow.

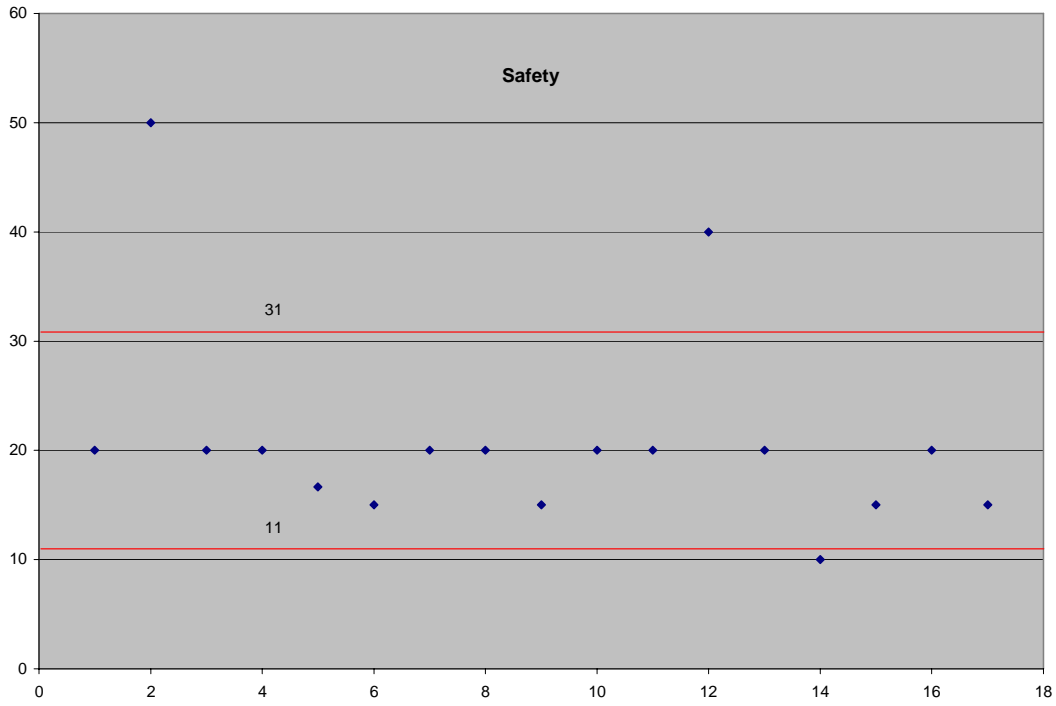


Figure 41: Scatter plot for Safety factor.

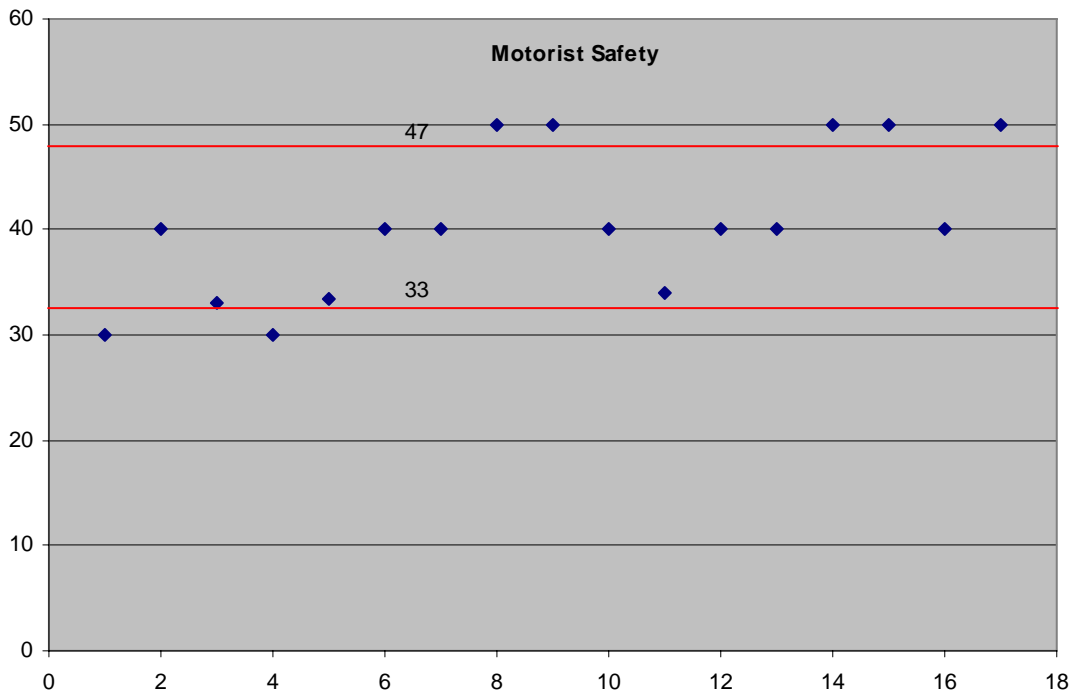


Figure 42: Scatter plot for Motorist Safety.

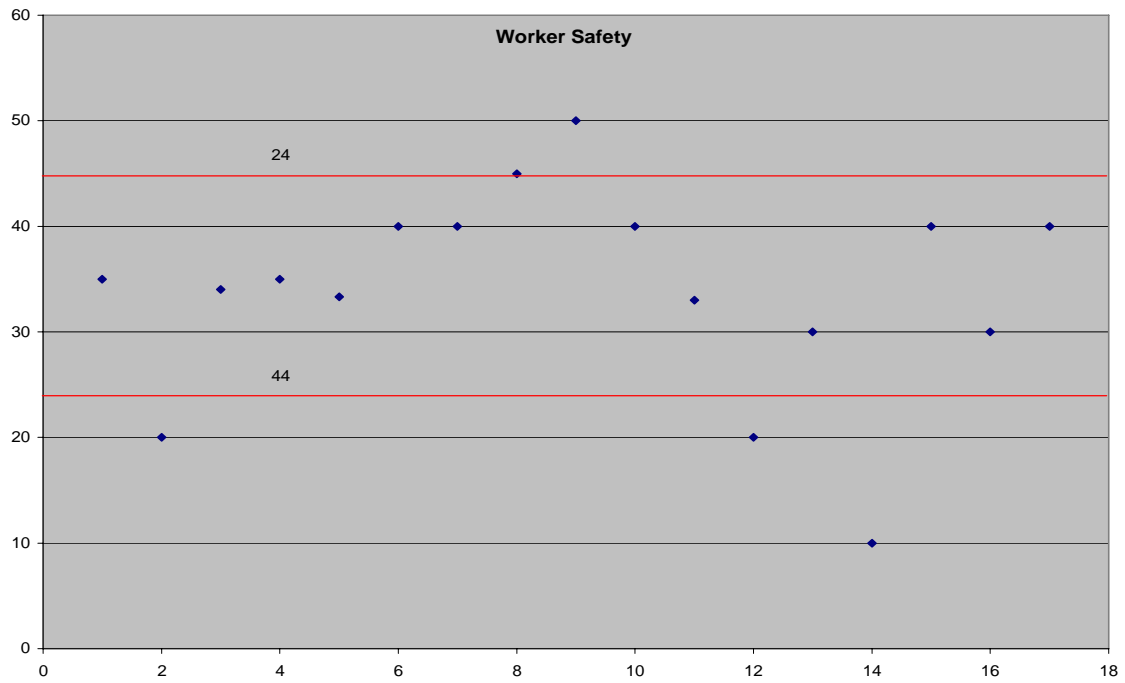


Figure 43: Scatter plot for Worker Safety factor.

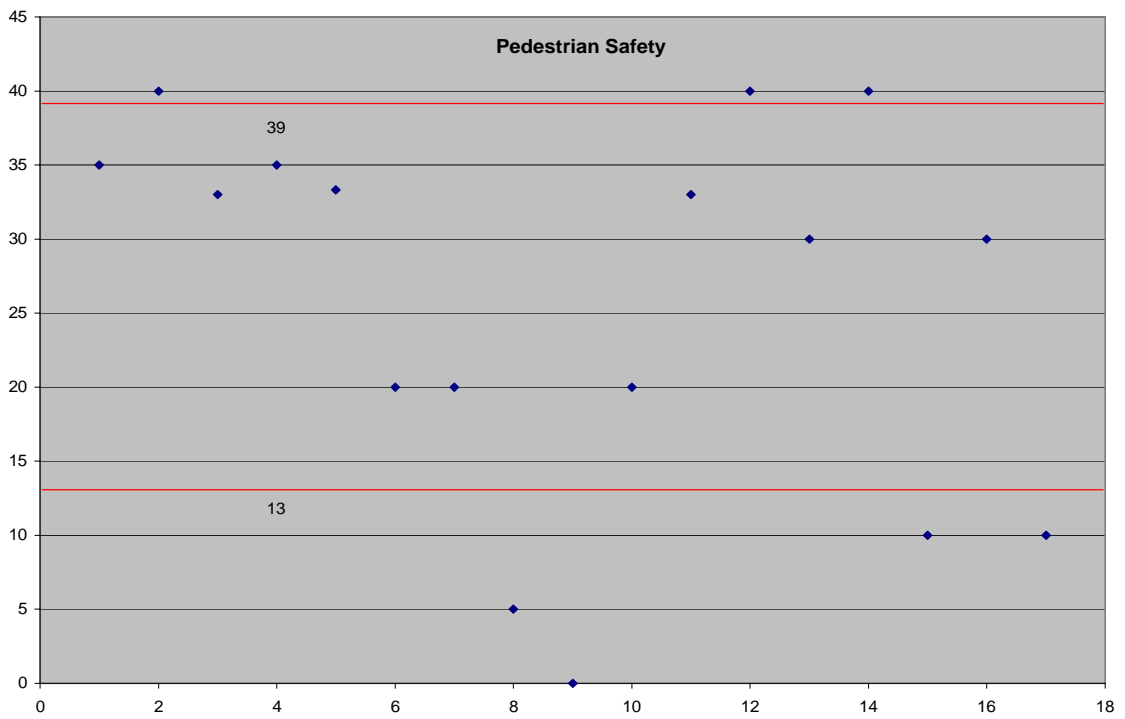


Figure 44: Scatter plot for Pedestrian Safety factor.

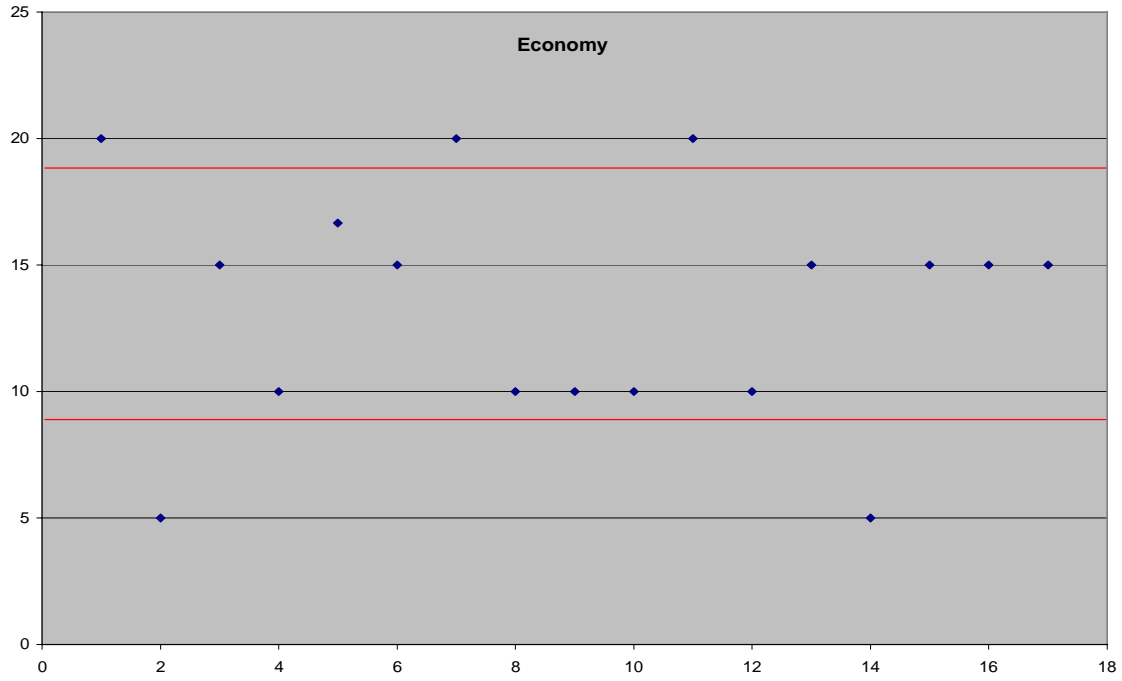


Figure: 45 Scatter plot for Economy factor.

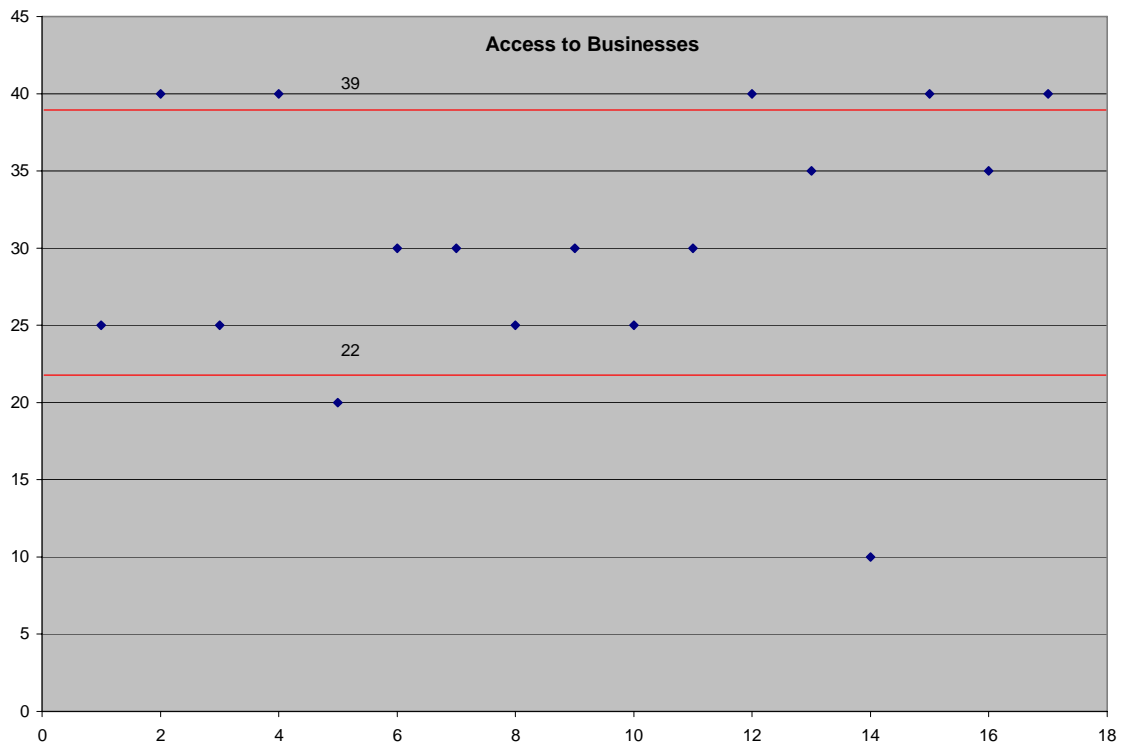


Figure 46: Scatter plot for Access to Businesses.

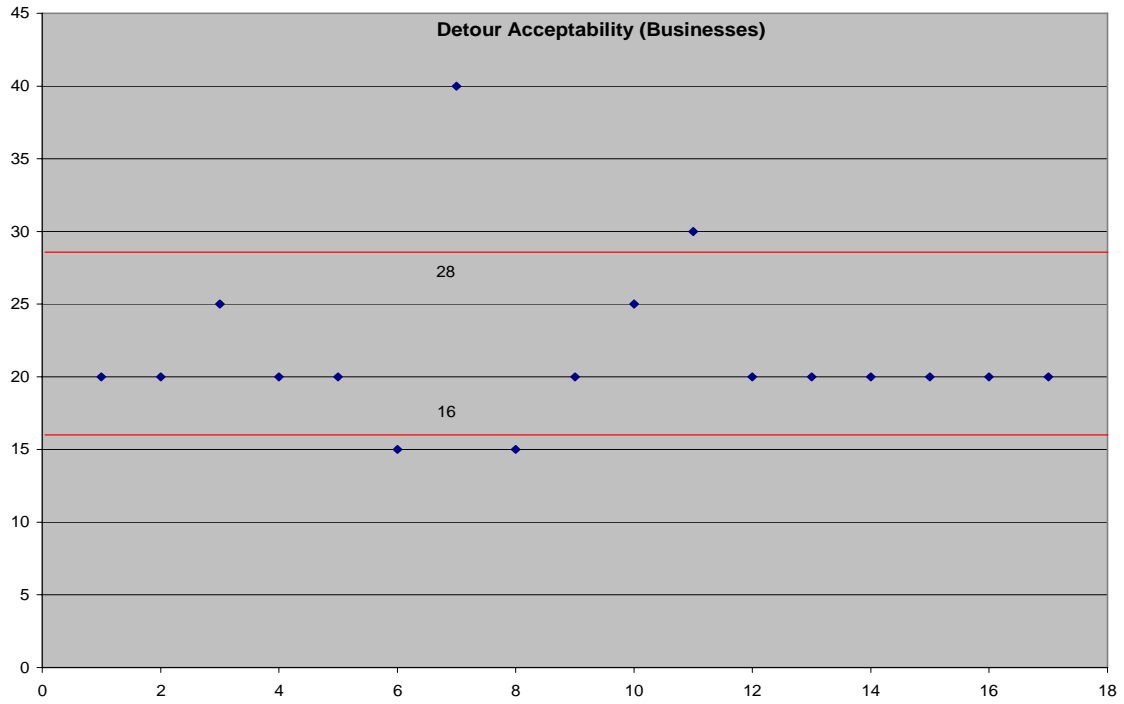


Figure 47: Scatter plot for Detour Acceptability (Businesses)

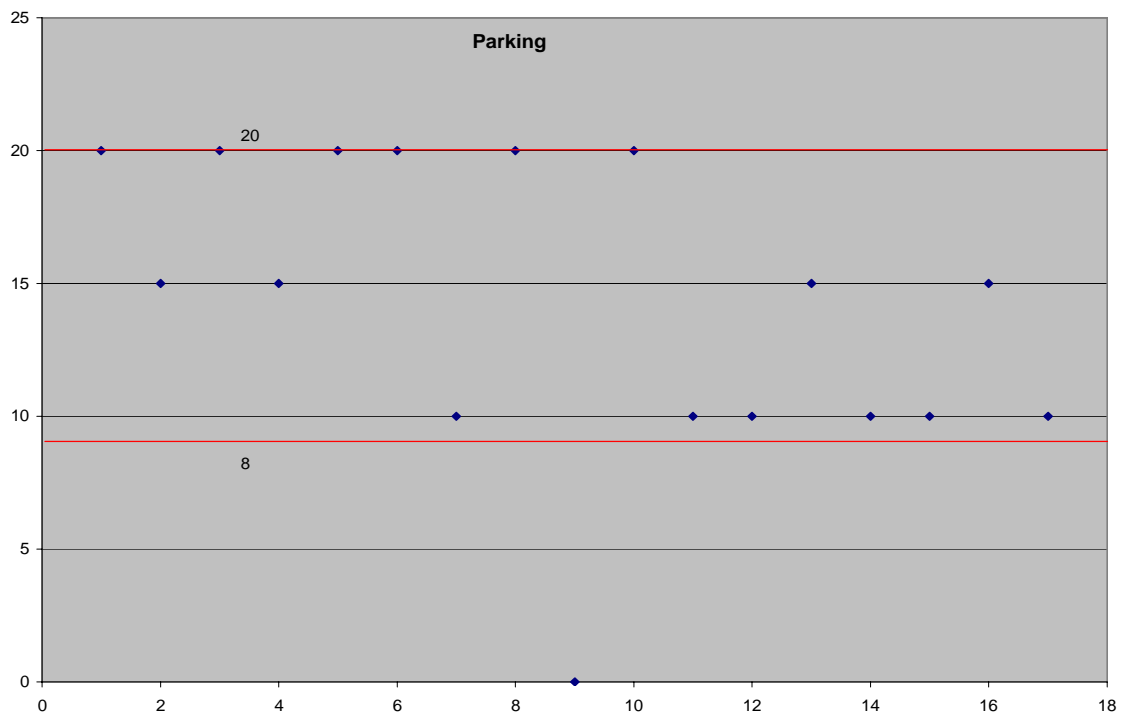


Figure 48 Scatter plot for Parking.

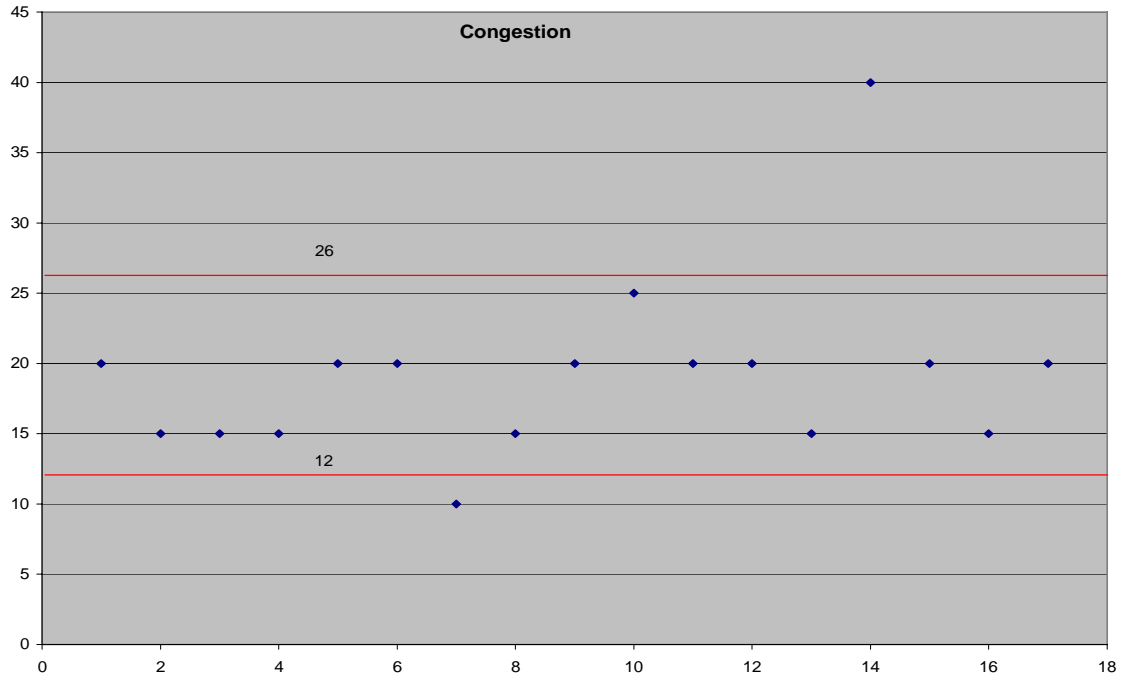


Figure 49: Scatter plot for Congestion factor.

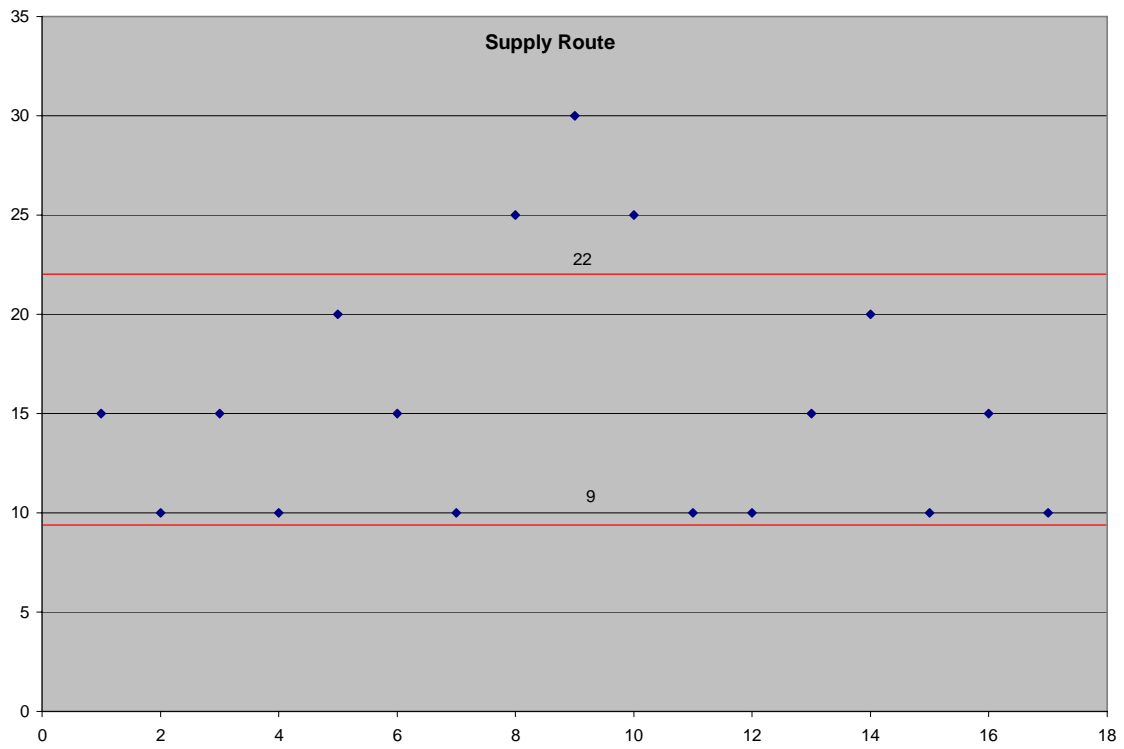


Figure 50: Scatter plot for Supply Route.

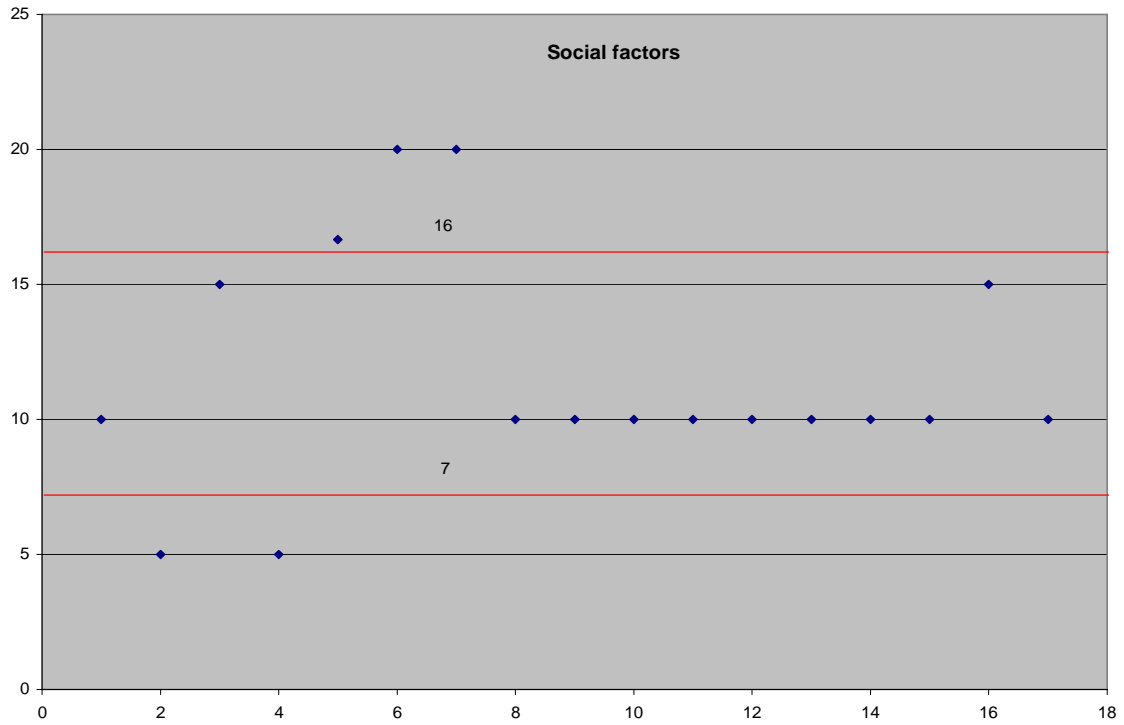


Figure 51: Scatter plot for Social factor.

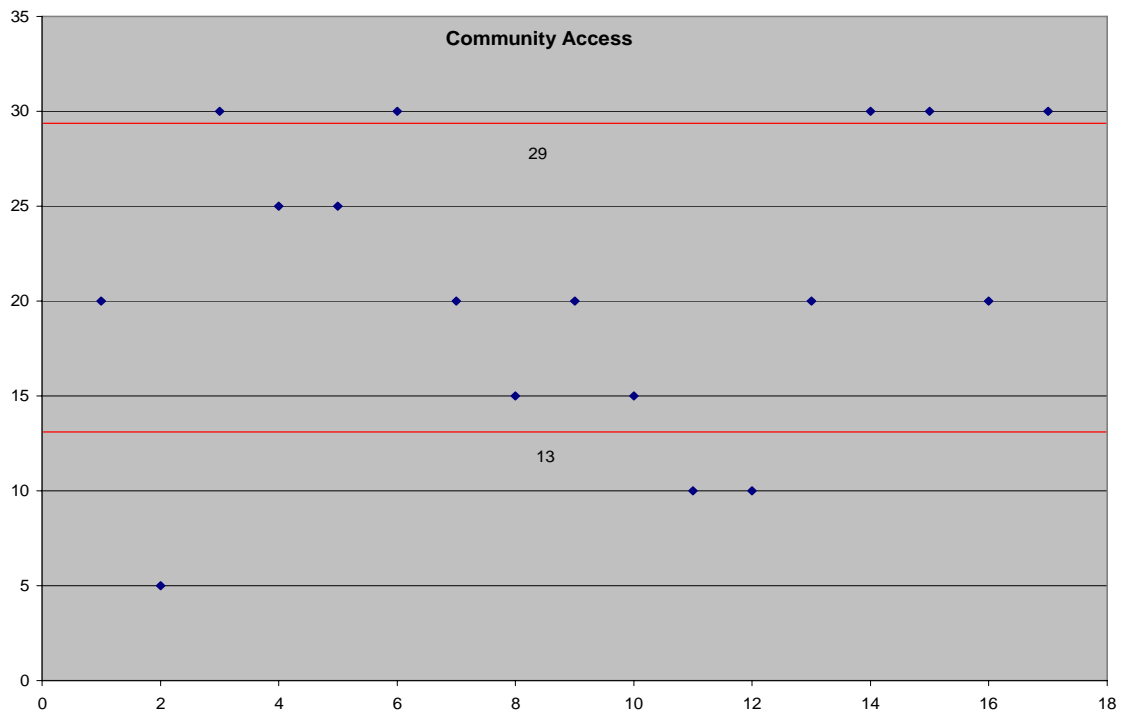


Figure 52: Scatter plot for Access to Community.

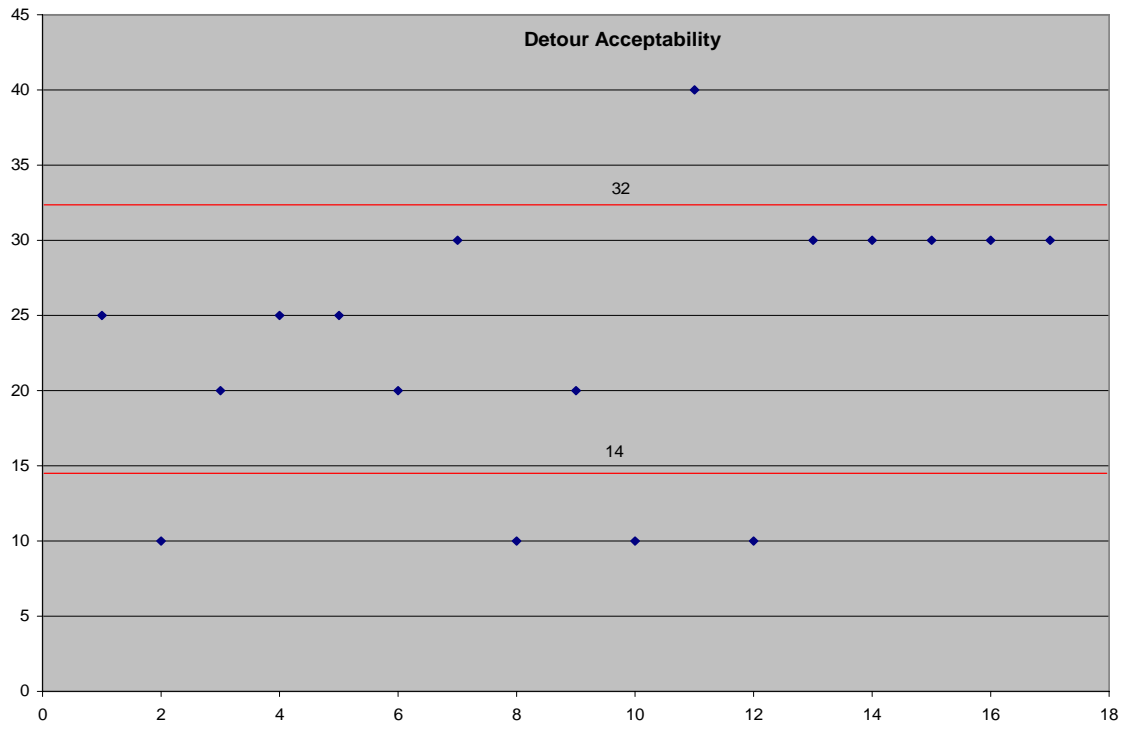


Figure 53: Scatter plot for Detour Acceptability.

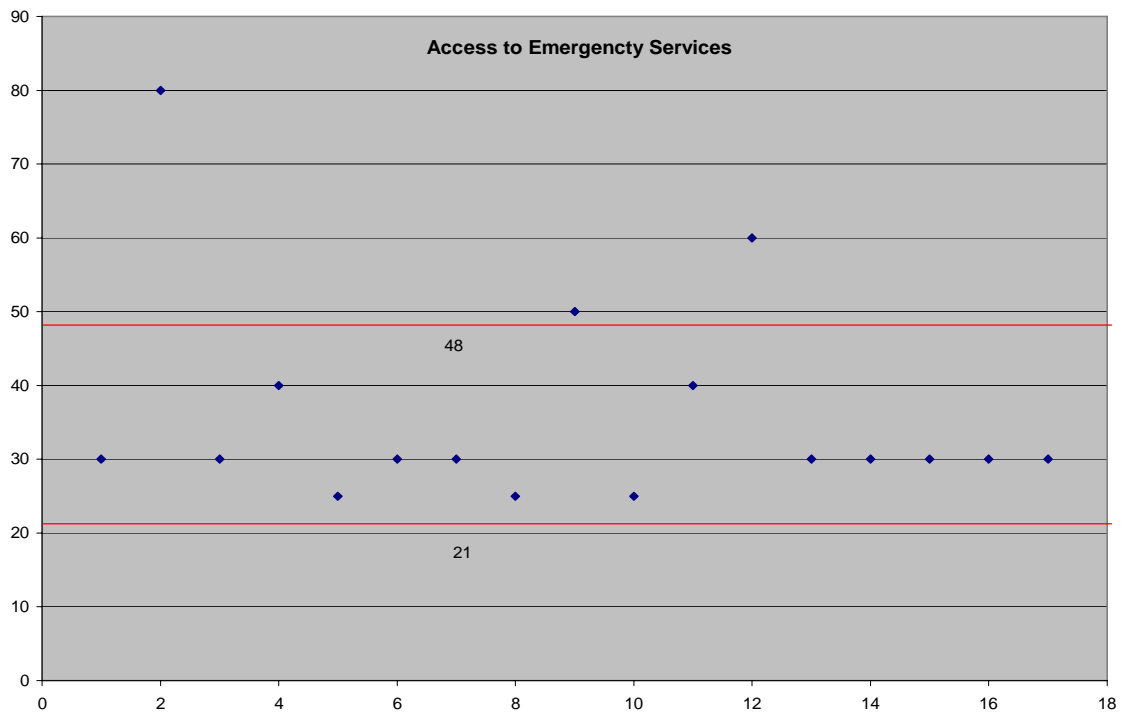


Figure 54: Scatter plot for Emergency Service Access.

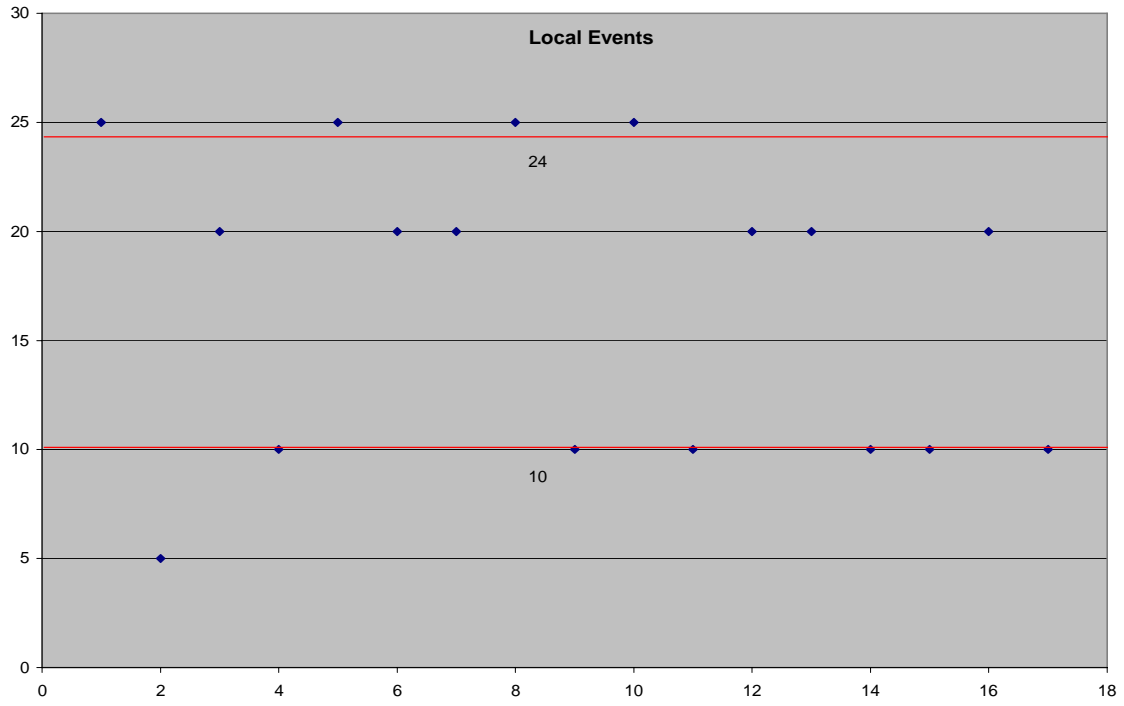


Figure 55: Scatter plot for Local Events.

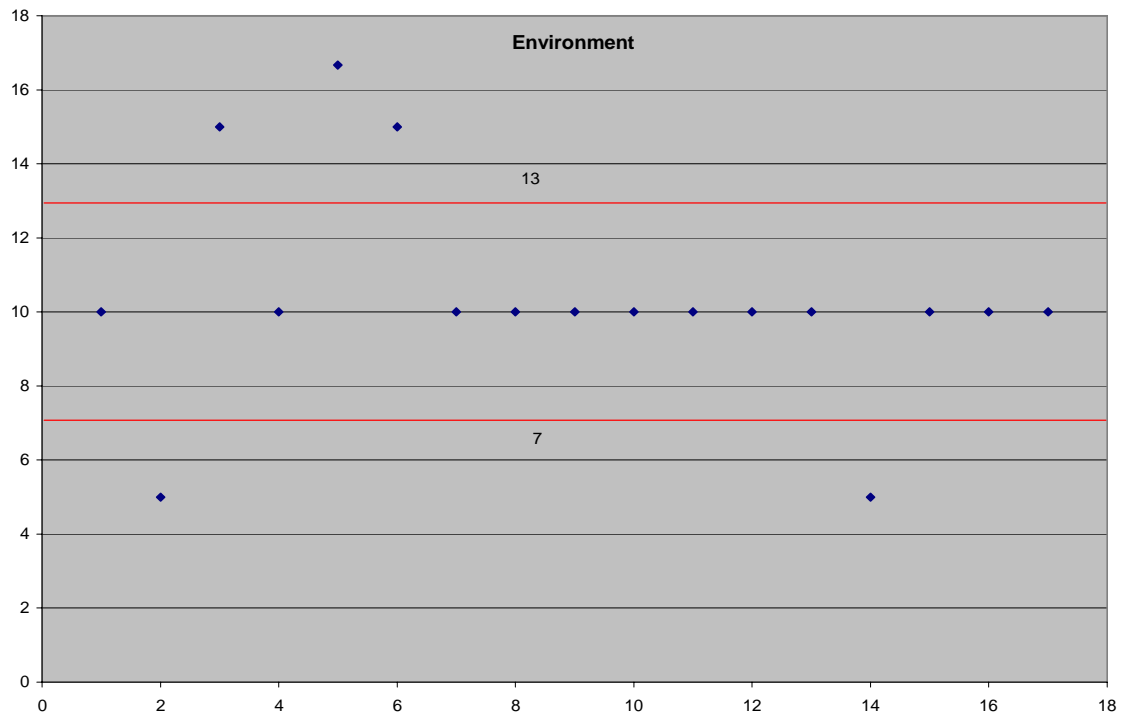


Figure 56: Scatter plot for the Environment.

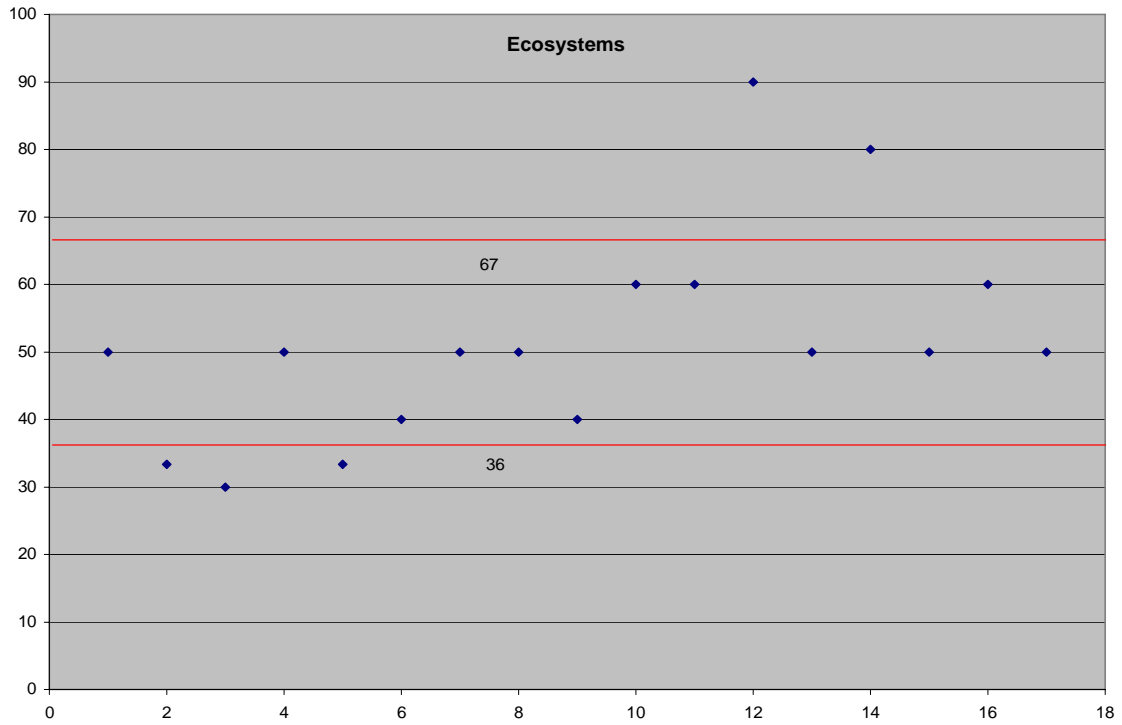


Figure 57: Scatter plot for Ecosystems.

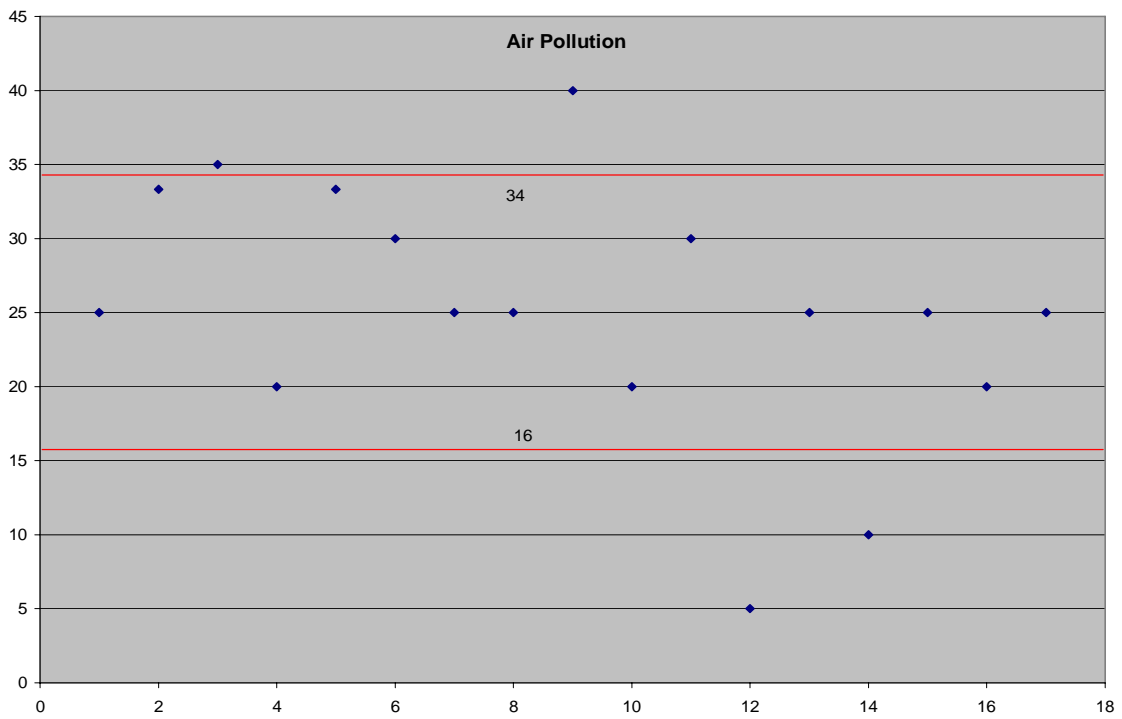


Figure: 58 Scatter plot for Air Pollution.

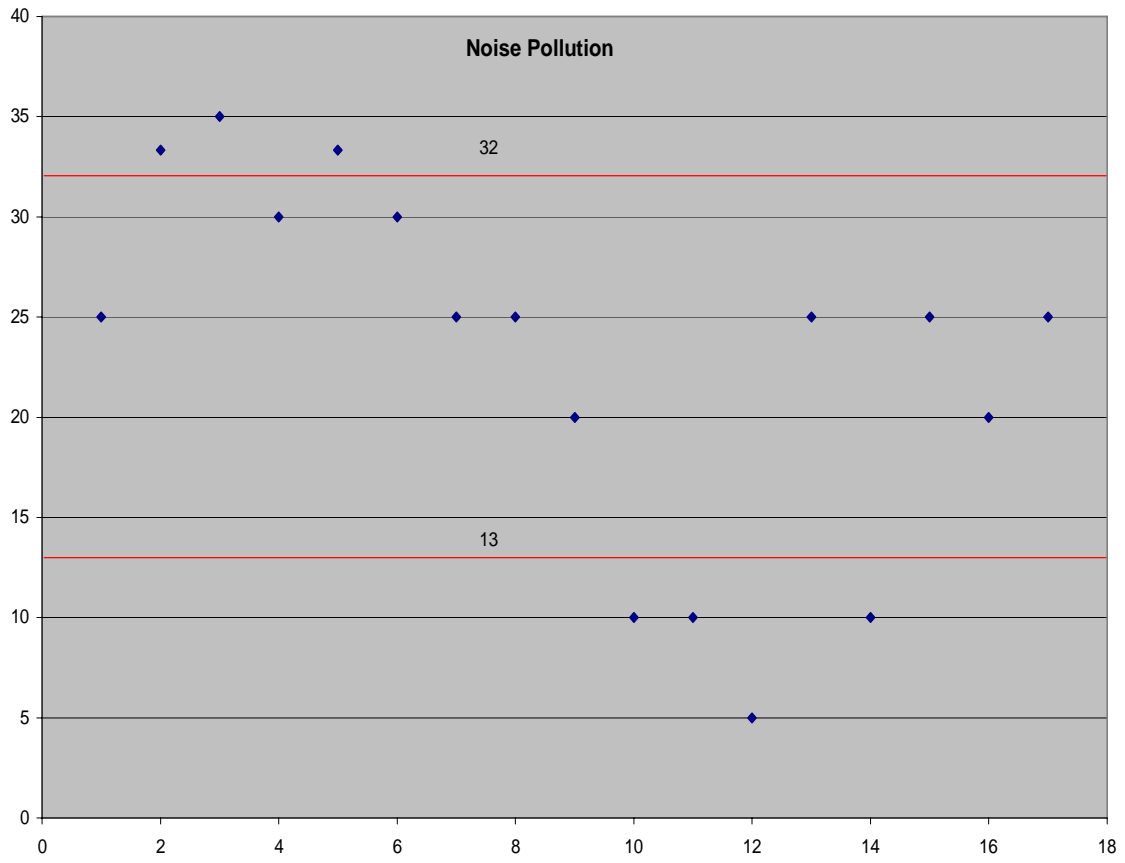


Figure: 59 Scatter plot for Noise Pollution.