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IDENTIFYING TRAFFIC CONTROL MECHANISM TO IMPROVE LEVEL OF SERVICE AND RESILIENCE IN ROAD NETWORKS BASED ON TOPOLOGICAL CREDENTIALS

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IDENTIFYING TRAFFIC CONTROL MECHANISM TO IMPROVE LEVEL OF SERVICE AND RESILIENCE IN ROAD NETWORKS BASED ON TOPOLOGICAL CREDENTIALS

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List of Abbreviations

AADT	Average Annual Daily Traffic
BC	Betweenness Centrality
DHV	Design Hourly Volume
DTA	Dynamic Traffic Assignment
LOS	Level of Service
MUTCD	Manual On Uniform Traffic Control Devices
NCHRP	National Cooperative Highway Research Program
OD	Origin Destination
RBC	Ring Barrier Controller
TUC	Traffic Responsive Urban Control

ABSTRACT

Traffic congestion mitigation strategies often include debating the merit of adding more roads versus optimizing the existing ones. Identifying and improving critical intersections, particularly by adjusting signal control mechanisms, may result in a cost-effective solution. During system disruptions, such as natural or man-made disasters, traffic patterns become unpredictable, leading to gridlocks at certain intersections. It is essential to proactively identify these intersections and apply time and cost-saving solutions. Research has explored various improvement strategies for signalized intersections, such as using actuated controllers or implementing urban traffic control strategies during peak demand. However, the literature does not provide enough guidance on how to prioritize one intersection over the others at the network level to improve level service as well as resilience. Moreover, none of the research conducted network analysis for improving transportation network reconfiguring traffic controllers using node-weighted and full- weighted (both edge and node weight) betweenness centrality (BC). This study presents a new traffic control mechanism technique for improved level of service and resilience in road networks based on topological credentials i.e., rank of relative importance (i.e., node centrality using both edge and node weights) of network elements such as intersections. The goal is to systematically improve the network performance by adopting specific intervention strategies (i.e., traffic controller setup) at certain intersections based on centrality and observing performance metrics such as total travel time, total delay, and Level of Service (LOS).

The study considered the Boise downtown network in Idaho to run these experiments in a simulated environment using Dynamic Traffic Assignment for two specific scenarios (i.e., normal and disrupted) under different network intervention schemes. Results indicate that interventions

made at certain intersections improved network performance. For example, changing fixed-time Ring Barrier Controllers (RBC) into actuated RBCs at 8 most important intersections reduces total travel time by 6.7%, total delay by 7.8% and 96 out of 175 turning and through movements at various intersections/nodes experienced better LOS when full-weighted BC ranking is considered. A higher reduction in total travel time (7.8%), total delay (8.8%) and increased number of turning and through movement improvement on intersection in terms of LOS (103 out of 175) is observed when 3 most important intersections are converted into roundabout and rest of the 5 most important intersections into actuated RBCs as per BC ranking. Under disrupted condition (i.e., removing the most important road segment/edge based on the ranking of edge BC measurement of edges of base network), the system performance (total travel time as an indicator) drops down to 96.49% when the original network is assumed to be working at 100% efficiency. After systematically applying node intervention strategies using the full- weighted BC ranking of nodes, the system performance recovers up to 105.95%. Future research should observe system performance by considering a combination of network properties as well as interventions made at other network elements such as roadway segments instead of intersections.

Keywords: *Fixed Ring Barrier Controller; Actuated Ring Barrier Controller; Topological Credentials; Network Science; Node-weighted Betweenness Centrality; Full-weighted Betweenness Centrality; Network Performance*

Chapter-1

1.1 Introduction

Efficient travel is a critical component of modern transportation systems. As the number of vehicles on the road continues to grow, urban planners, engineers, and lawmakers have made it a priority to develop effective ways to reduce travel time and congestion. When traffic load almost exceeds capacity, different strategies are implemented to improve traffic congestion. It was debated whether it is worth providing more roads for the increasing traffic, and arguments were placed regarding what would benefit the most (*1*). Stop signs, which require vehicles to come to a complete stop before proceeding, are one of the most prevalent junction control devices. Excessive delays at stopped approaches are possible in scenarios with large traffic flows. Two-way stop control is advantageous in this case because it allows more critical flows to continue without stopping, resulting in minimal delays for these flows. Four-way stop control, on the other hand, can be contentious. It has the potential to make drivers impatient due to stop signs and may result in longer average delays than other management methods. This impatience of drivers can cause accidents. When traffic volumes on all approaches are similar and total traffic volumes are relatively modest, multiway stop signs should be considered. However, if two-way stop control has no fixed safety issues and signalization is not yet warranted, the four-way stop sign option may be used (*2*).

In a study of three locations in New Hampshire, New York, and Washington state, when stop signs or traffic signals were replaced by roundabouts, 89% reduction in average vehicle delay and a 56% reduction of stop delays were discovered (*3*). This data demonstrates that roundabouts might be a much better option at optimizing traffic flow and minimizing congestion than other traffic control systems. A similar type of result was found from the tests undertaken in Kansas, Maryland, Nevada, New Hampshire, New York, and Washington. It showed depending on the geography, the vehicle delay savings range from 13% to 89% (*4*). With the advancement in technology, studies have investigated signalized roundabouts as well. A study in Jordan, determined the best placements for queue detectors on all approaches of roundabouts. It revealed that the ideal queue detector site was 97 meters from the roundabout's stop line utilizing micro-simulation with VISSIM and Python programming and this helped to improve the Level of Service (LOS) of the roundabout from LOS F to LOS D (*5*). So, there are different ways intersections can be improved. Therefore, it is required to effectively identify the junctions that will require improvement by making changes to the signal control system. This would be one of the most cost-effective solutions. There are studies that tried to compare traffic control strategies between two-way stop and all-way stop signs, unsignalized intersections. There is a study in China by Yus and Ji (2013) that investigated the average vehicular delay under varying traffic flows and compared between stop and yield signs. It was found that if there are no turning vehicles at the approaching roadways and the volume is less than 1800veh/h, the yield sign and two-way stop sign intersections will have shorter delays (almost same) than all-way stop sign intersection. But when the volume is more than 1800veh/h, the delay of the all-way stop sign intersection changes very less compared to yield and stop signs which increase dramatically. When turning vehicles are present in the entrances and the total volume is less than 1500veh/h, the delay of the two-way stop sign intersection becomes nearly equal to that of the yield stop sign intersection. The yield sign delay becomes the lowest. In this condition, the most significant delay was observed at the all-way stop sign intersection. When the total traffic exceeds 1500veh/h, the delay of the all-way stop sign intersection changes slightly and delays at the yield sign intersection and the two-way stop sign intersection increase dramatically. So, they concluded that stop and yield signs can be used in places where the volume is lower than 1500veh/h and all-way stop signs can be used in places where the traffic volume is within 1500 to 1800veh/h (*6*).

Moreover, there are studies that identified strategies to make improvements in signalized intersections, for example by effectively using actuated controllers (*7*) or traffic responsive urban control (TUC) strategy for networks during saturated traffic demand (*8*). In this study, (TUC) technique was developed to provide coordinated and responsive signal control under conditions of heavy traffic. The study showed that TUC includes high efficiency, robustness against measurement errors and disturbances, minimal measurement requirements, and low computational effort. It only considered the saturated condition of an urban area, which is a traditional approach.

A typical network consists of nodes and links (*9*). In a transportation network, intersections are considered as nodes, and roads are introduced as links or edges. The science that can explain different empirical phenomenon formed in real life complex networks is known as network science (*9*). Most of these studies mentioned above only consider the traffic volume in the approaching roads to determine traffic control mechanisms. None of these studies investigated traffic controllers based on the importance of the intersections or nodes using network science. Many concepts, properties, and measurements have been developed because of several experiments performed on real networks. In a study by (*10*), it was found that the nodes that have less connections with other nodes or low degree and less central (less important position in a network), they are less vulnerable to disruptions. On the other hand, in a real network, when high central nodes are disrupted, Derrible and Kennedy (2000) in their study found a significant reduction in the overall performance of the network (*11*). In the Boise, Idaho road network, Ahmed, Kayes and Sadri (2023) showed that based on the topological credential, when lane interventions are applied on critical or most central nodes, there is an improvement in the level of service from LOS F to LOS E (*12*). They also found that the delay was reduced by 15.7% from the base case of the road network when lane intervention was applied on critical road segments and the delay reduced by 8.6% when lane intervention was applied on least critical road segments. However, this study used static traffic assignment which cannot capture real life traffic condition as static assignment models used in transportation planning performs traffic flow in which vehicles are forced to travel predetermined paths (*13*). But in real world networks, as road networks expand, drivers frequently have more than one option for a route, therefore a realistic traffic allocation among these possibilities is not possible in static assignment. Traffic assignment, a crucial step in transport planning, allocates demand across different routes in the network. This entails first identifying and evaluating potential routes, then modeling drivers' discrete choice theory-based path selection decisions. Static assignment assumes fixed traffic demand and network characteristics, which is not reflective of reality as in reality, traffic demand and network conditions change over time. These time variations are considered via dynamic assignment, which is essential for precise modeling. Moreover, even though they used topological credentials to systematically improve the network, they used lane interventions which can be very expensive in real life and time sensitive as it involves road infrastructure improvement. Furthermore, due to heavy construction involved in road infrastructure changes, there is a chance of temporary traffic congestion from construction. Moreover, such heavy construction requires allocation of higher budget, so, it will not be an efficient solution. As explained, there are different network measurement techniques that can be used to find important nodes in the network particularly, centrality measurement. This study tries to use topological credentials, a ranking based approach, to improve the overall performance of the transportation network. Moreover, the systematic approach used in this study can also be applied to new cities where the traffic volumes are unknown, and the budget is limited. In such scenarios, based on topology of the new transportation network, the type of traffic control mechanisms applicable to critical intersections can be determined and it would be a cost-effective solution for the new project.

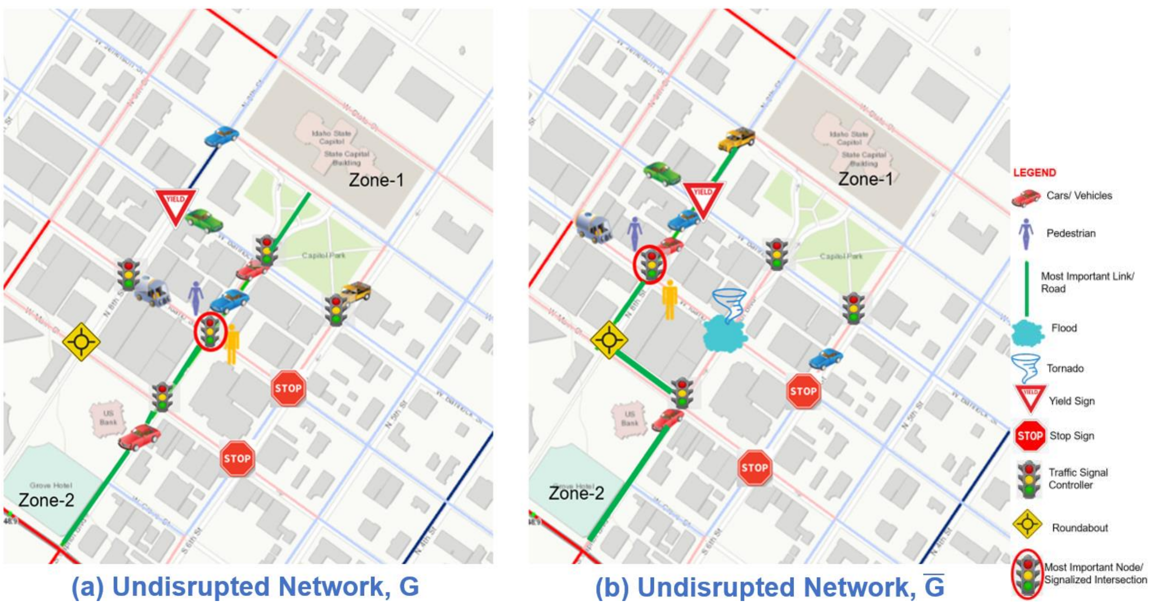


Figure 1: Conceptual Figure showing both Disrupted Condition (a) and Undisturbed Condition (b)

The optimization of traffic flow in both undisturbed and interrupted networks is the main emphasis of this work. The shortest path between zones in the undisturbed situation (Figure 1(a), network G) usually goes through a critical intersection (red circled traffic signal), which frequently results in congestion. At these crossroads, implementing better traffic control systems can increase network efficiency. An additional aspect to explore is to determine the outcomes following the abrupt inundation or tornado impact on a critical intersection. In that situation, drivers are likely to switch to alternative routes, so the most important intersection changes and shifts to the disrupted network as shown in Figure 1(b) and the graph changes to $\bar{G}$. Network efficiency can be recovered by implementing sophisticated traffic control algorithms at these critical places. Literature suggests that there are different ways of determining the most important nodes in the network. So, it is crucial to determine which topological credential can best identify the most important node or intersection in the network. The goal of the study is to reduce travel time and improve network performance by identifying these important crossings using a variety of topological measurements.

Figure 2: Conceptual Figure Showing 4 Different Highly Central Nodes Based On 4 Different Topological Credential

Figure 3 shows four different highly central nodes with shortest path based on topological credentials formed with unweighted centrality measurement, edge weights (such as traffic volume) node weights (such as signal timing) and combined weights (considering both edge and node weights) centrality measurement. From the conceptual figure above (Figure 1(a), the shortest path and the most congested intersection is shown under undisrupted condition.

Figure 2 tries to show the type of topological credential that can best identify the most important intersection in the network. For example, the most important intersection of Figure 2(d) best represents the most important intersection located in the most congested situation shown in Figure 1(a) that should be prioritized in terms of improvement. So, if this intersection is improved using better traffic control mechanism, it is supposed to have more impact in the overall network improvement than any other intersections in the network. This is the basis of this study. Thus, this study investigates the topological credentials that can help traffic engineers to improve the network more systematically. However, both Figure-1 and 2 represent a hypothetical situation, the highest central node might not always be different for different topological credentials, but the ranking of other nodes might differ as the ranking goes down. Thus, it is necessary to not only focus on the highest central node but also improve more intersections sequentially to determine the difference. Moreover, this study as mentioned previously explores disrupted condition as well. So, this study will also determine the type of topological credentials that can help identify the most important road segment by removing which can be used to create worst case scenario for the network and determine the most important intersections to improve the disrupted network.

Thus, the goal, objectives, research questions and hypothesis based on the above concepts and ideas are given below in detail.

1.2 Goals, Objectives, Research Questions & Hypothesis

1.2.1 Goals:

The goal of this research is to sequentially improve the traffic network performance by implementing specific intervention techniques (such as signal controller configuration) at selected intersections based on different types of centralities and compare the performance indicators like system travel time, and Level of Service (LOS).

1.2.2 Objectives:

i. Determine which topological credentials have better ranking in identifying the most important node in the network based on reduced system travel time.

ii. Determine which nodes (intersections) are more important than the others in a road network.

iii. Compare traffic control mechanisms in terms of decreasing travel time and delay in the network.

iv. Evaluate the system performance and resilience of the road network.

1.2.3 Specific Research Questions

i. ***RQ1:*** *Is there any difference found in the topological credential based on different types of weights (edge, node, or full weights) in the network?*

ii. ***RQ2:*** *What type of nodes (highest central or least central) have higher impact in reducing the system travel time and delay?*

iii. ***RQ3:*** *Under Undisrupted Condition*

a) *Which topological credential (edge weighted/ node weighted or full weighted (considering both edge and node weights) works best in identifying important nodes for intervention in the uninterrupted network.*

b) *How to prioritize certain intersections so that the network travel time can be decreased faster under undisrupted conditions.*

c) *What type of intervention (traffic signals or roundabouts) needs to be applied to improve network efficiency?*

d) *Which signal controller setup (Fixed or Actuated) decreases network travel time and delays more?*

iv. ***RQ4:*** *Under Disrupted Condition*

a) Applying which topological credential (unweighted or edge weighted) the highest central link when removed forms the most disrupted network?

b) How to prioritize certain intersections so that the network recovery is faster under the disrupted condition.

c) What type of traffic control mechanism (traffic signals or roundabouts) can help recover the system to its undisrupted state under disrupted condition.

d) Which signal controller setup (Fixed or Actuated) can decrease network travel time and delays more?

1.2.4 Hypotheses

i. Implementing different weights while measuring topological credential gives varying topological credentials for an uninterrupted network.

ii. The highest central node helps reduce the network travel time and delay more than that of least central nodes in the network.

iii. Under Undisrupted Condition:

a) Full weighted (both edge and node weighted) topological credential gives better ranking to identify the most important nodes in the network.

b) Implementing topological credentials at specific intersections will result in faster reduction of travel time under undisrupted conditions.

c) A combination of traffic controllers like traffic signals or roundabouts will improve network efficiency.

d) Utilizing an actuated type of signal controllers will reduce the network travel time and delays.

iv. Under Disrupted Condition:

a) Highest central link based on edge weighted centrality measurement ranking or topological credential when removed will produce the most disrupted network in comparison to the removal of highest central link based on unweighted topological credentials.

b) Implementing topological credentials at specific intersections will result in faster recovery to its undisrupted state.

c) A combination of traffic controllers like traffic signals and roundabouts will recover to its undisrupted state.

d) Utilizing an actuated type of signal controllers will reduce the network travel time and delay.

Chapter-2

2.1 Literature Review

The 2009 Manual on Uniform Traffic Control Devices (MUTCD) specifies how to deploy several types of traffic control measures at unsignalized crossings (*14*). Despite substantial advances in traffic engineering, the content of Part 2B relating to the selection of these interventions has remained constant since 1971. Notably, the criteria for selecting the proper traffic control, as defined in Sections 2B.04, 2B.06, 2B.07, and 2B.09 of the 2009 MUTCD, have not been researched since that time. In response to this current need, the National Cooperative Highway Research Program (NCHRP) initiated a research program. The primary purpose of this project was to develop modernized criteria and accompanying resources to aid in the selection of the best traffic control strategies at unsignalized junctions. These tactics ranged from no control measures to the implementation of yielding control, two-way stop control, and all-way stop control. The findings of this study were intended to be smoothly integrated into a revised edition of the 2009 Manual on Uniform Traffic Control Devices (MUTCD), with an emphasis on Sections 2B.04–2B.09. The primary goal of this initiative was to bring the handbook up to date with modern traffic engineering practices, ultimately contributing to increased safety and smooth traffic flow at unsignalized intersection (*14*). In this way there have been several research that worked on improving the MUTCD guidelines to make it representative of the current demand of traffic. Thus, it is important to understand the different types of traffic controllers and their warrants for installation in the intersections.

2.1.1 Yield Sign in Intersections

The yield sign directs traffic on specific approaches to crossroads. Vehicles regulated by a yield sign must slow down or stop as needed to prevent interfering with opposing traffic. The Federal Highway Administration's study on "Stop, Yield, and No Control at Intersections," found that switching from stop signs to yield signs reduced overall road user costs (including time and operating expenses) by around 8% (*15*). The reduction in wait time was the key source of these savings. Vehicle running costs, which included fuel usage, had a minor impact on the overall cost of vehicle operation when compared to factors such as tires, oil, and other maintenance. Furthermore, there was an increase in pollution at intersections with stop signs compared to those with yield signs.

In addition, the use of YIELD or STOP signs should be considered at the intersection of two minor streets or local roads where the intersection has more than three approaches and where one or more of the 3 conditions exist that includes approaches to have an average of 2000 vehicles per day, conflicting traffic sufficient to yield and 3 or more crashes in 2 years. records (*16*). From MUTCD guidelines, it can be understood that to provide yield signs, it depends a lot on the intersection design with the approaching volume. It also focuses on a particular intersection. It doesn't give a full idea of how the other intersections might be affected by it.

2.1.2 Stop Signs in Intersections

The most frequent traffic control devices at intersections in metropolitan areas of North America are stop signs and traffic lights. There are different warrants issued by the federal, state, and provincial governments for the installation of control devices. "As per MUTCD guidelines, the stop signs may be warranted when it fulfills 4 conditions like intersection of unimportance, restricted view, greater speed, entering a street or highway, etc. (*16*) A low-traffic intersection's installation of a traffic signal can drastically increase crashes and delays. The increase in delays and stops leads to increased fuel use, longer travel times and higher pollution. A variety of things directly affect how long the delay will be. For instance, traffic volumes and the requirement to properly accommodate pedestrians crossing the intersection approaches have an impact on cycle length. The time restrictions for pedestrian crossings could dramatically lengthen the required cycle times. Although studies have shown that traffic signals can decrease the overall frequency of incidents at an intersection, some crashes (such as rear-end collisions) may increase when a signal is placed (*17*). So, in this situation it is better to use stop signs. There are different types of stop signs. These are discussed below:

2.1.2.1 Two-way Stop Controller

Two-way stop control refers to placing stop signs on both sides of one street's approaches while allowing the other street to continue without any traffic at a conventional crossroads with four legs. The intersection of an arterial and non-arterial street is where this condition is most frequently observed. The arterial roadway has the right of way when stop signs are in place to regulate traffic on streets that cross an arterial. The warrants for two-way stop signs are the same as the general stop sign warrants.

2.1.2.2 Multiway Stop Controller

The multi-way stop is a temporary solution that may be implemented rapidly to control traffic while preparations are being made for the installation of traffic signals where they are justified and urgently required. When vehicles at an intersection alternate with the right-of-way, all-way stops are successful. They work best when there are frequent car collisions at the intersection, which often occurs when there is a lot of traffic, and when the traffic is evenly distributed among the intersecting streets (*18*). As per MUTCD, all-way or multiway stop controls are installed for interim measure before signal installation, 5 or more crashes and when 3 conditions for minimum traffic volume are met.

Communities "positively controlled" by stop signs have "safer" residents. Positively controlled implies that arbitrary stop signs are in control of traffic on the roadways. On a "calmed" roadway, homeowners on the residential collector feel safer (*19*). In a study by Wegner (*20*), four-way stops were found to be justified at generally balanced volumes in the range immediately below that for signal warrants in a study of 38 crossings that were converted from two-way to "four-way STOP control." Another study discovered that switching from two to four way stop signs at low volume intersections resulted in an average yearly road user cost increase of $2,402.92 (1988 cost) per intersection (*21*). Stop signs were previously thought to be good for speed control. But MUTCD and much research found that it is not true. The only academic study that provided evidence in favor of "unwarranted" multi-way stop signs was the Chicago study (*22*). It was discovered that they work well to lessen accidents at crossroads with poor sight distances and on-street parking. Persaud's 1986 study on Philadelphia included the conversion of one-way streets to all-way stop control (*23*). The goal of the study was to determine how traffic volumes among other variables affected the number of crashes at urban all-way stops. The study concluded that, contrary to what the MUTCD mandates, the effectiveness of turning intersections into all-way stops in metropolitan settings is not restricted to a particular range of approaching traffic volumes. In other words, the study showed that regardless of whether the daily approaching traffic volumes are fewer than 6,000 or higher, this conversion technique is equally successful for lowering crashes, both overall crashes and right-angle crashes.

2.1.3 Signal Controllers in Intersections

There are lot of signal controllers that are used in solving signalized intersection problems. Pretimed or fixed time signal controllers have a fixed timing (cycle length, green time, and splits for each phase) for a specified period. A delay model and the formalization of green time for each phase were proposed by Webster (*24*), which laid the groundwork for actuated signal control. The same year, the electronic set up for actuated signal controls with detectors first became available. It enables green times to be modified in real time based on vehicles detected in approaching traffic movements. A phase is skipped if no vehicle is detected. As opposed to prefixed time that requires fixed operating time, actuated controllers require other parameters (maximum green time, extension time, and the distance between stop line and detector) to operate each phase. Guo and Ma in their study tried to improve the Vehicle Actuated Programming (VAP) signal controller of VISSIM software into improved VAP (*25*). They found that both the travel time and delay dropped to a significant level when the improved actuated signal controller was used. In a semi actuated traffic signal controller, at least one phase will be fixed, and the rest will remain actuated, and detectors are placed only on minor approaches. Semi-actuated signal and pedestrian push button's vehicular actuations when work at the same time, it can improve the coordinated movements in four leg signal intersections on major roads without deteriorating the network performance (*26*). But when pre-timed signal control is used, placing pedestrian signals at a pedestrian crossing with few pedestrians may reduce both the road's mobility and the effectiveness of signal management. Red-light running may occasionally result from it. As a result, the Manual of Uniform Traffic Control Devices (MUTCD) advises installing pedestrian push buttons when the number of pedestrians warrants them. So, traffic signals are developed based only on traffic congestion and most studies tried to solve the problems of each individual signal controller. The focus on improving network efficiency by identifying important intersections was not involved.

2.1.3.1 Comparison Studies Among Traffic Signal Controllers

Based on the history of traffic patterns, the signal timing in the cycle of a fixed or pretimed signal controller is fixed (*27*). In an actuated traffic controller, the green times are continuously adjusted with traffic demand and skips phases when there is no traffic by detecting through vehicle detectors placed in the roadways. This type of controller has been used since the early 1930s. In 1997, Akçelik, Chung and Besley while trying to find the calculations for actuated signal timing compared average delay of the intersection by changing the signal timing based on signal calculation parameters (*28*). They found that when fixed signal green timing is used and the intersections are actuated, it gave reduced average delay than when fixed time signal controller was setup with its fixed signal timing. But when maximum green time signal timing was reduced to 25s and 10s for two phase signal timing, the average delay was reduced even more. In 1986, Jovanis and Gregor studied how actuated arterial traffic signal systems coordinated (*29*). By modifying yield points and force offs at non-essential junctions, they formed a new actuated timing flexibility. A dataset representing noon traffic conditions on a six-signal urban arterial system in central Illinois was used to evaluate this approach. Remarkably, the outcomes of the simulation revealed that pretimed coordinated control performed better than actuated coordinated control overall. But another study in Kingsville, Texas, by Chang and Koothrappally (1994) proved the efficacy of coordinated actuated control (*30*). When they compared several control systems, they discovered that coordinated semi-actuated control outperformed coordinated pretimed or uncoordinated full-actuated control in terms of operational improvements. Their findings demonstrated that, in comparison to pretimed coordinated timing, semi-actuated control resulted in less delay and fewer stops. They also discovered that higher coordination cycle lengths resulted in fewer arterial stops but more system delays overall. Day et.al. (2008) found out that the traffic volume and v/c ratio of phase 2&6 was higher with actuated coordinated phases than with non-actuated coordinated phases. So the study recommended to use actuated coordinated signal to effectively respond to changing traffic conditions (*31*). A research conducted at Slovakia in 2022, Kalasova et.al., studied that approximately there is an 85% delay reduction when an isolated intersection converted from fixed to actuated controller (*32*). A common thing about all these studies is that they all compared the traffic control mechanisms but without any systematic approach. All these studies' aim was to change either the entire network or focus on improving the traffic controller itself. None of these studies investigated selective intersections for overall improvement in the network.

2.1.3.2 Traffic Signal Warrant

In practical field, the intersections are mostly installed based on whether the intersections meet the signal warrants. There are 9 traffic signal warrants based upon which traffic control device are installed or improved (*33*). These are usually approved by the local authority. But engineering judgement will always be required.

Warrants from 1 to 3 are all based on approaching traffic volume on a particular intersection (*33*). These warrants cannot justify whether the adjacent traffic volume will have any effect on the intersection that we are working on.

In warrant 6, coordinated signal system, the need for a traffic control signal shall be considered if an engineering study finds that one of the following criteria is met:

A. On a one-way street or a street that has traffic predominantly in one direction, the adjacent traffic control signals are so far apart that they do not provide the necessary degree of vehicular platooning.

B. On a two-way street, adjacent traffic control signals do not provide the necessary degree of platooning and the proposed and adjacent traffic control signals will collectively provide a progressive operation.

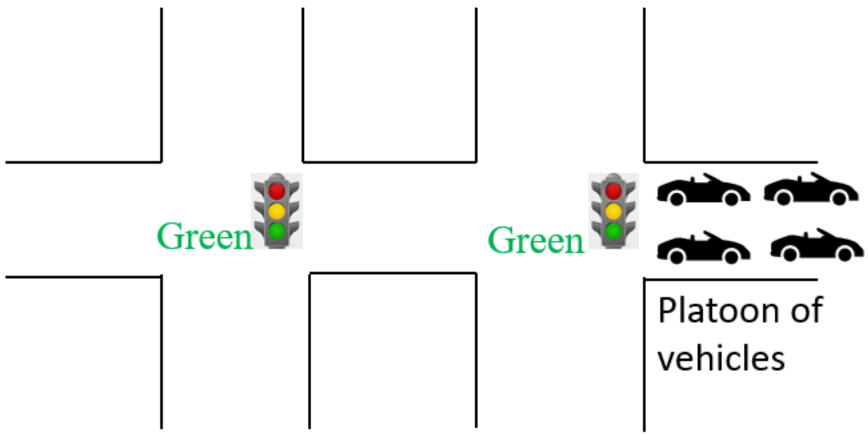


Figure 3*:* Coordinated Traffic Signal

Coordinated traffic signals cannot be placed where the resultant traffic signal spacing is less than 1000 feet. In both conditions, it refers to progression of vehicle platoons. In signal coordination, a group of vehicles need to cross adjacent intersection without interruption. To maintain this progression, it is important that these vehicles are moving together as well. This only happens when signals are close to each other. If we increase the spacing of signals, then the group of vehicles start to dissipate, so they are no longer moving together. It is because some start moving at lower speed and some at higher, so, they are no longer in the form of a group. Thus, if signals are not close to each other, they start to go far from each other. Only vehicles at the front will be able to cross without stopping. As a result, the coordination will be ineffective. If the next signal is close but not less than 1000 feet, then there is no chance of dissipation. To maintain this progression, we can provide a signal in the middle, and the group will remain together. For maintaining progression, signals are provided in the middle and this signal will remain in coordination with the previous signal. When the 1st signal is green, the platoon of vehicles will not stop only when the middle signal is also green. This warrant has been established looking into the problems of two or three intersections. It still does not say how many coordinated signals need to be provided or what will be the effect of this coordinated signal on two or more adjacent signals.

Warrant 8 focuses on installation of traffic signals when two or more significant roads converge. To examine this warrant, a thorough inspection of the entire road network, not just the intersections, is required. So, warrant 8 is also one of the warrants that investigates the overall network. But the emphasis is on identifying major routes across the transportation system. Despite studying the entire traffic system, traffic volume is primarily examined at crossroads where two or more major routes intersect. Thus, this warrant is also similar to the traditional approach. Nonetheless, the statement underlines a limitation: it may not give a comprehensive solution for determining whether to put traffic signals in a new city where assessing traffic volume is difficult.

While designing, the 1st three warrants are mostly investigated. These traffic signal warrants have been developed in 1935 (*16*). So, these MUTCD guidelines on traffic warrants are revised with the changing traffic volume and need. One of the inconsistencies is the conflict between adhering to warrant standards and considering community preferences and concerns. Local communities may aggressively urge for a traffic light at an intersection even if it does not satisfy the standard criteria in some situations. This raises concerns (*34*). Thus, even though the traffic warrants must be met while installing traffic signals, engineering judgement while designing plays an important role.

2.1.4 MUTCD 11th Edition Changes from 2009 MUTCD

The MUTCD 11th edition was published in December 2023 (*35*). Changes were finalized in 2020, but the full draft as a final version was published in 2023. It was effective from January 2024. So, it took almost 15 years to make changes making it the longest time it has taken for a new edition of MUTCD in history. There are almost 600 substantive changes made in this edition. Here the changes made in terms of traffic control mechanisms have been described. In MUTCD 2009 edition it was written, "The need for a traffic signal shall be considered if…" In MUTCD 11th edition, 2023, it says, "The need for a traffic signal should be considered if…" So, signal warrants are now guided not standards, but it doesn't mean there is no requirement to follow the MUTCD. But it gives an idea that engineering conscience now has more power over the manual. In the previous edition it was only mentioned that an engineering study shall be performed to determine if a signal is justified to install signals. In the new edition, in addition to this line, alternative signals should be considered has been included.

2.1.4.1 Pedestrian Volume Warrant

To meet warrant no 4, which is the pedestrian volume warrant, a line in a graph was supposed to be met to fulfil the warrant. But in the new edition, in addition to this line, there are two lines that needs to be met, the pedestrian volume threshold may be reduced by upto 50% if the 15th percentile pedestrian walking speed is less than 3.5 ft/sec (*35*). Overall to meet the pedestrian volume warrant, a huge number of pedestrian volumes is required. With the addition of the second line, this means now pedestrians' walking speed needs to be measured, which wasn't required previously.

2.1.4.2 Crash Experience Warrant

The other warrant that has big change is the crash prediction warrant. Previously in 2009 edition, if in an interchange, there is a susceptible crash number greater than or equal to 5 correctible crashes per year, then this warrant is met. In the 11th edition, they have included two long tables, one is crashes in 1 year and the other is crashes in 3 years, which includes consideration of the road type, number of lanes and total of angle, severity of crashes, etc.

All the above changes have been made based on a lot of research that has found what level of crashes is justified for a crash warrant or what volume or pedestrian speed required for a pedestrian warrant to be met for installing the signal. Apart from these traffic signal warrants, bicycle signals, bicycle pavement markings, signs etc. have significant changes.

2.1.5 Roundabouts on Intersections

Roundabouts, sometimes referred to as traffic circles or rotaries, are crucial tools for traffic management and offer several advantages over conventional intersections with stop signs or traffic lights. One of their main advantages is it is safer than the conventional intersections. By preventing high-speed, right-angle collisions (frequent at conventional intersections with traffic signals or stop signs), roundabouts greatly minimize the severity of accidents. Elvik in 2003 showed in study that number of injury accidents significantly lowers from 30% to 50% when intersections are converted to roundabouts. Additionally, he found that there is an even greater decrease in fatal accidents, ranging from 50% to 70% (*36*). Retting et al., (2004) studied that 36% of drivers supported roundabouts during construction and they also found that the average intersection delay reduces by 83-93 percent. In fact, the traffic congestion was also reduced by 58-84 percent (*37*). In another study in Minnesota, a part of Trunk Highway-22 corridor was analyzed in VISSIM to study how the corridor would operate under different setups like signalized intersections, roundabouts, or metered roundabouts (*38*). It was found that in 2030, when 9 roundabouts are incorporated on the intersections of the corridor, it showed a 50% decrease in delay than the present condition and 2 to 5 percent reduction in travel time was determined.

2.1.6 Importance of Network Science

Network science concepts are increasingly being used in a growing amount of research to better understand how transportation networks operate. To understand this, researchers are examining the connections that exist between various components of network science (*11*). Ahmed, Kayes and Sadri (2023) in their study found that traffic flow has a good relation to the topological properties of networks (*12*). To capture the important nodes or links in a network, betweenness centrality plays an important role in transportation network analysis. The graph-based technique for identifying critical locations within a transportation network was introduced by Furno et al. (2018) (*13*). They used a framework to establish the connection between network's overall efficiency and betweenness centrality (BC). They were able to determine network vulnerability and resilience in the event of disruptions by ranking the nodes according to BC values. By examining the relationship between BC and overall effectiveness, this study sought to gain important knowledge about the weak spots and general resilience of the transportation system. Ganin et al. analyzed the effectiveness of the traffic network as a function of delay in 40 cities across the 13 United States using a weighted graph technique (*14*). To capture network resilience during a flooding event, Kermanshah and Derrible (2016) used a variety of factors, including network topology and trip demand (*15*). Eventually with identifying important nodes or links in a network, researchers started focusing on network resilience.

2.1.7 Importance of Node and Edge Weights in Topological Credentials

The majority of the research on full weighted networks has concentrated weights on edges, mainly ignoring the weights provided to nodes (*39*). Only a few studies have been conducted to investigate the significance of node weights in real-world networks. One of the such studies by Akanmu, Wang and Yamoah (2014) found that when Clique/Node-Weighted centrality metrics are analyzed, they demonstrate an 18% increase in accuracy over the weighted marking method for predicting Distribution Center locations in Supply Chain Management (*40*). Singh, Singh and Iyengar (2014) in their study have extended the unweighted and edge-weighted centrality metrics in two ways while taking the weights on the nodes into account (*41*):

- Node-weighted centrality measures: all edge weights are taken as one, and only the node weights are considered for the study.
- Fully weighted centrality measures: when both edge and node weights are considered.

In their study, they have demonstrated an example to show the importance of node weights in centrality measurement. Fig-4 is one of the examples that is assumed to be a communication network in which the size of nodes represents their weights (in this case, importance/vitality). They assumed that communication takes place over the shortest paths, and that the relevance of a communication is proportional to the importance of the nodes between which it occurs. It is supposed that the function computes the multiplication of the importance of communicating nodes. The goal in the study was to determine which node manages the network's most vital communications. Applying betweenness centrality, a tool specifically designed for this type of situation, yields node C while ignoring the important attribute, size of population of the node. If size was considered along with the shortest path, node J would have been the solution as it helps to manage communication between the most significant nodes in the network. So, the current centrality measurement that focuses only on the path or includes only the edge weight is highly prone to produce incorrect results. As a result, they proved that the meaning of edge-weighted and unweighted centrality measures needs to be updated and node weighted centrality measure needs to be included.

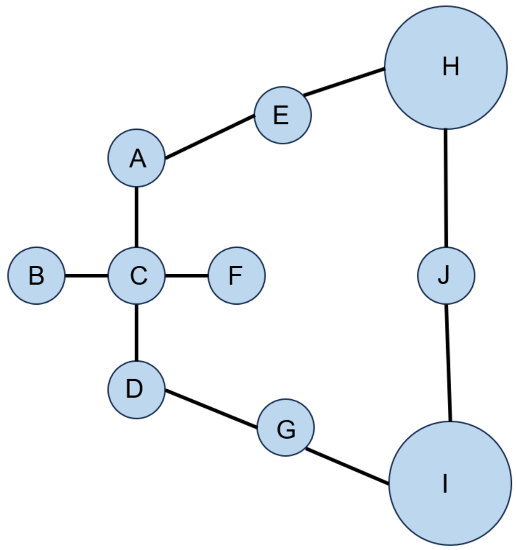


Figure 4: Network considering size of nodes as node weightage (*41*).

2.1.8 Resilience in Transportation Networks:

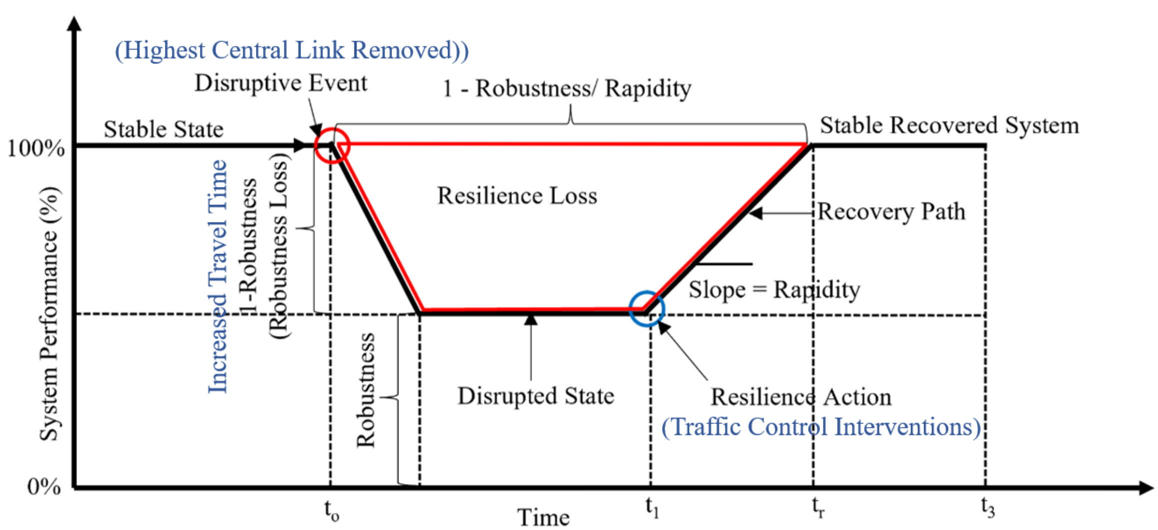


Figure 5: System Functionality and the Concept of Resilience Measure (*42-45*).

A transportation network's resilience is defined as its capacity to adjust and operate efficiently at the time of extreme conditions, or disruptions, as well as to accommodate growing traffic demands and guarantee mobility and travel time recovery (*20*). The "resiliency triangle" in Figure 5 shows how the network absorbs shocks in this manner (*17*). The transportation system becomes unusable when a disruption occurs. The remaining serviceability that the system provides is referred to as "robustness." Rapidity, which is determined by the system's capacity and the demand it must meet, is the rate at which the system recovers along the recovery path. The process through which speed reaches a steady-state condition is known as "redundancy," and it involves options like other route possibilities or mode selection. This concept is very important to capture the improvement of the overall performance in a network. Although network science has been applied on identifying the important nodes or links and performing evaluation of network resilience in a transportation network, not much research focused on improving the network applying traffic controllers based on the importance of the network sequentially. So, the contribution of this study is applying these concepts of identifying important nodes in a network using betweenness centrality values by ranking, improve the nodes or intersections of the transportation network by changing the signal controllers and then find the improvement in the overall performance of the network. In Figure 5, it shows that under any disrupted state, when a resilience action is applied to the system, the system starts to recover at its original state. A similar concept has been applied in this study under disrupted conditions. This study applies node intervention like different traffic controllers on important intersections to recover the disrupted system approximately to its original state. This systematic approach has not been previously applied to the intersections of a transportation network. So, this study brings new approaches to signal interventions.

Chapter-3

3.1 Data Collection and Methods

3.1.1 Data Collection

The study area of this research is a real network, Boise Downtown, Idaho. This network is used for analysis and traffic simulation. A hypothetical labeling of the intersections is shown in Figure 8. Each of these intersections are nodes and road segments are links. There are 33 intersections and 70 links in this network. Since it's built around a downtown area, most of the roads are one-way. To make the traffic condition more realistic, dynamic traffic assignment is performed (*46*). The network is divided into 18 zones (as shown in Figure 6). This is used as the traffic count data for developing the Origin Destination (OD) matrix for a peak hour from 5:00 pm to 6:00 pm. As per Federal Highway Administration (FHWA) guideline, DHV is one of the most appropriate data for designing purpose of a transportation network. So, to make the ranking more realistic, while determining the weighted betweenness centrality values of the nodes, DHV data is used as the edge weights (*47*). On the other hand, since the intervention is conducted on the intersections, it is important to identify which nodes need more improvement. Thus, it is necessary to consider the node weights as well. In this study, two different types of node weights are considered. One type considers the total green time in each intersection during one complete cycle as node weights, and the other is considering only the maximum green time of No-2 phase in each intersection during one complete cycle as node weights. Maximum green time of phase-2 is considered as a node weight because maximum intersections have 4 phases and phase-2 is the signal phasing for the major road, and its maximum green timing varies at different intersections in the original network or base condition. So, this can be an important factor that can guide the study to identify the intersections that need an increase or decrease in the maximum green time. Last but the most important weight to consider is both edge and node weights. This type of hybrid centrality measurement helps in optimizing the shortest distance considering both the DHV and the maximum green signal timing weights. The centrality values found from this measurement are mostly likely to be the most optimized values basically becomes the most standard values and so the highest central nodes tend to be the most optimized node that has higher chances of making significant change in the overall performance in the network if intervened appropriately.

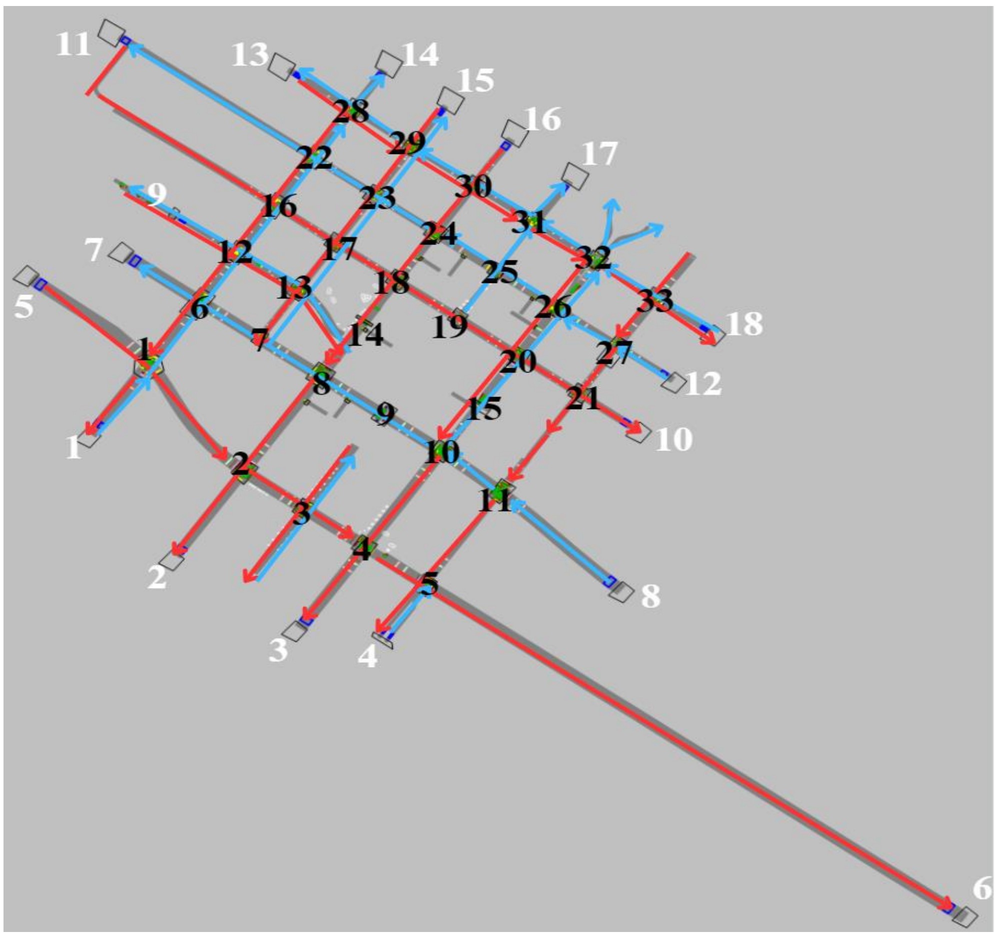


Figure 6: Network showing intersections and directions of traffic flow with 18 zones under base condition.

Figure 7 shows the lane configuration figure under base condition of the network with traffic controllers. It can be observed that intersection or node-7, 14 and 15 are the only intersections that has no signal traffic controllers. Node-7 is all-way stop controlled and node-14 & 15 are under priority controlled (or yield signed in real life). So, on every table due to repeatation and space issue, all intersection are at fixed RBC signal controllers except node-7,14 & 15, this has not been mentioned in the rest of the writing. So, when all intersections are mentioned as fixed RBC it is meant all intersections are fixed RBC except node-7,14 & 15. Also, from the figure it can also be observed that there are some 4 or 5 lane roadways. So, due to high number of lanes, as per MUTCD guidelines, it should be signalized intersections. Moreover, it also means that there is a higher no. of vehicles that travels through those roadway for which the number of lanes are higher, so signalized intersection with 4 or 5 lanes roadway cannot be improved by converting into unsignalized intersection or only providing stop signs. Thus, this study did not try intervening or improving the network with stop controlled intersections. This study mostly converted fixed time RBC to actuated RBC and at the end hybridizing the intersections with both actuated and roundabout intersections. More details are desbribed in the rest of the writing.

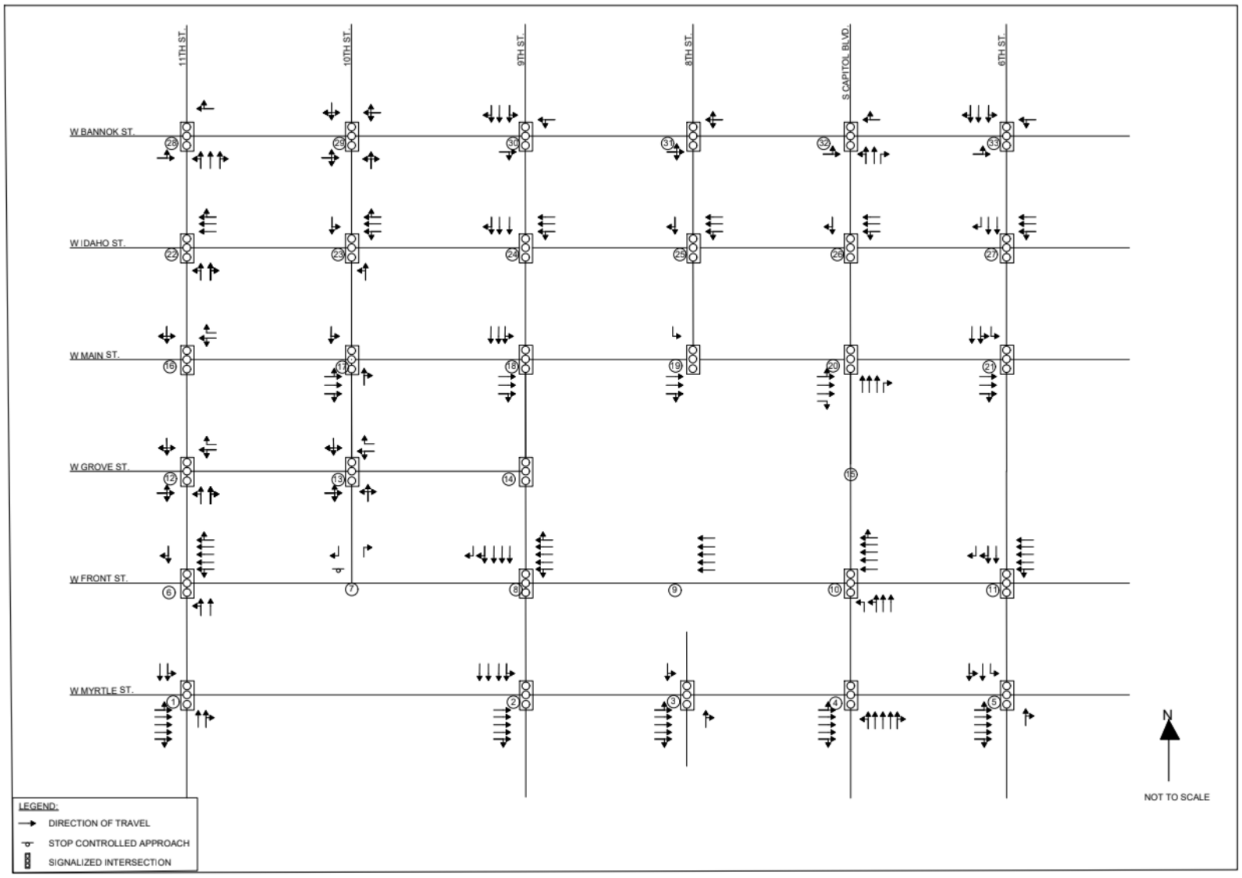


Figure 7: Existing Lane Configuration

3.1.2 Methods

The methodology is divided into two parts. The following chart shows the steps followed in accomplishing the work:

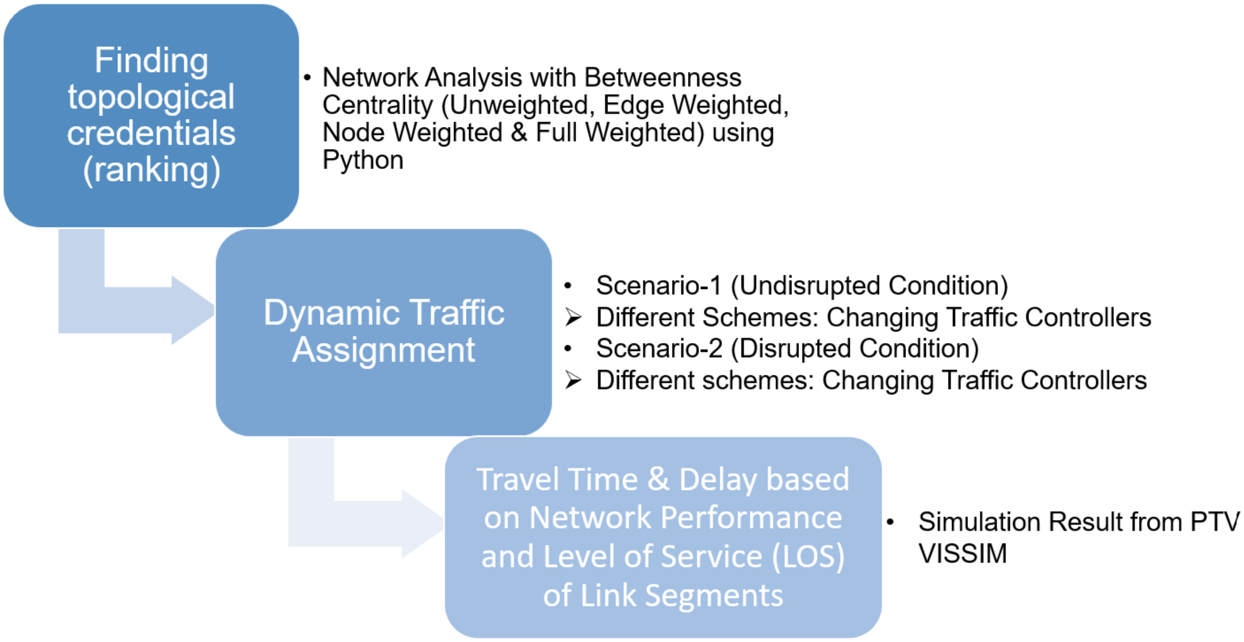


Figure 8: Steps in Completion

3.1.3 Network Analysis

Network analysis is performed under two conditions. First undisrupted condition and then under disrupted condition of the network which are discussed in detail below:

3.1.3.1 Undisrupted Condition

Undisrupted condition is the existing condition of the network without any removal of road segments. For network analysis of undisrupted network, first the topological credential or ranking based on the important position of nodes, i.e., betweenness centrality values of the nodes are found out using Python programming with Networkx library.

Generally, an unweighted betweenness centrality measurement is conducted to determine the position of nodes in the directed network. The degree to which a node is located on the shortest paths between any two nodes is measured by betweenness centrality (*48*). It is denoted by $C_B(i)$ and is formulated as:

$$C_B(i) = \frac{g_{jk}(i)}{gjk} \tag{1}$$

where, the number of shortest paths that pass-through any two nodes in the network is g_{jk}, and $g_{jk}(i)$ number of all the shortest paths that pass through the node, i (*49*). Then based on the ranking of the nodes in the network, the signalization is changed under base condition to check whether it improves the network or not.

3.1.3.1.1 Edge Weighted Betweenness Centrality

Similarly, an edge weighted betweenness centrality is measured where links or road segments will have weights. The link weight used in this study is DHV as mentioned previously, and these weights are multiplied to each of the portion of the node that appears in the shortest paths.

Table 1: Network Edge Weighted Edgelist

Source	Target	Weight	Source	Target	Weight
1	2	2850	19	25	100
1	6	235	20	21	600
2	3	2700	20	15	734
3	4	2700	20	26	734
4	5	2550	21	11	630
6	1	235	22	16	235
6	12	235	22	28	235
7	6	3300	23	22	400
7	13	114	23	17	114
8	7	3300	23	29	114
8	2	1600	24	23	400
9	8	3300	24	18	1050
10	9	3300	25	24	750
10	15	734	25	31	100
10	4	1600	26	25	750
11	10	2600	26	20	734
11	5	420	26	32	734
12	6	235	27	26	620
12	13	55	27	21	620
12	16	235	28	22	235
13	12	55	28	29	198
13	14	55	29	28	198
13	7	114	29	23	114
13	17	114	29	30	222
14	8	1050	30	29	222
14	13	55	30	24	840
15	10	734	30	31	222
15	20	734	31	30	222
16	12	235	31	32	282
16	17	600	32	31	282
16	22	235	32	33	132
17	18	600	32	26	734
17	13	114	33	32	132
17	23	114	33	27	620
18	14	1050			
18	19	600			
19	20	600			

3.1.3.1.2 Node Weighted & Full Weighted Betweenness Centrality

This section offers centrality measures that consider node weights while keeping edges equal in importance in a network. These measurements are referred to as node-weighted centrality measurements.

Let G represent an undirected, unweighted graph. Weights on nodes can be described as a function of W: V → R, where R is the set of real numbers. This allows each node to have a weight (Wx). Although the definitions do not explicitly employ Wx, a function of Wx (or Wx and Wy, depending on the parameters) is utilized without compromising generality, allowing the weight function to be adjusted as needed. For convenience, (*41*) uses f(Wx) = Wx. To normalize these new centrality metrics, the numerator in the following formulas is divided by the highest central value that any node can get. So, in betweenness centrality, f(Wx,Wy) is supposed to transfer the weights assigned to nodes x and y to a real number indicating the importance of flow between x and y. The betweenness centrality with node weights of a 'u' node is given below:

$$\frac{\sum_{s,t,u\in V:|\{s,t,v\}|=3} f\left(W_s,W_t\right).\frac{\sigma_{st}(u)}{\sigma_{st}}}{\sum_{x,y,u\in V:|\{x,y,v\}|=3} f\left(W_x,W_y\right)} \quad (2)$$

Here, $f(W_x,W_y)$ denotes the weights of nodes x and y that gives the importance of flow occurring between x and y. This equation is used both for the node and full weighted betweenness centrality measurement. In node weighted betweenness centrality, the edge weights are 1. In full weighted betweenness centrality measurement, along with node weights, edge weights have values greater than 1. In this study, two types of node weights are considered, one is total maximum green time in a cycle and maximum green time of only phase 2 of each of the intersections. Since, node-7,14 and 15 are unsignalized intersections, they don't have any green signal timing, so, their weights are considered as 1 instead of 0, as 0 in betweenness centrality means infinite weight which is an incorrect weight for these nodes whereas 1 means unweighted or no weight (based on the above discussion on weights) which is the actual case for these nodes. Below is the table showing the node weights based on total maximum green time and maximum green time of only phase 2.

Table 2: Node Weight of the network in terms of total maximum green time and maximum green time of Phase-2

Nodes	Node Weight (Total Maximum Green Time)	Node Weight (Maximum Green Time of Phase-2)
1	100	35
2	50	25
3	100	35
4	50	30
5	50	30
6	220	82
7	1	1
8	110	65
9	130	110
10	110	62
11	110	61
12	100	30
13	100	25
14	1	1
15	1	1
16	50	31
17	100	25
18	50	20
19	50	25
20	50	19
21	50	18
22	50	35
23	50	25
24	50	33
25	50	35
26	50	25
27	50	25
28	100	25
29	100	25
30	100	25
31	69	55
32	100	31
33	50	25

3.1.3.2 Disrupted Condition

Disrupted condition is when any road segment is destroyed or removed from the network due to any unnatural cause like natural disasters. So, this study tries to improve or recover such destructed network (by removing the most important link in the network) to its original condition by identifying the most important intersections in the network. To create such a situation, it is important to identify which link/edge has the most impact in the network. Thus, betweenness centrality of edges can help determine the most important edge in the road network. Let betweenness centrality of edge, e is determined which means the summation of all shortest paths that pass through the edge, e (*50*). The equation is given below:

$$BC(e) = \sum_{x,y \in Z} \frac{\theta(x,|e)}{\theta(x,y)} \quad (3)$$

where,

Z = number of nodes,

θ (x, y) = quantity of smallest (x, y) routes, and

θ (x, y |e) = number of paths that passes through link e

So, at first, the highest central edge is found out from unweighted and edge weighted betweenness centrality measurement of the edges as shown in Appendix-A. Two disrupted networks edgelists are formed similar to Table-1 by removing the edges between node 18 and 19 as marked in red in Appendix-A as per unweighted edge betweenness centrality ranking and the 2nd disrupted network edgelist is formed by removing the edge between 29 and 30 (both directions). To improve the network through traffic control intervention, it is important to identify nodes based on node betweenness centrality measurement. So, two topological credentials of the two new disrupted networks (removing the highest edge in the network) are calculated. Thus, ranking of node betweenness centrality of two disrupted networks is used to check whether the efficiency can be improved even under disrupted condition. The betweenness centrality values of the new disrupted networks are found out and according to the new ranking, the intersection, or nodes are improved with better signalization. Then considering travel time as the network resilience indicator, the system performance of the network is determined.

3.1.4 Scenario Analysis

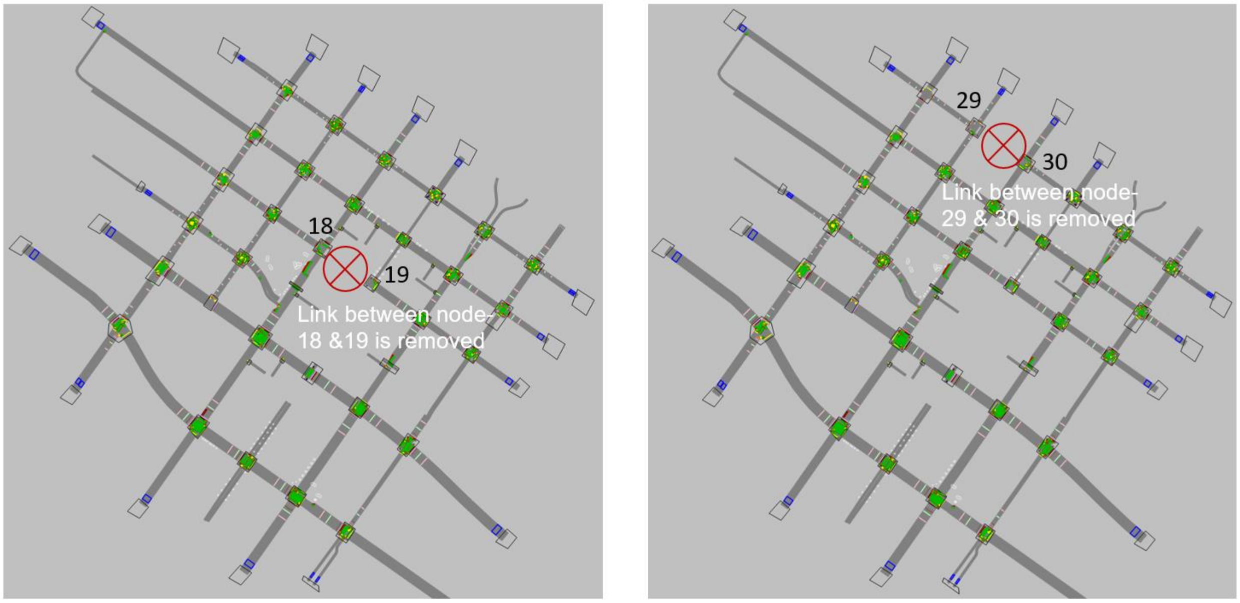
The traffic simulation is run under two different scenarios and within those scenarios, the network is improved based on topological credentials found from network analysis.

Scenario-1

Scenario-1 is the base condition when the network is operating without any disruption. This scenario is again divided into 7 different schemes converting fixed RBC controlled signals into actuated RBC signal controllers based on 4 different ranking or topological credentials of the nodes.

Scenario-2

Two disrupted networks as shown in Figure 9 (a & b) when the most central edge-18&19 (based on unweighted edge BC value) is removed and the other by removing the most central edge based on edge weighted BC values, edge between node-13 & 17 is removed. This scenario is analyzed with 5 different schemes using the type of topological credentials that gives the highest improvement in scenario 1.



(a) 1st Disrupted Network formed by removal of edge between node-18&19

(b) 2nd Disrupted Network formed by removal of edge between node-29&30

Figure 9: Scenario-2 (Disrupted Condition)

3.1.5 Traffic Simulation

In this study, traffic simulation is conducted using PTV VISSIM. For the simulation, a time of 4500s (1hr) is set and 900s as the initialized time. The simulation resolution used here is 10. A 10-simulation run for each scenario and scheme is considered. The higher the simulation runs, the better the average results get. A random seed of 70 as the initial value is used but the random increment used here is 0 since a Dynamic Traffic Assignment is performed in this study (*51*). To get the result quickly, maximum simulation speed is considered.

3.1.5.1 Dynamic Assignment Parameters

The cost or OD matrix for peak hours from 5:00 pm to 6:00pm is developed and the start time is from 5:00:00 to 6:00:00.

Defining Travel Cost

Each path in a network is associated with cost. It includes financial cost, travel time information, the distance of the path and surcharge that is defined by the user. The simulation is performed based on same time interval as the previous simulation run. For cost calculation, the sum of all the travel times along an edge is selected which means any sort of vehicle that travels over that edge will be included. Simulation is operated by looking at travel times for all the past iterations not just the last one. There are different moving methods to determine the influence of these iterations. Exponential smoothing with a smoothing factor of 0.2 is used in this study and it means that over each iteration, the weight of that iteration is going down by a quarter, and it explains the influence it has on the current iteration.

Path Search

For path search, 'search for new paths that will be added to the existing path set before vehicles make their path selection' is chosen in this study. Now if we have an OD pair that has a low volume set in the matrix less than 1, for some simulations, one vehicle may get placed on the network and other cases no vehicles may get placed on the network due to rounding. To avoid such problems and to keep those paths so that those vehicles have a place to go, 'keeping paths for OD pair for zero volume' is selected.

Then 'the decision of choosing paths at the beginning in their origin parking lot' is selected. For path choice or the probability of choosing a particular destination parking lot, logit model is used. It is formulated in the following (*51*):

$$\mathrm{p}(R_j) = \frac{e^{k+v_j}}{\sum e^{k+v_j}} \tag{4}$$

where, k of 1.50 is considered. k determines the sensitivity of the function. The larger the value of k, the more the vehicles prefer high utility parking lot. The default lower logit limit of 0.00100 is used.

Path Choice Assignment

The stochastic assignment or Kirchhoff is used for path choice assignment. It uses a utility function which is going to be the inverse of the cost, so using the cost function, the utility function is created and then it is applied in the path probability function for vehicles to be able to choose which path to take. In this study the default exponent value represented by k= 3.50 is used. It means higher values of k are going to put more weight on the best route that's going to have a higher utility. The following is the Kirchhoff's utility function and path probability formula (*51*):

$$U_j = \frac{1}{\mathrm{Cost_j}} \tag{5}$$

where, U_j is the utility function and $Cost_j$ is the cost function.

$$\mathrm{p}(R_j) \;= \frac{U_j^k}{\sum U^k} \tag{6}$$

where, $p(R_j)$ is the path probability and k, the Kirchoff's sensitivity exponent.

Convergence

Now it is required to let the simulation know when that conversion is reached. This allows the user to define different criteria to just stop the DTA process automatically. There are a few different conditions that can be set. The first one is the travel time on the path, travel time along the edges and lastly volume on the edges. Then the number of other percentage of paths or edges that are required for convergence to be met can be selected. In this study, travel time on path is selected and 95% of paths have a no change required share of converged paths and 15% don't have a change in travel time. But in this study, in different scenarios, even after the simulation is reached, for consistency in the result, the simulation is set to continue. For route guidance, the default route guidance strategy is used.

3.1.6 Traffic Parameters

Travel Time

The time required for a particular vehicle to travel from one point to another is basically the travel time of that vehicle (*52*). State road authorities in Australia regularly conducts travel-time surveys in the nation's capitals after Austroads identified it as a crucial system performance indicator (*53*). So, trave time is considered one of the most important parameters used by transportation engineers to determine system performance of the network. Usually, in the field, license plate technique is followed to determine the travel time. It is found out in the following ways:

- Roadside observers can record license plate numbers as vehicles pass designated points along the route.
- Time of passage and license plate numbers are noted and matched later to calculate the travel time.

Highway Capacity Manual (HCM) provides various travel time formulas under different traffic conditions and scenarios. The basic travel time formula is the following which has also been used in PTV VISSIM software:

$$\text{Travel Time} = \frac{\text{Distance}}{\text{Average Speed}} \tag{7}$$

In this study, total travel time from network performance of vehicles from simulation result tab in the VISSIM software is used to determine the system travel time of the network. This travel time is the total travel time of all the vehicles that exit the network, reach the destination parking lot or vehicles that are still within the network at the end of the simulation (*13*). The distances for the travel time of each of the vehicles of the network is the shortest path each of these vehicles cover. So, the time taken for each of these vehicles to travel the path in the network and the summation of these travel time of the vehicles gives the total travel time. This travel time is used in this research as this study is trying to determine overall performance of the network.

Delay

Delay is defined as the difference between the time needed to traverse the observation area and the time that would have been needed if the car had continued to move at the recorded speed when it first entered the area. An artery may experience delays owing to signal delays, mid-block impediments, or other forms of traffic congestion. Due to the difficulty of defining travel time for a point location, delay becomes more significant at signalized and STOP-controlled intersections. There are different types of delay models. In this research, the total delay is assigned for each scenario and scheme analysis in the transportation network. In PTV VISSIM, the total delay is determined by subtracting the amount of time it takes the vehicle to travel if it were moving at the desired speed (the posted speed limit or the fastest safe turning speed if there was no signal controller in the network whichever is less) from the travel time at actual speed the vehicle is moving in the network (*13*).

Level of Service

As per Highway Capacity Manual (HCM), the Level of Service or LOS of traffic on a road section is used to assess how well the road is perceived by the road users and the performance measures are also used to assess it. LOS criteria for arterials are based on v/c (volume by capacity) ratios as provided in the *HCM*. LOS is divided into six classes (from LOS A to LOS F). LOS A is the free flow condition (less than 60% of the roadway capacity is used) and LOS F represents extreme congestion (the roadway is being used beyond 100% capacity). The volume-to-capacity (v/c) ratio and control delay are now considered when determining the level of service (LOS) thresholds for lane groups at signalized junctions. LOS 'F' is identified by a v/c ratio greater than 1.0, irrespective of control delay (*54*). Nevertheless, control delay remains the only factor used to determine LOS thresholds for approach and overall intersection LOS.

In PTV VISSIM, the LOS (transport quality) thresholds are considered in slightly different way for the vehicle mode at a signalized intersection as shown in the accompanying table. The LOS in VISSIM is based on the result attribute, ‘Vehicle Delay (average)’. In this study, LOS is used to find out the congested condition of the road segments connected to the important nodes and through different scenario analysis to check whether changing the traffic control mechanism, the LOS level improves or not. The LOS in PTV VISSIM is found from node result after simulation. So, the LOS is given for each of the movements that takes place within each of the nodes. Among the average of the 10-simulation run, the total number of node movement’s that assigned LOS result is 175. In this study, among 175 node movement’s LOS, it assigns the number of node movement’s LOS improved for each alternative or scheme from the base condition. The table below shows the range at which the LOS are defined in PTV VISSIM software used in the analysis.

Table 3: Table showing LEVEL of Service (*13*).

	Signalized Intersection	Non-signalized Intersection
LOS_A	Delay < 10s or no volume, as no vehicle is moving, also due to traffic jam	
LOS_B	>10s to 20s	>10s to 15s
LOS_C	>20s to 35s	>15s to 25s
LOS_D	>35s to 55s	>25s to 35s
LOS_E	>55s to >80s	>35s to 50s
LOS_F	>80s	>50s

3.1.7 RBC Signal Controller Mechanism

In the built-in real-world network, Boise, the signalization in the intersections is all Ring Barrier Controllers (RBC). As per MUTCD, it is an improved signal phasing technique that tries to separate different traffic movements into different phases. Typically, it is divided into 8 phases by a barrier. Figure 10 shows that 2, 4, 6 and 8 are through and right turn movements whereas 1, 3, 5, and 7 are protected left turn movements. In this signalization, no phases in one barrier can work simultaneously with the phases in the other barrier. Even phases under the same barrier within the same ring cannot also work simultaneously like phases 1 and 2 cannot concurrently work but phase 1 can work with 5 or 6. In this study, Boise downtown mostly has 2, 4 ,6 and 8 traffic movements, so the phasing is developed accordingly.

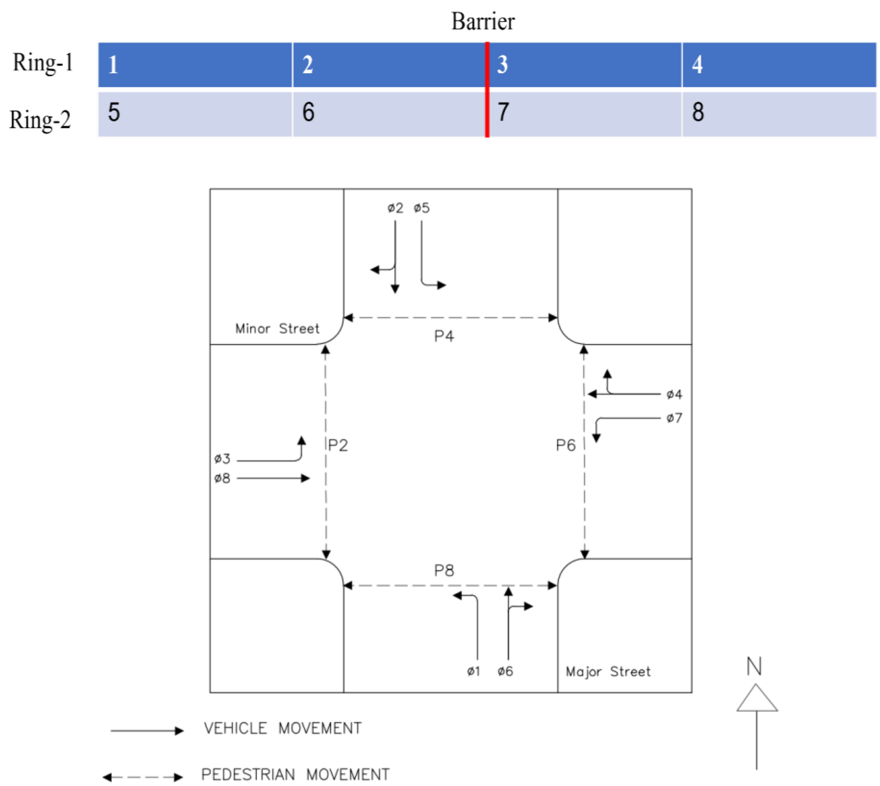


Figure 10: Ring barrier phasing and a typical four leg intersection showing vehicular and pedestrian movements (*55*).

In developing traffic phasing and timing plan, it is required to follow the MUTCD guideline. In one of the steps after finding out the number of phases required, the minimum cycle length needs to be determined. As per MUTCD, cycle length is the sum of the individual phase lengths or the splits. It is calculated by the following formula:

$$C = \frac{L.X_c}{X_c - \sum_{i=1}^{n}(\frac{v}{s})c_i} \tag{9}$$

where,

C_{min} = minimum necessary cycle length in seconds (typically rounded up to the nearest 5sec)

L= total lost time for cycle in seconds,

Xc= capacity utilization for the intersection,

$\left(\frac{v}{s}\right) c_i$ = Flow ratio for critical lane group i, and

n= Number of critical lane groups.

In this study, an approximate cycle length and green times is determined to change the signalization of the important nodes to improve the network. In that case, as per the number of phases as given in the previous condition, minimum cycle length is found out. A capacity utilization of 0.9 is used, the flow ratio for critical lane group is determined by using the average volume found in the approaching link after running simulation under base condition and the DHV for the entire road as given in the Idaho Department of Transportation is considered as the capacity for that link. In this way, the ratio for each of the phases is determined. This time, X_c is calculated as per MUTCD guideline using the formula given below:

$$X_c = \frac{C_{min} * \sum_{i=1}^{n} (\frac{v}{s}) c_i}{C - L} \tag{10}$$

After calculating X_c, the effective green time for each phase is determined. The time during which a traffic movement is effectively utilizing the intersection is known as effective green time. To allocate effective green time to different phases, the following formula is used:

$$g_i = \left(\frac{v}{s}\right)_{ci} \cdot \left(\frac{C}{X_c}\right) \tag{11}$$

where,

g_i=Effective green time for phase i,

$\left(\frac{v}{s}\right)_{ci}$ =Flow ratio for critical lane group i,

C=Cycle length in seconds,

X_c=Capacity utilization for the intersection.

Apart from these, there are other parameters used in actuated signal controller which are discussed below:

Vehicle Extension

Let a phase has minimum green time of 9s, maximum green time of about 14 secs and vehicle extension time of 3s. Generally, as a phase turns green, a countdown timer starts in the controller and it goes from 9 to 8, 8 to 7 and goes on until it reaches 0, the moment it reaches 0, it goes yellow, to red and to the next phase. But in the actuated controller when there is a vehicle extension of 3s, if it detects any vehicle after 3s, it reaches back to 3s, and creates gap of 3 sec and then it starts counting down again. Thus, for 3s if it keeps on detecting vehicles, it will keep on bumping back to 3s till the maximum green time. In this way bumps are created in vehicle detection. If the detector notices no activity for 3 seconds, it will terminate at that time before the maximum green time. But if the detector keeps sensing vehicles till the maximum green time, it becomes a straight line which is called constant call. After it reaches maximum green time, it goes to yellow and the right of way changes. The maximum split is the summation of maximum green, yellow and red time. So, when actuated uncoordinated signal is coded, it is what the maximum split means. When reading or coding the actuated uncoordinated, the timing sheet will have maximum green time, so, to find out the maximum split, yellow and red time are added to code actuated uncoordinated signal. In RBC configuration of VISSIM software, this vehicle extension is still assigned even if it is at fixed RBC signal timing, because in fixed signal timing, maximum recall must be selected which helps to keep the maximum green signal timing fixed. This keeps the fixed RBC from fluctuating between maximum and minimum green signal timing that usually occurs in actuated signal timing because of vehicle extension.

3.1.7.1 Fixed RBC

All the intersections in the base condition of Boise Downtown, Idaho are fixed RBC except node-7 is stop controlled and node-14 & 15 are priority controlled. As per PTV VISSIM Manual (*13*), to configure uncoordinated or free moving fixed time RBC, it is required to change pattern into free moving and making the cycle length 0 in the basic configuration page of RBC signal. Cycle length is mentioned when it is coordinated RBC timing. Minimum green time is mandatory to be above 0 or to provide a value. Maximum green time is the actual green time for fixed RBC when maximum recall is selected (*13*). Because in PTV VISSIM to make the RBC timing fixed, selecting maximum recall means, in a cycle, the maximum green signal time will always max out or will be always at maximum operating timing as a green signal timing. Then the start-up signal group or the signal group that will start at the beginning of the simulation is selected. It is to be noted, in this study, all the intersections are set at the same minimum green time at 4s, vehicle extension time at 3s, amber time at 4s, red clearance time at 1s, pedestrian walking time at 5s and pedestrian flash don't walk at 9s. Most of the cycle lengths of the intersections are either 60s or 120s. Very few are set at different timings. Below is shown one of the fixed time free moving RBC signal configurations of node-29 under base condition.

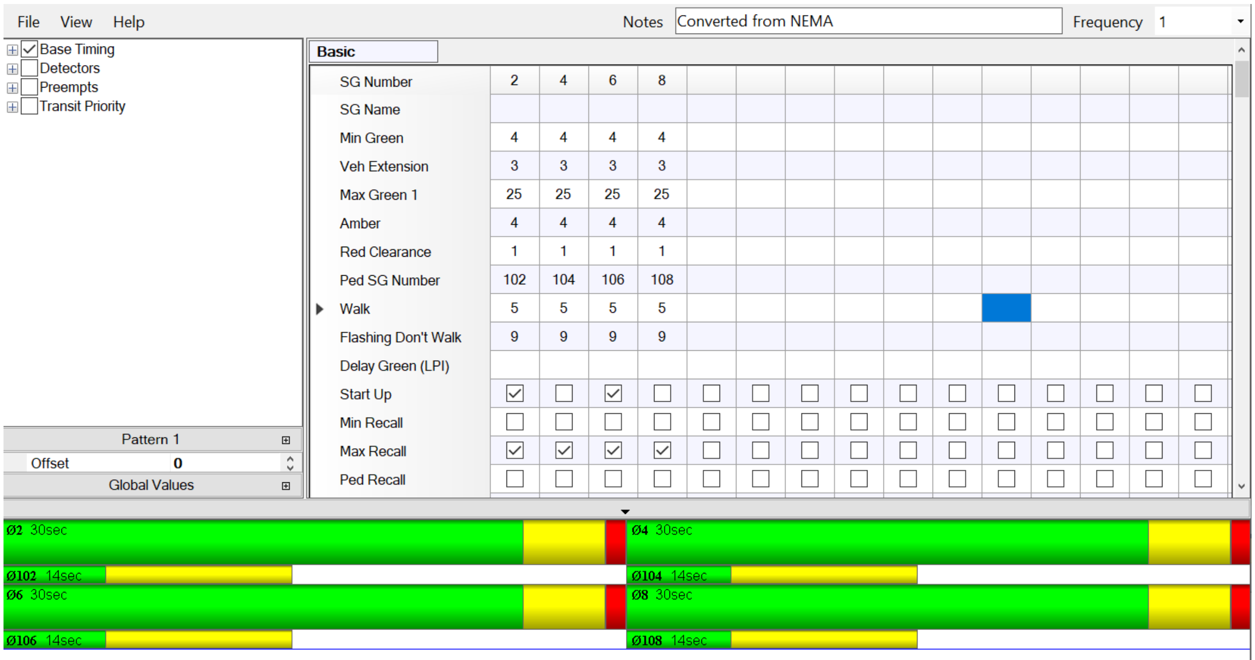


Figure 11: Fixed RBC Configuration

3.1.7.2 Actuated RBC

In actuated RBC uncoordinated signal, the cycle length is not mentioned in the basic configuration tab of RBC signal timing page (*13*). The maximum, minimum or pedestrian recall can be selected in actuated depends on the signal timing sheet. In this study, none of the signal timing in actuated RBC considers maximum or minimum recall. While changing the signal controllers to actuated RBC, all the signal parameters mentioned above are kept the same except for the maximum green signal timing. The reason for keeping the timings similar is because after manual calculation by using eq-9, 10 & 11 and from FHWA guidelines, it is found that 25s is the appropriate green signal timing for that intersection with approach volume found after running the base condition simulation. Detectors are placed in the approaching traffic roads. These equations are also used in fixed time traffic controller. Same calculation procedure can be used for actuated just the degree of saturation (v/c ratio) need to be 0.95 as per Highway Capacity Manual (*56*). Following is an example of the signal configuration when node-29 is converted to actuated signal timing:

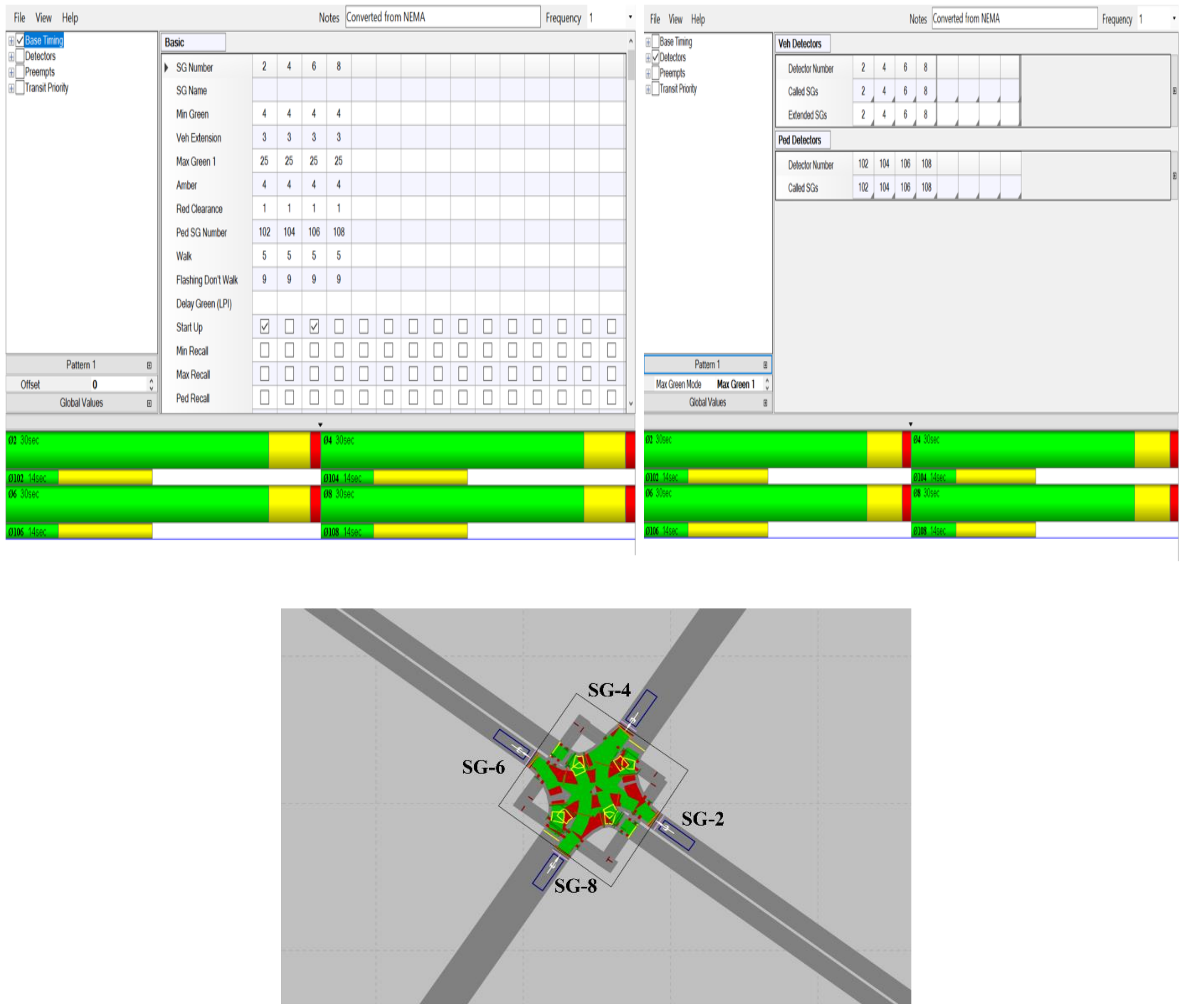


Figure 12: Actuated RBC Configuration

In this process each of the intersections as per different topological credentials, the intersections are converted from fixed RBC to actuated RBC. It is to be noted as per (*57*), the intersections that are very close to each other or are in coordinated signal timing can be converted into fully actuated signal timing during some hours of the day. Especially in urban settings, intersections are mostly closer to each other, and more fluctuations can be seen from very high volume to low volume. In such situations, fully actuated signal timing helps to reduce the delay. Thus, in this study, fully actuated RBC timing is selected for the improvement of the Boise downtown, Idaho urban network which are all very closely packed intersections. To convert from fixed RBC to actuated, the mentioned signal timing equations are used to calculate the green, amber, yellow timing and cycle length for each of the networks. It is to be noted that Boise Downtown, Idaho urban roadway classification is not a simple one. It is classified both into minor collector and local roadway as shown in Figure 13. Since the volume in each of the approaching movements of the intersections came out to be not that high, the green signal timing is mostly considered 25s considering local roadway classification as shown in Table 4. Moreover, a study compared delay between semi actuated and fixed controller intersections (*58*). In semi-actuated intersections, the major road was actuated, and minor was fixed. In fixed intersection, all the major and minor were fixed signal timing setting. So, it was found from that study that keeping a fixed control system needs primary lane green light durations to be longer than a semi-actuated control arrangement would ideally allocate to green time. Since, in this research, all the approaching roadways of the intersection will be converted to actuated, it is better to lower the signal timing which has higher signal timing during fixed time controller setup under base condition.

Figure 13: Functional Classification of Roadway of Boise downtown in Idaho (*59*).

Table 4: Maximum Green Signal Timing of Actuated RBC as per Facility Type (*60*)

Phase Type	Facility Type	Maximum Green (Seconds)
Through	Major Arterial (Speed Limit>40 mph)	50 to 70
	Major Arterial (Speed Limit <= 40 mph)	40 to 60
	Minor Arterial, Collector	30 to 50
	Local, Driveway	20 to 40
Left-Turn	Any	15 to 30

Below is the table showing the conversion of different nodes from fixed RBC to actuated RBC when most important nodes are identified based on different types of topological credentials and simulated accordingly.

Table 5: Node wise conversion of Fixed RBC to Actuated RBC signal timing.

Node Numbers	Signal Configurations	Fixed RBC	Actuated RBC
Node-1, 3	Total No of Signal Groups	4	4
	Maximum Green Signal Time of Phase-2&6	35s	25s
	Maximum Green Signal Time of Phase-4&8	15s	25s
Node-2,13,17,28,29 & 30	Total No of Signal Groups	4	4
	Maximum Green Signal Time of Phase-2&6	25s	25s
	Maximum Green Signal Time of Phase-4&8	25s	25s
Node-6	Total No of Signal Groups	4	4
	Maximum Green Signal Time of Phase-2&6	82s	82s
	Maximum Green Signal Time of Phase-4&8	28s	28s
Node-8	Total No of Signal Groups	2	2
	Maximum Green Signal Time of Phase-2	65s	65s
	Maximum Green Signal Time of Phase-4	45s	45s
Node-9	Total No of Signal Groups	2	2
	Maximum Green Signal Time of Phase-2	110s	110s
	Maximum Green Signal Time of Phase-1	20s	20s
Node-10	Total No of Signal Groups	2	2
	Maximum Green Signal Time of Phase-2	62s	65s
	Maximum Green Signal Time of Phase-4	48s	45s
Node-11	Total No of Signal Groups	2	2
	Maximum Green Signal Time of Phase-2	61s	65s
	Maximum Green Signal Time of Phase-4	49s	45s
Node-12	Total No of Signal Groups	4	4
	Maximum Green Signal Time of Phase-2&6	30s	25s
	Maximum Green Signal Time of Phase-4&8	20s	25s
Node-16	Total No of Signal Groups	2	2
	Maximum Green Signal Time of Phase-2	31s	25s
	Maximum Green Signal Time of Phase-4	19s	25s
Node-18	Total No of Signal Groups	2	2
	Maximum Green Signal Time of Phase-2	20s	25s
	Maximum Green Signal Time of Phase-4	30s	25s
Node-19,23,26,27,28&33	Total No of Signal Groups	2	2
	Maximum Green Signal Time of Phase-2	25s	25s
	Maximum Green Signal Time of Phase-4	25s	25s
20	Total No of Signal Groups	2	2
	Maximum Green Signal Time of Phase-2	19s	25s
	Maximum Green Signal Time of Phase-4	31s	25s
21	Total No of Signal Groups	2	2

	Maximum Green Signal Time of Phase-2	18s	25s
	Maximum Green Signal Time of Phase-4	32s	25s
Node-22,25&26	Total No of Signal Groups	2	2
	Maximum Green Signal Time of Phase-2	35s	25s
	Maximum Green Signal Time of Phase-4	15s	25s
Node-24	Total No of Signal Groups	2	2
	Maximum Green Signal Time of Phase-2	33s	25s
	Maximum Green Signal Time of Phase-4	17s	25s
Node-31	Total No of Signal Groups	2	2
	Maximum Green Signal Time of Phase-2	55s	55s
	Maximum Green Signal Time of Phase-1	14s	14s
Node-32	Total No of Signal Groups	4	4
	Maximum Green Signal Time of Phase-2&6	31s	31s
	Maximum Green Signal Time of Phase-4	24s	24s
	Maximum Green Signal Time of Phase-8	14s	14s

3.1.8 Furness Method

In this study, due to time constraint, OD survey was not conducted in the traffic analysis zones to perform the dynamic traffic assignment. So, a prior matrix is formed using the Furness method of trip distribution. It was invented by K.P Furness (*61*). In this method it is required to estimate the future traffic originating and terminating at each zone. The design hourly volume of each of the roadways where the origin and destination were inserted to match the simulated volume with the real-world volume. This method gives the base year distribution. The origin growth factors, and destination growth factors were calculated and through few iterations, the origin and destination matrix are formed. Fratar method is also popular in formatting the OD matrix, but Furness method is computationally easier. Thus, this has been used in this study. In static assignment, in each approaching roadways, traffic can be assigned in VISSIM. But in dynamic assignment, OD matrix plays as the traffic that will be generated from each zone. That's why to represent real world volume, OD matrix is formed based on DHV values. However, DHV data for the roadways for

Boise downtown, Idaho are not point data, these are in roadway segment wise data, so it is quite impossible to form a precise prior matrix with this data. That's why due to lack of data, it was not possible to conduct a properly calibrated model.

3.1.9 Calibration

Calibration is the process of systematically modifying model parameters so that the model matches the observed traffic conditions in the study area. Calibration measurements are divided into two basic categories: 1. Localized (segment or intersection-level) performance; 2. Systemic (route, corridor, or system-level) performance (*62*). Minimum at least two types of calibration need to be performed. The throughput or traffic volume as a localized (segment level) calibration and speed which is system performance level calibration which were conducted in this study. It should be noted that the PTV-VISSIM software already had the Boise Road network created and tested, therefore calibration and validation was not entirely necessary for this research (*12*). But since dynamic traffic assignment is conducted, that's why this study tried to conduct the calibration very simply with few data available online.

Driving behavior is one of the most important parameters for calibration (*63*). There are 8 different driving behavior models. But the most used are urban (motorized) and freeway. Under the following section within any of these driving behavior models, the first calibration parameter is the lane changing behavior where there is look ahead distance. It is the distance the vehicle can see forward to react to other vehicles or objects that are infront of it or side of it within the lower bound. Second is the maximum distance, which is the distance where the vehicles won't see anything outside of this distance. Thirdly, the look back distance which is a boundary the vehicles can see other vehicles behind them. This parameter is usually more important in bicycle modelling.

In this study none of these parameters have been changed. Urban and freeway driving behaviors follows two types of the Car following model, Weidmann model 1974 and Weidmann model 1999 respectively (*13*). In Weidmann 1974, three different parameters can be considered for calibration. This model has a non-linear relationship in terms of speed and desired safety distance. For low speeds below 50 or 80 mph, it is better to use a larger value of desired safety distance. The desired safety distance is larger for this model than Weidmann 99 which makes this model particularly suitable for urban arterials and even low speed weaving section. Safety distance is calculated with different components. The first component is average standstill distance. This is the desired distance between any stopped vehicle. This will have a variation of plus or minus 3 feet, as the vehicles are coming to a full stop to wait behind another vehicle. The second component is the additive part of desired safety distance. This is going to control any of the base headway information and increase the following distance based on the speed of the vehicle. Thirdly multiplicative part of safety distance. This third part determines the amount of variation that exists between a vehicle's following distance. On the other hand, in Weidmann 99, there are 10 parameters that can be configured. In this model, the relationship between desired safety distance and speed is quite linear. So, this makes this model more suitable for performing any freeway modelling. Boise downtown, Idaho is basically an urban region. Mostly the roads are arterials with low speed. So, it is appropriate to use Weidmann 74 Car Following model. Thus, this study uses the Weidmann 74 model, and the calibration is performed changing the three parameters of the model. To calibrate the model comparing with the DHV values, the safety distance was increased to 10 m from 6.56 m (default value) and the minimum clearance distance (front/rear) from lane change section is changed to 3 ft from 1.64 ft. 48% of the link segments through volume had GEH value less than 5 as given in Appendix B. But the requirement of a calibrated model is to have 85%

road segments through volume to be less than 5 (*64*). Then the simulated flow-density curve with default parameters and calibrated parameters were formed and compared with real flow-density curve which has been formed with DHV and density was derived by dividing DHV by the distance of the link segment. Appendix C shows that the full bell curve was not formed with the calibrated parameters. It should be noted that due to time constraint, it was not possible to do an OD survey from the field, so, as mentioned previously that a prior OD matrix was developed by Furnessing. So, it wasn't possible to calibrate the model properly. Most of the time for comparison of throughput volume for calibration, field data or 24-hr traffic count data is used as the base for comparison during calibration and as per WSDOT, DHV data can also be used in throughput volume calibration(*64*). Since it was not possible to collect 24-hr traffic count data from field, DHV data was used as the base for calibration. Now, it should be mentioned, in VISSIM while doing Dynamic Traffic Assignment, OD matrix is the only way to input traffic volume for the network without actual OD matrix formed through field data collection, it was very difficult to calibrate with DHV data. But this model is still acceptable as per WSDOT VISSIM Protocol, if there is difficulty in calibrating the model, further adjusting to the model is not necessary and for some projects if there is proper justification, the model can be approved by technical advisors. So, it's crucial to emphasize that the main goal of this research is to provide a methodology for determining the best intervention nodes to improve the network's Level of Service (LOS). It's also important to remember that this study does not make a direct comparison between the present and the future (changing the OD matrix by multiplying with growth factor for future). Rather, it uses fictitious circumstances to present alternate scenarios (without changing OD matrix, etc.). Thus, one could argue that rather than forecasting future advancements based on adjusted volume, this study functions more as a comparative examination within current conditions. In support of this approach, the main goal of this study is not to predict future conditions but rather to establish a framework for possible identifying interventions. As such, although extensive calibration would certainly enhance precision, it might not be entirely deemed in this study.

Chapter-4

4.1 Result

VISSIM, a traffic simulation software is utilized to examine the downtown road network in Boise, Idaho. Numerous interventions on the highly central nodes are implemented to increase the LOS of the road network. After the interventions, the total travel time, total delay, and the total number of LOS improved for different node movements are compared with the base condition from the simulation. Finally, a comparison assessment between the results is presented. Under disrupted conditions, for each scheme, another parameter called system functionality is calculated using travel time as an indicator to show the resilience of the network.

4.1.1 Undisrupted Flow Result Analysis

To find out the most important nodes, first an unweighted and edge weighted betweenness centrality (BC) values for 33 nodes in the directed network under undisrupted base condition is determined. As per the BC values, both the ranking of the undisrupted (base condition) network is shown in Appendix D.

As discussed in the methodology, both edge weighted and node weighted betweenness centrality values are also determined. In Appendix E & F, node weighted (considering total maximum green time and maximum green time of phase 2) and full weighted betweenness centrality measurement is shown.

From Appendix E, the blue highlighted rank 4 is from where the ranking slightly changes for using different type of node weights to determine BC values. The reason for slight changes in the ranking even after using different node weight is most likely because the maximum green time of phase-2 is a part of total maximum green time. Total maximum green time is the summation of maximum green time of all phases (phase sequence-2,4,6,8 or 2,4 or 1,2 or 2,4,8) combinations. In all these combinations, maximum green time is the most used one. So, the total maximum green time varies mostly because of the maximum green time of phase 2. Thus, the ranking based on these two weights is almost the same. For easier interpretation and time constraint, this study conducts scenario analysis for network improvement based on topological credential considering node weights of only total maximum green time.

The ranking of full weighted BC values using edge weights (DHV) and node weights (both total max green time and max green time of phase 2 are almost identical. The ranking changes from rank 7 as highlighted in Appendix F, so, there is very little chance of difference in the improvement of the network based on reduction of total travel time and total delay. Thus, only full weighted topological credential where node weights are the total maximum green time is used for the scenario analysis. The scenario analysis with different node/intersections operating at different schemes for undisrupted condition is given in Table-6. These operating conditions are used throughout the analysis process for undisrupted networks.

Table 6: Scenario-1 (base condition) with nodes operating at different schemes based on different topological credentials.

Scenario/ Scheme	Node Operations Unweighted BC Ranking	Node Operations Edge-Weighted BC Ranking	Node Operations Node-Weighted BC Ranking	Node Operations Full Weighted BC Ranking
Scenario-1 (Base Condition	All Fixed RBC except (node-7,14&15)	All Fixed RBC except (node-7,14&15)	All Fixed RBC except (node-7,14&15)	All Fixed RBC except (node-7,14&15)
Scheme-1	Highest Central Node-18 is actuated RBC and rest fixed	Highest Central Node-17 is actuated RBC and rest fixed	Highest Central Node-17 is actuated RBC and rest fixed RBC	Highest Central Node-17 is actuated RBC and rest fixed RBC
Scheme-2	Lowest Central Node-5 is actuated RBC and rest fixed RBC	Lowest Central Node-24 is actuated RBC and rest fixed RBC	Lowest Central Node-27 is actuated RBC and the rest fixed RBC	Lowest Central Node-9 is actuated RBC and rest fixed RBC
Scheme-3	Node-18&17 are actuated RBC and rest fixed RBC	Node-17&13 are actuated RBC and rest fixed RBC	Node-17&13 are actuated RBC and rest fixed RBC	Node-17&13 are actuated RBC and rest fixed RBC
Scheme-4	Node-18,17,20&13 are actuated RBC and rest fixed RBC	Node-17,13,29&23 are actuated RBC and rest fixed RBC	Node-17,13,23,&29 are actuated RBC and rest fixed RBC	Node-17,13,29&23 are actuated RBC and rest fixed RBC
Scheme-5	Node-18,17,20,13,19,26,8&24 are actuated RBC and rest fixed RBC	Node-17,13,29,23,30,31,20&12 are actuated RBC and rest fixed RBC	Node-17,13,23,29,10,18,8&30 are actuated RBC and rest fixed RBC	Node-17,13,29,23,31,30,25&12 are actuated RBC and rest fixed RBC
Scheme-6	Node-18,17,20,13,19,26,8,24,10,23,25&32 are actuated RBC and rest fixed RBC	Node-17,13,29,23,30,31,20,12,26,25,18&32 are actuated RBC and rest fixed RBC	Node-17,13,23,29,10,18,8,30,25,31,19&11 are actuated RBC and rest fixed RBC	Node-17,13,29,23,31,30,25,12,32,2,3&18 are actuated RBC and rest fixed RBC
Scheme-7	Node-18,17,20,13,19,26,8,24,10,23,25,32,30,12,31&29 are actuated	Node-17,13,29,23,30,31,20,12,26,25,18,32,19,10,8&11 are	Node-17,13,23,29,10,18,8,30,25,31,19,11,12,24,21&32 are	Node-17,13,29,23,31,30,25,12,32,2,3,18,4,5,6&8 are actuated

	RBC and rest fixed RBC	actuated RBC and rest fixed RBC	actuated RBC and rest fixed RBC	RBC and rest fixed RBC
Scheme-8	Node-18,17,20,13,19,26,8,24,10,23,25,32,30,12,31,29,16,6,9&11 are actuated RBC and rest fixed RBC	Node-17,13,29,23,30,31,20,12,26,25,18,32,19,10,8,11,6,21,33&2 are actuated RBC and rest fixed RBC	Node-17,13,23,29,10,18,8,30,25,31,19,11,12,24,21,32,16,2,6&3 are actuated RBC and rest fixed RBC	Node-17,13,29,23,31,30,25,12,32,2,3,18,4,5,6,8,19,16,28&1 are actuated RBC and rest fixed RBC

4.1.1.1 Result Discussion of Scenario-1 (Undisrupted Condition) Using Unweighted Topological Credentials

In scenario-1, all the intersections are in fixed RBC except node-7 is stop controlled, 14 and 15 under yield or priority controlled. In Table 7 where the network operates under base condition, the travel time is 2,664,000 vehicle-hours and total delay is 2,300,400 hours. The highest central node found from network analysis is node-18 using unweighted betweenness centrality measurement ranking. In scheme-1, the signalization of critical node-18 is changed from fixed RBC to actuated RBC as shown in Table-6, all other nodes fixed RBC except node-7,14 & 15 as discussed in detail in the methodology. The simulation result shown in Table-6 shows that the total travel time reduces by 0.5% and delay by 1.9%. From the traffic simulation, it is found that the travel time decreased very insignificantly, but the LOS of 26 node movements out of 175 node movements improved from the base condition. In scheme-2, the least central node as per unweighted BC value ranking shown in Table-7 is now converted into actuated RBC just to prove the hypothesis that highest central node reduces travel time and delays more than that of least central node. It is found that, least central node-33 indeed has less travel time reduction (0.3%) and less delay reduction (0.9%) than that of highest central node-18. The difference could have been more, that’s why it is important to check with other topological credential ranking by including weightage. In scheme-

3, node-18 & 17, which are sequentially the most highly ranked nodes in the network, are all changed into actuated RBC with the same configuration mentioned in the methodology. The simulation result shows that 12 hours of travel time is saved and 3.6% delay reduces. This time, more road segments improved in terms of LOS (49 out of 175). Eventually in scheme-4 more improvement is found after converting two more highly central nodes (total node-18,17, 20 & 13) into actuated. In scheme 5, 4 more nodes converted into actuated. So, in total 8 nodes are converted into actuated RBC, and it is found that much better improvement in the LOS is captured (93 node movements). Similarly, by adding 4 more nodes each time, finally at scheme-8, 20 highly central nodes (node-17,20,13,19,26,8,24,10,23,25,32,30,12,31,29,16,6,9,11&21) are converted into actuated RBC keeping other nodes at fixed RBC, total travel time reduced by 10.8%, total delay by 11.4% and 117 links improved in LOS from the base condition.

Table 7 Summary of Result Analysis Under Scenario-1 (Undisrupted Condition) based on Unweighted Topological Credential

Scenario/ Scheme	Total Travel Time (Vehicle-hour)	Change in Total Travel Time (%)	Total Delay (hour)	Change in Total Delay (%)	No of Node Movement's Improved in LOS
Scenario-1	2,664,000	-	2,300,400		-
Scheme-1	2,649,600	-0.5	2,257,200	-1.9	26
Scheme-2	2,656,800	-0.3	2,278,800	-0.9	10
Scheme-3	2,620,800	-1.6	2,217,600	-3.6	49
Scheme-4	2,534,400	-4.9	2,163,600	-5.9	79
Scheme-5	2,498,400	-6.2	2,142,000	-6.9	93
Scheme-6	2,448,000	-8.1	2,120,400	-7.8	102
Scheme-7	2,397,600	-10	2,048,400	-10.9	111
Scheme-8	2,376,000	-10.8	2,037,600	-11.4	117

4.1.1.2 Result Discussion of Scenario-1 (Undisrupted Condition) Using Edge Weighted Topological Credentials

Since, one of the research questions this study wants to answer is which of the topological credential ranking help to identify the most impactful node in the network, under similar scenario-1 (base condition when no disruption occurs), different topological credentials are determined in which one of the credentials is using the edge weightage. So, under base condition, edge weighted BC values are found out and ranked accordingly. Now in Table-11, it can be observed that node-17 is the highest central node when edge weights are considered. So, node-17 is now converted to actuated RBC keeping all other signal controllers at fixed RBC. This time the total travel time decreased by 1.1% and total delay by 2.3% which is greater than when node-18 signal controller is converted into Actuated RBC as per unweighted topological credentials. In scheme-2, least central node-24 as per edge-weightage ranking, it is converted into actuated RBC from fixed RBC, the travel time reduces by only 0.2% and delay by 0.8%. This means, when the least central node is used, there are very insignificant changes in the overall network performance based on total travel time and total delay. So, it can prove one of the hypotheses that highest central node has higher impact in the network than least central node. Also, as from the result discussion when unweighted topological credential is used, node-18 can reduce travel time by 0.1% whereas node-17 (most central node under edge-weighted ranking) can reduce upto 1.1%. And even the lowest central node-33 under unweighted ranking has higher reduction in travel time and delay than the least central node-24 under edge-weighted ranking which proves that edge-weighted ranking has better impact. Moreover, node-33 ranks 22 as per Appendix F under edge-weighted ranking. Perhaps, this is the reason why the travel time and total delay reduction is moderate even though it is the least central node in unweighted ranking as shown in Table-6.

Now, in Table-8, in the similar way as mentioned in the result discussion in unweighted analysis, each scheme is formed by converting 4 new nodes into actuated RBC following the topological ranking of edge weighted betweenness centrality values mentioned in Table-8, 20 nodes are finally converted into actuated RBC signal at the last scheme-8 keeping all other at fixed RBC. This time, with 20 node conversion, total travel time reduced by 11.6%, total delay by 12.7% and 122 node movements LOS improved.

Table 8: Summary of Result Analysis under Sceneraio-1 (Undisrupted Condition) based on Edge-Weighted Topological Credentials

Scenario/ Scheme	Total Travel Time (Vehicle-hour)	Change in Total Travel Time (%)	Total Delay (hour)	Change in Total Delay (%)	No of Node Movement's Improved in LOS
Scenario-1	2,664,000	-	2,300,400		-
Scheme-1	2,631,600	-1.1	2,246,400	-2.3	30
Scheme-2	2,656,800	-0.2	2,282,400	-0.8	11
Scheme-3	2,606,400	-2.1	2,199,600	-4.4	56
Scheme-4	2,552,400	-4.2	2,163,600	-5.9	78
Scheme-5	2,491,200	-6.4	2,131,200	-7.4	93
Scheme-6	2,440,800	-8.3	2,106,000	-8.5	101
Scheme-7	2,383,200	-10.5	2,037,600	-11.4	113
Scheme-8	2354400	-11.6	2,008,800	-12.7	122

4.1.1.3 Result Discussion of Scenario-1 (Undisrupted Condition) Using Node Weighted Topological Credentials

Similar to the edge weighted centrality measurement analysis, node weighted betweenness centrality ranking is applied to determine the most important node in the network that can improve the efficiency of the network. As mentioned in the description of Table-9, phase-2 plays the main factor for varying in the node weights, since total green time consists of maximum green time of phase-2, both the node weights produce similar ranking using BC values. For this reason, both the results will give almost similar results as such, any one of the rankings can be used. So, in this study, only total maximum green time is used for scenario analysis. Interestingly, from Table-6 it can also be found that the highest central and second highest central node are node-17 and node-13 which is similar to edge-weighted ranking, So, the 1st two scheme results were similar. But the least central node based on this ranking is in Table-9, from the simulation result it is found using node weighted centrality credential, after converting 20 nodes into actuated, 120 node movements LOS improved from 175 node movement under base condition. This shows that node weighted centrality using signal timing as node weights doesn't give better improvement than it did using edge weighted BC value ranking or topological credential to determine the most important nodes or intersections in the network even though their highest central node is same.

But as the rank goes in the descending order, the node rank differs from edge weight ranking and hence difference in result. Moreover, the reason for getting a little higher travel time at the last scheme-8 compared to the scheme-8 when edge weighted ranking is used might perhaps be as per Dijkstra algorithm, finding shortest path is based on the distance between the nodes as well as the weights when node weights are used. The least resistance paths are usually chosen when lower weights are prioritized in the context of shortest paths. As a result, the node with the highest centrality is typically the one that is traversed the most frequently within the shortest paths when calculating betweenness centrality values using node weights. This suggests that either the node's weight of its neighboring nodes is lower or that the node itself tends to weigh less than others. It may not be the lowest weight in the network, but it is most likely to be lower. In this study, a lower node weight indicates a shorter green signal time compared to other nodes. The traffic volume on that roadway is probably lower under the base condition, and there might not be as many lanes. Therefore, while switching to an actuated system, there isn't much of an adjustment needed to switch to an actuated system because the maximum green signal timing is already very short (19, 25 seconds, etc.). As a result, there is not any significant decrease in travel time from the base condition. Moreover, a study found that decreasing the signal timing from the fixed signal timing to make actuated signal timing gives higher result (*28*). So, in this study, nodes with lower weights were required to increase the signal timing from 19s to 25s or 25s, keeping the other parameters same and for this reason, not as significant change is observed as that when edge-weight ranking is used.

Table 9: Summary of Result Analysis of Scenario-1 (Undisrupted Condition) based on Node-Weight Topological Credential

Scenario/ Scheme	Total Travel Time (Vehicle-hour)	Change in Total Travel Time (%)	Total Delay (hour)	Change in Total Delay (%)	No of Node Movement's Improved in LOS
Scenario-1	2,664,000	-	2,300,400		-
Scheme-1	2,631,600	-1.2	2,246,400	-2.3	30
Scheme-2	2,646,000	-0.68	2,293,200	-0.31	8
Scheme-3	2,606,400	-2.2	2,199,600	-4.4	56
Scheme-4	2,563,200	-3.8	2,174,400	-5.5	72
Scheme-5	2,491,200	-6.5	2,142,000	-6.9	91
Scheme-6	2,430,000	-8.8	2,098,800	-8.7	102
Scheme-7	2,379,600	-10.7	2,034,000	-11.6	112
Scheme-8	2,361,600	-11.4	1,994,400	-13.3	120

4.1.1.4 Result Discussion of Scenario-1 (Undisrupted Condition) Using Full Weighted Topological Credentials

Finally, full weighted betweenness centrality measurement is used as the topological credential to determine the important nodes to intervene in the network. The most important node after network analysis in this case is also found to be node-17. In fact, the ranking between edge weighted and full weighted is the same till rank-7 and the least central node is also similar so, till scheme-4, the total travel time & total delay reduction percentage and no. of node movements LOS improvements remains the same as the results given for edge-weighted in Table-10. From scheme-5, higher improvement is observed where the travel time reduces by 6.7%, total delay by 7,8% and 96 node movement's LOS improved which are all better improvements than that of edge weighted scheme-5 results (travel time reduction=6.4%, total delay reduction=7.4% and 93 node movements LOS improved). So, this slight increase in the network performance might perhaps be because of the change in node-25 (full weighted ranking) from node-20 (edge-weight ranking) having all other nodes same. This means, full weighted BC value ranking or topological credential gives better result than that of edge weighted which was the best topological credential till the last discussion. This can further be proved when at the last scheme 8, it gives much higher reductions in total travel time and delay and number of node movement's LOS improvement compared to all other result summary discussed so far based on other topological credentials. Thus, it can be said that for better system performance of the network, it is better to use full weighted BC value ranking. The difference in the result is very slight in this study, the reason most likely because of signal timing being the node weightage. But in communication networks, when population size is used as the node weight, it is found to have much greater impact as mentioned previously (*41*). In that study it suggests updating the betweenness centrality to full weighted (considering both node and edge weights) centrality measurement to get much more reliable result. Thus, this study proves no difference. It is ideal to use full weighted betweenness centrality measurement ranking.

Table 10: Summary of Result Analysis under Scenario-1 (Undisrupted Condition) based on Full Weighted Topological Credential

Scenario/ Scheme	Total Travel Time (Vehicle-hour)	Change in Total Travel Time (%)	Total Delay (hour)	Change in Total Delay (%)	No of Node Movement's Improved in LOS
Scenario-1	2,664,000	-	2,300,400		-
Scheme-1	2,631,600	-1.1	2,246,400	-2.3	30
Scheme-2	2,656,800	-0.2	2,282,400	-0.8	7
Scheme-3	2,606,400	-2.1	2,199,600	-4.4	56
Scheme-4	2,552,400	-4.2	2,163,600	-5.9	78
Scheme-5	2,484,000	-6.7	2,120,400	-7.8	96
Scheme-6	2,430,000	-8.7	2,095,200	-8.9	108
Scheme-7	2,376,000	-10.8	2,026,800	-11.9	116
Scheme-8	2,347,200	-11.9	1,987,200	-13.6	125

4.1.1.5 Result Comparison between 4 different Topological Credentials

From the above discussions, three graphs below show the percentage of trave time, delay reduced, and number of LOS of node movements improved compared to the base condition with the number of nodes converted into actuated RBC from fixed RBC using 4 different topological credentials. In this graph, scheme-2 where lowest central node is converted into actuated RBC is not shown. This graph shows that total travel time and total delay reduced very less when unweighted topological credential is used compared to the other topological credentials. The percentage reduction total delay curve of edge weighted topological credential is almost similar to the percentage reduction delay curve of full weighted betweenness centrality and the curve is much steeper than the rest of the curves which means that both of these two topological credentials can identify the most important nodes that requires changes much more sequentially than the rest of the centrality measurements. From Figure 14(c), the number of LOS improved using full weighted BC value ranking is the highest than the rest. That means, overall, full weighted betweenness centrality measurement provides the best topological ranking than the rest of the centrality measurements.

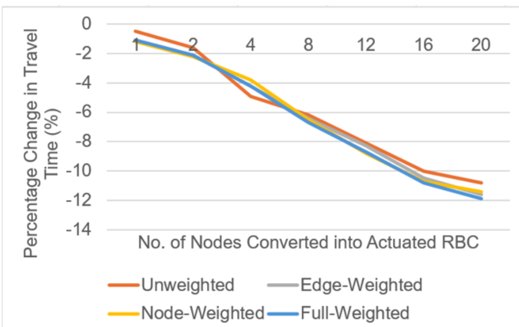


Figure 14(a). % Change in Total Travel Time with Increasing No. of Nodes Converted Into Actuated RBC

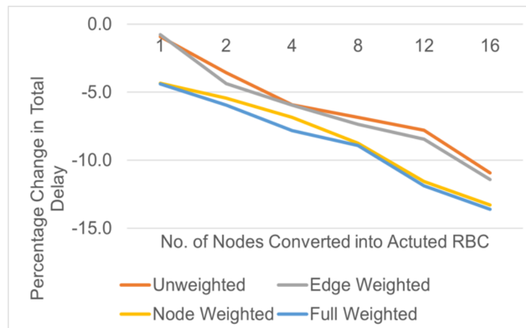


Figure 14(b). % Change in Total Delay with Increasing No. of Nodes Converted Into Actuated RBC

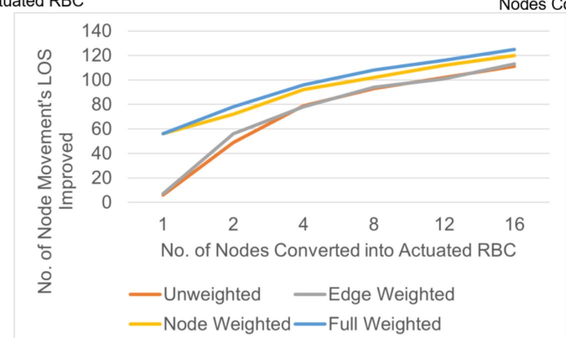
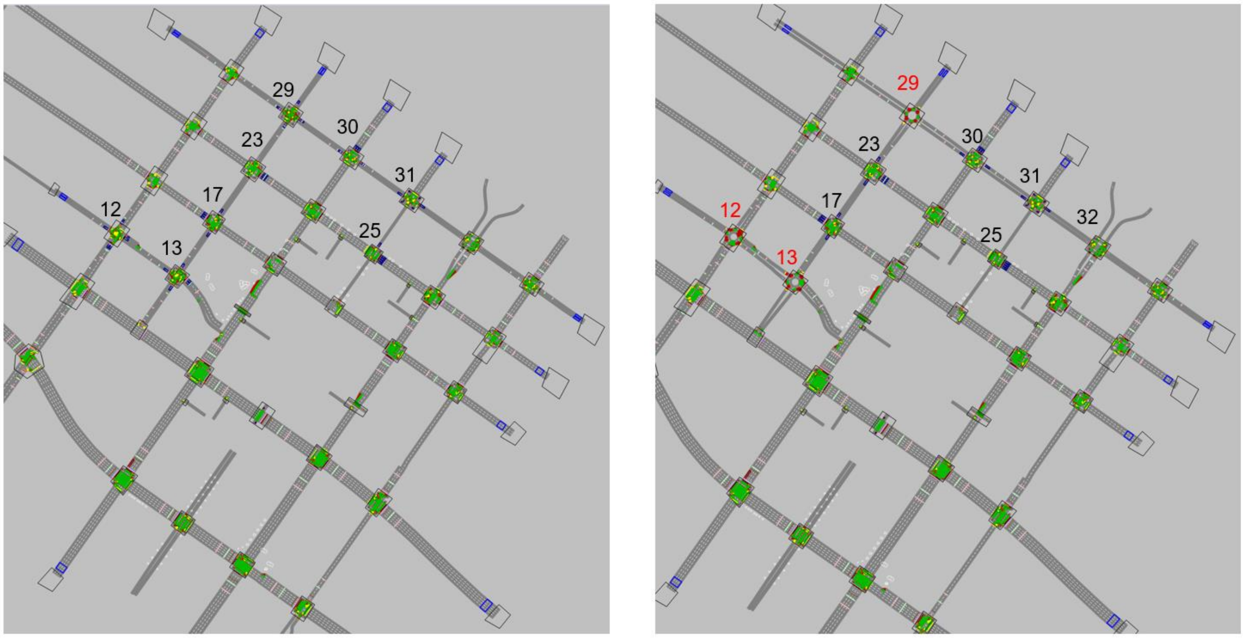


Figure 14(c). No. of Node Movement's LOS Improved with Increasing No. of Nodes Converted Into Actuated RBC

Figure 14: Comparison Figure showing Travel Time, Delay and LOS improvements based on different topological credentials with increased number of nodes.

4.1.1.6 Roundabout under Undisrupted Condition

Since warrants for roundabouts are not included in the Manual of Uniform Traffic Control Devices (MUTCD), it does not fall under the purview of warranting procedures. The best way to treat intersections without roundabouts is to assess each roundabout on its own merits. However, when traffic volumes are close to the threshold of warrant for traffic signals, roundabouts can be evaluated. Since from comparing the topological credentials in terms of percentage reduction of travel time, delay and LOS improvements, full weighted topological credentials gave the best result, so full weighted topological credentials of scheme-5 are used to compare with roundabouts. So, scheme-5 using full weighted topological credential is shown in Figure-15(a) where 8 nodes are first converted into actuated RBC. Roundabouts are categorized into many types (*65*). It is 1st categorized as single lane and multi-lane. Another category is in terms of the number of lanes provided, i.e., single lane, and multilane roundabouts. In this study, the type of roundabout that is used in this is mostly single lane (similar to mini roundabouts), non-traversable and without truck apron roundabout. As per NCHRP, single lane roundabout will have one or more entry lanes in each roadway which makes it a 4-way entry roadway which is a typical circular roundabout (*65*). Now among 8 of the nodes, only 3 of them have 4 approaching lanes. So, only those three nodes-12, 13 & 29 are converted into roundabouts from actuated RBC which was also initially at fixed RBC setting. Figure-15(b) shows the network with the roundabouts and actuated RBC based on full weighted topological credential.



(a) Undisrupted Network with 8 nodes converted into actuated RBC

(b) Undisrupted Network with 6 nodes converted into actuated RBC and node-12,13 & 29 converted into roundabouts

Figure 15: Comparison between Conversion into Actuated RBC and Hybrid (both Roundabout & Actuated RBC)

From the result comparison in Table-11 shows that by converting three intersections into roundabouts, it is giving much reduced travel time, delay and no. of node movements LOS improved manifold. Thus, it can also be concluded that roundabouts give better network improvement than actuated RBC.

Table 11: Comparison Table Between Actuated Conversion and Hybridized (Including both Roundabouts and Actuated RBC) based on Full Weighted Topological Credentials under Scenario-1

Scenario/ Scheme	Operating Condition	Total Travel Time (Vehicle-hour)	Change in Total Travel Time (%)	Total Delay (hour)	Change in Total Delay (%)	No of Node Movement's Improved in LOS
Scenario-1	Base Condition (All Fixed RBC)	2,664,000	-	2,300,400		-
Scheme-5 (Without Roundabout)	Nodes-17,13,29,23,31,30,25, &12 are Actuated RBC & Rest Fixed RBC	2,484,000	-6.7	2,120,400	-7.8	96
Scheme-5 (With Roundabout)	Node-17,13&29 Converted into Roundabout and Nodes-23,31,30,25, &12 are Actuated RBC & Rest Fixed RBC	2,455,200	-7.8	2,098,800	-8.8	103

4.1.2 Disrupted Flow Result Analysis

As from previous analysis and from literature, it is found that the highest central link has highest influence in the overall performance in the network. So, from both unweighted and edge weighted centrality values, the highest ranked (edge between 18 and 19) based on unweighted edge centrality measurement under base condition (Appendix A) is removed in the network and another disrupted network is formed by removing the link between 13 and 17 based on edge weighted centrality measurement under base condition (Appendix A). Now, both disrupted networks topological credential is found out with full weighted centrality measurement to identify the most important node in the network that can help recover the overall performance of the network almost to its original condition. This time instead of edge weighted or node weighted betweenness centrality measurement, full weighted betweenness centrality measurement is conducted as from the results in undisrupted network, full weighted topological credentials gave better results. So, using fully weighted topological credentials, Appendix E is formed that shows the ranking of the edges of the base directed network under disrupted condition. In scenario-2, the base condition is assumed to be operating at 100% efficiency and all the intersections are in fixed RBC except node-7, 14 and 15. From Table 12, in the network operating in base condition, the travel time is 24,864,000 vehicle-hours. Due to disruption in the network, the network performance decreases. So, in such situations, the nodes are improved as per different topological credentials to recover the network and improve the network resilience. Below is the table that shows the nodes that are operating at different schemes under scenario-2 or disrupted condition for two different disrupted networks.

Table 12: Scenario-2 showing different nodes operating at different schemes under two disrupted network condition based on topological credentials.

Scenario/ Scheme	**Node Operations of 1st Disrupted Network using Full Weighted BC Ranking**	**Node Operations of 2nd Disrupted Network using Full Weighted BC Ranking**
Scenario-1 (Base Condition	All Fixed RBC except (node-7,14&15)	All Fixed RBC except (node-7,14&15)
Scheme-1	Highest Central Node-23 is actuated RBC and rest fixed	Highest Central Node-17 is actuated RBC and rest fixed
Scheme-2	Lowest Central Node-9 is actuated RBC and rest fixed RBC	Lowest Central Node- 9 is actuated RBC and rest fixed RBC
Scheme-3	Node-23&13 are actuated RBC and rest fixed RBC	Node-17&13 are actuated RBC and rest fixed RBC
Scheme-4	Node-23,13,17&29 are actuated RBC and rest fixed RBC	Node-17,13,25&23 are actuated RBC and rest fixed RBC
Scheme-5	Node-23,13,17,29,30,31,32&12 are actuated RBC and rest fixed RBC	Node-17,13,25,23,18,12,2&19 are actuated RBC and rest fixed RBC
Scheme-6	Node-23,13,17,29,30,31,32,12,26,2,6&8 are actuated RBC and rest fixed RBC	Node-17,13,25,23,18,12,2,19,31,3,4&5 are actuated RBC and rest fixed RBC
Scheme-7	Node-23,13,17,29,30,31,32,12,26,2,6,8,3,4,5&19 are actuated RBC and rest fixed RBC	Node-17,13,25,23,18,12,2,19,31,3,4,5,24,30,29&8 are actuated RBC and rest fixed RBC
Scheme-8	Node-23,13,17,29,30,31,32,12,26,2,6,8,3,4,5,19,16,24,1&28 are actuated RBC and rest fixed RBC	Node-17,13,25,23,18,12,2,19,31,3,4,5,24,30,29,8,6,26,16&32 are actuated RBC and rest fixed RBC

4.1.2.1 Result Discussion of 1st Disrupted Network

From the methodology, it is shown that two disrupted networks are formed. One is through the highest central edge removal based on unweighted BC value ranking and the other is removing the highest central edge based on edge-weighted edge BC values ranking under base condition. 1st disrupted network is the one formed using unweighted edge BC values ranking. Here, the scenario-1 (base condition) is assumed to be working under 100% efficiency. Now, when the edge between node-18&19 is removed, the 1st disrupted network after running simulation increases travel time by 3.3% and delay by 3.9%, so, the network efficiency decreases to 96.76% from 100%. After calculating full-weight centrality measurement, it is found from Appendix G that the highest central node is 23. So, in scheme-1, node-23 is converted to actuated RBC, and it is found that total travel time and delay significantly decreases resulting in an increase in the system functionality of the network (97.80%). So, from Figure-16, the recovery can be seen with the decrease in travel time due to intervening the highest central node of the disrupted network. Similarly, converting two nodes in each scheme into actuated RBC increases the system performance exceeding 100% efficiency to 105.53%. There is no such thing as efficiency greater than 100%. But in this study, this means that with increasing number of nodes into actuated RBC, the original network with fixed RBC setup even improves due to decrease in travel and delay time.

Table 13: Summary of Result Analysis of Scenaro-2 (1st Disrupted Network) based on Full Weighted Topological Credentials

Scenario /Scheme	Total Travel Time (Vehicle-hour)	Change in Total Travel Time (%)	Total Delay (hour)	Change in Total Delay (%)	Resilience Indicator (System Performance in %)	No of Node Movement's Improved in LOS
Scenario-1	2,664,000	-	2,300,400	-	100	-
Scenario-2	2,750,400	3.3	2,390,400	3.9	96.76	-
Scheme-1	2,721,600	2.2	2,365,200	2.8	97.8	66
Scheme-2	2,732,400	2.6	2,376,000	3.3	97.41	61
Scheme-3	2,646,000	-0.6	2,304,000	0.2	100.58	108
Scheme-4	2,602,800	-2.3	2,282,400	-0.8	102.21	116
Scheme-5	2,516,400	-5.5	2,271,600	-1.3	105.53	134

Figure 15 shows the different recovery path generated due to conversion of intersections into actuated RBC from fixed RBC sequentially. The black solid line from scenario-2 to scenario-2 in this figure is used to show that all the schemes are compared from the same region (base scenario to disruption and then recovery based on different schemes). It can be observed that at scheme 5, the highest recovery path can is formed as it exceeds 100% base condition to 105.53%. So, it can be concluded that with sequential improvement in the network, even under disrupted conditions the network can not only be recovered to its original condition but also can be improved if one of the road segments is removed or destroyed. The case might vary if more than one road segment is removed which due to time constraint has not been analyzed.

Figure 16: System Performance under Different Schemes in 1st Disrupted Network

4.1.2.2 Result Discussion of 2nd Disrupted Network

The 2nd disrupted network is formed by removing the highest central edge between node-29&30 based on edge weighted centrality measurement ranking under base condition. With the removal of this edge, from Table-12, it can be observed that the network performance decreases to 96.49% by 3.6% which is a greater decrement to the 1st disrupted network when edge between node-18&19 is removed based on unweighted edge centrality measurement. This means, when the highest edge based on edge weighted BC values is removed, the impact in the system is higher. This answers one of the research questions that the worst-case scenario for disrupted network can be formed by removing highest central edge using edge-weighted betweenness centrality measurement. Then like the previous scenario analysis, full weighted BC values of 2nd disrupted network are determined and ranked as given in Appendix G. This topological credential is used to convert fixed

RBC to actuated RBC systematically. The highest central node-17 is 1st converted into actuated RBC and it is found that the system performance increases by 98.59%. In this way, from Figure 17, it can be observed that with the higher number of nodes converted to actuated RBC, the network becomes more efficient even under disrupted conditions.

Table 14: Summary of Result Analysis under Scenario-2 (Disrupted Condition of 2nd Network) based on Full Weighted Topological Credentials

Scenario/ Scheme	Total Travel Time (Vehicle-hour)	Change in Total Travel Time (%)	Total Delay (hour)	Change in Total Delay (%)	Resilience Indicator (System Performance in %)	No of Node Movement's Improved in LOS
Scenario-1	2,664,000	-	2,300,400		100	-
Scenario-2	2,757,600	3.6	2,408,400	4.7	96.49	73
Scheme-1	2,700,000	1.4	2,332,800	1.4	98.59	68
Scheme-2	2,732,400	2.6	2,354,400	2.3	99.49	54
Scheme-3	2,635,200	-1	2,293,200	-0.3	100.99	112
Scheme-4	2,584,800	-2.9	2,268,000	-1.4	102.9	120
Scheme-5	2,505,600	-5.9	2,246,400	-2.3	105.95	137

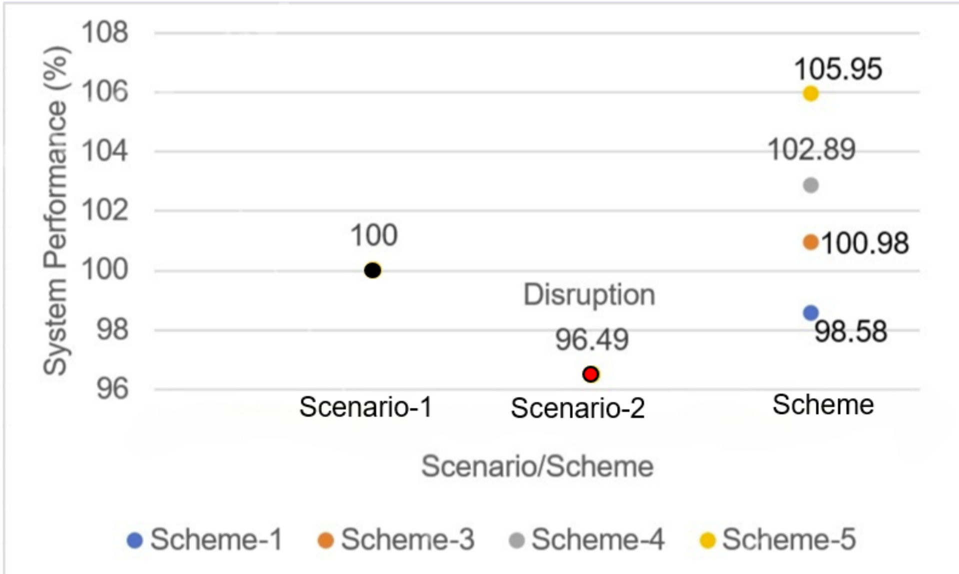
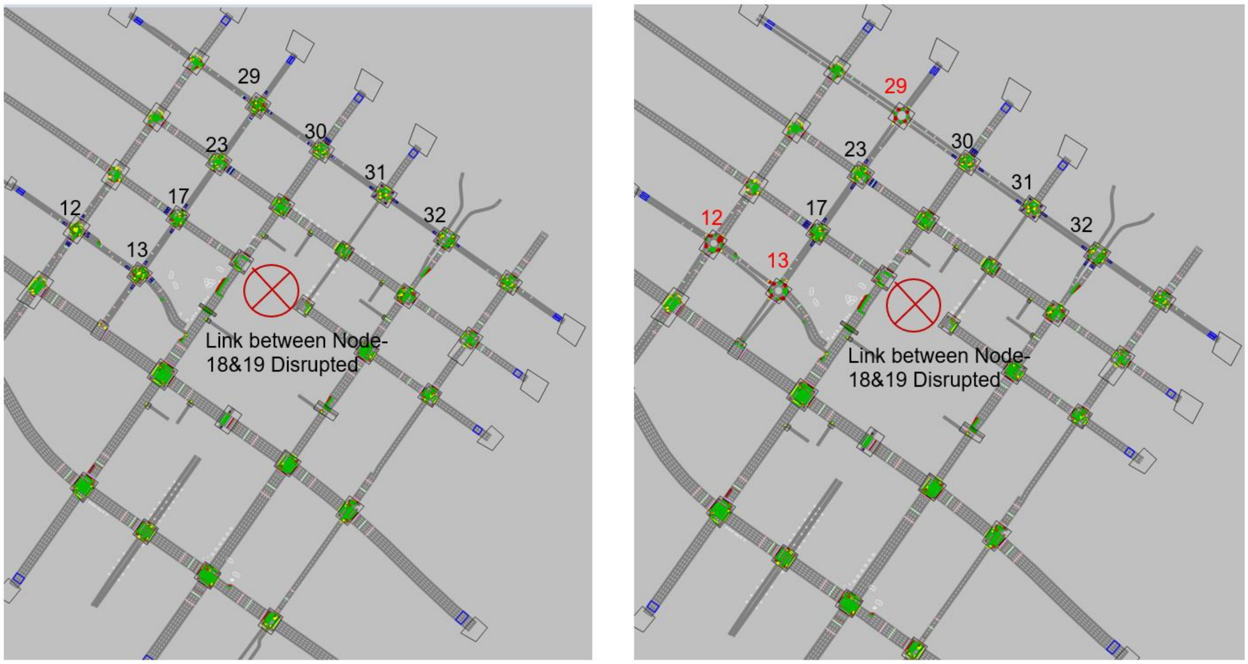


Figure 17: System Performance under Different Schemes in 2nd Disrupted Network

4.1.2.3 Adding Roundabouts Under Disrupted Condition

Figure 18(a) shows the 1st disrupted network when 8 nodes are actuated as per the full weighted BC ranking of 1st disrupted network and Figure 18(b) shows three of the nodes are reconfigured to roundabouts under similar ranking. From Figure 19(b) it can be observed that due to conversion of three nodes into roundabouts, a much higher recovery from the 1st disrupted condition is formed compared to when they were converted into actuated RBC. So, one of the hypotheses that roundabouts give better improvement than that of actuated RBC even under disrupted condition is proved.



(a) 1st Disrupted Network with 8 nodes converted into actuated RBC

(b) 1st Disrupted Network with 5 nodes converted into actuated RBC and nodes-12,13 & 29 converted into roundabouts

Figure 18: 1st disrupted network at scheme-5 (with and without roundabouts)

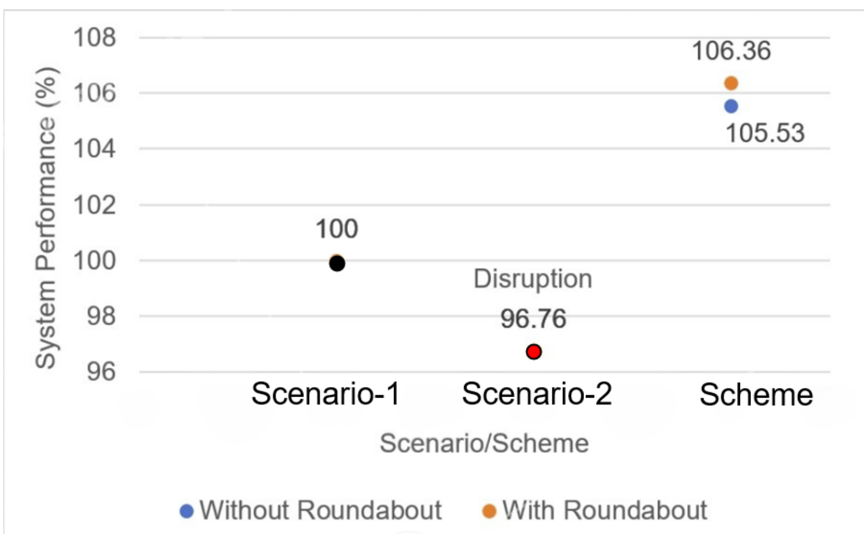
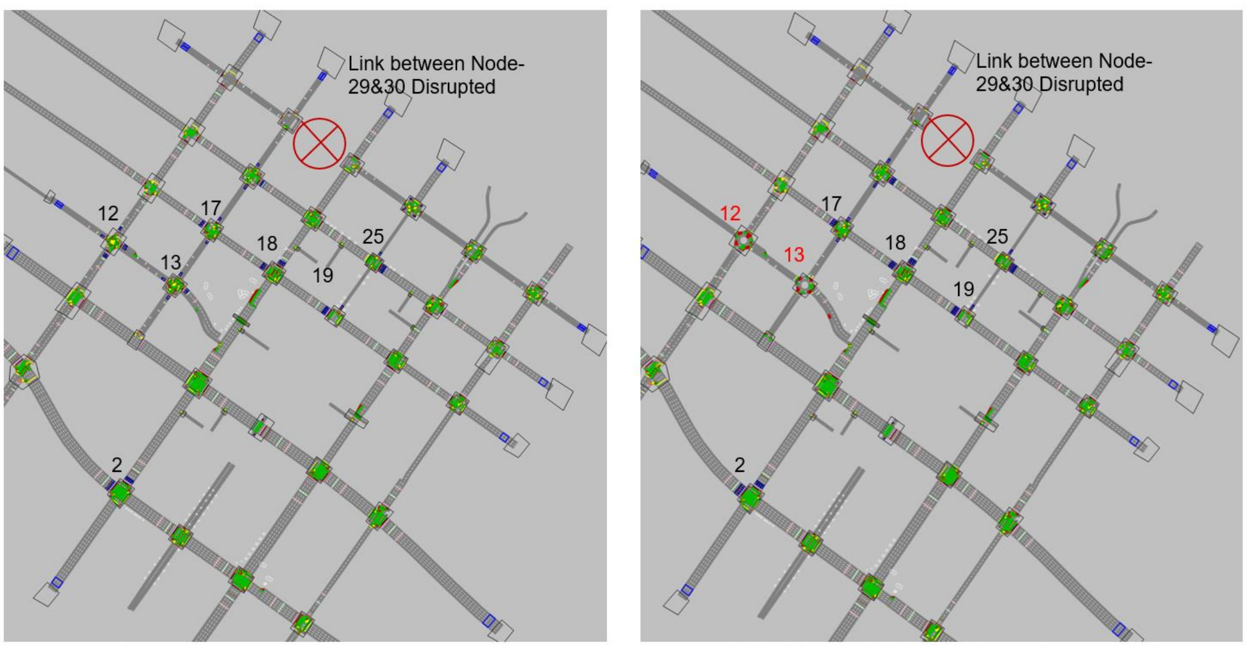


Figure 19: System Performance Comparison Between Just Actuated RBC Implementation and Roundabout Implementation in Scheme-5 of 1st Disrupted Network

A similar situation is observed from Figure 21 where due to reconfiguring 2 nodes into roundabouts, a better recovery is formed than when those nodes were converted into actuated RBC. Thus, this hybrid traffic control mechanism increases network resilience. The reason of reconfiguring only two nodes among 8 other nodes is because as per typical non traversable, without a truck apron, circular roundabouts tend to have approached lanes on all its legs. In this network, from Figure 20(a), it can be observed that among 8 of those intersections as per full weighted ranking of 2nd disrupted network, only node-12 & 13 are four legged intersections. For this reason, only two roundabouts are implemented in this 2nd disrupted network.



(a) 2nd Disrupted Network with 8 nodes converted into actuated RBC

(b) 2nd Disrupted Network with 6 nodes converted into actuated RBC and nodes-12&13 converted into roundabouts

Figure 20: 2nd disrupted network (with and without roundabouts)

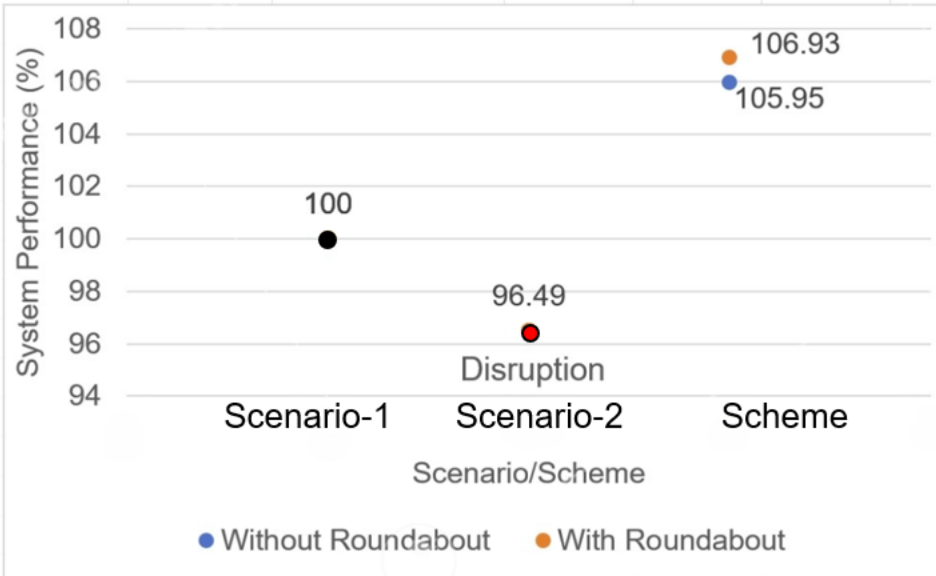


Figure 21: System Functionality Comparison Between Just Actuated RBC Implementation and Roundabout Implementation in Scheme-5 of 2nd Disrupted Network

So, in both disrupted networks, implementing roundabouts increases the network efficiency more than it did just by converting into actuated RBC.

Chapter-5

5.1 Conclusion

This study presents a new traffic control mechanism for improved level of service and resilience in road networks based on topological credentials i.e., rank of relative importance (i.e., node centrality) of network elements such as intersections. The goal is to systematically improve the network performance by adopting specific network intervention strategies (i.e., signal controller setup and roundabout) at certain intersections based on centrality and observing performance metrics such as system travel time and Level of Service (LOS). The study considers the Boise downtown network in Idaho to run these experiments in a simulated environment using Dynamic Traffic Assignment (DTA) for two specific scenarios (i.e., normal and disrupted) under different schemes using different topological credentials. Results indicate interventions (i.e., changing fixed-time Ring Barrier controllers into actuated Ring Barrier Controller) made at certain intersections improve system performance as well as resilience of the network. Moreover, a much better travel time and delay reduction is observed when the network is hybridized using both actuated and roundabouts at certain intersections based on topological credentials of the network. In terms of topological credential, the study also shows that using same centrality metric (i.e., betweenness centrality) as well as the ranking and system performance can change when different combination of edge weight (DHV) or node weights (total maximum green signal time) are introduced into the network. However, it is found from this study that the ranking based on full weighted betweenness centrality measurement ranking gives the most improved network performance in terms of reduced total travel time, total delay, and increased number of turning and through movements LOS compared to other topological ranking. When 8 nodes are converted into actuated RBC using full weighted BC ranking, a 6.7% reduction in total travel time, 7.8%

reduction in total delay and 96 node movements (through and turning movements) LOS improved out of 175 node movements. But with the addition of roundabouts in 3 nodes (based on ranking and that meets the 4-legged entry lane criteria) and keeping 5 nodes in actuated RBC and the rest in fixed RBC, a higher reduction in total travel time (7.8%), total delay (8.8%) and increased number of node movements LOS (103) improved is observed. Under disrupted condition, two disrupted networks are formed by removing edges based on unweighted and edge-weighted betweenness centrality ranking. The highest central edge based on edge-weighted betweenness centrality produced the worst-case scenario or highest disruption (96.45% network efficiency) when removed from the base network (100% efficiency) compared to when edge is removed using unweighted betweenness centrality ranking (96.76%). After scenario analysis of the network under different intervention schemes, the study observed a 105.95% efficiency in the system performance of the disrupted network from its 96.49% disrupted condition. Similar analysis with roundabout on disrupted network was conducted which increased the system performance of the network (106.93) more than that when intersections were only reconfigured into actuated RBC (*30*).

The number of interconnected nodes and the degree of nodes (i.e. intersections changes based on network importance still need exploration for systematic network improvement. Moreover, future studies should explore beyond nodes and focus on overall network properties such as radius, density, alternative edges, etc. While this study has identified key nodes and effective signalization controllers, more traffic control mechanisms need to be assessed in monitoring network performance.

5.2 Limitations

Optimizing traffic flow at busy intersections requires managing green light duration effectively. Often, green light times may be extended during saturation to minimize startup and clearance times, thus maximizing intersection throughput. The amber light also needs to be long enough to allow drivers to comfortably decelerate. In an actuated signal control system, the light duration is determined by programming logic based on information from detectors. However, these systems treat each intersection as an isolated entity, not considering the broader traffic network, which can lead to capacity reductions at adjacent signals if not synchronized properly. One solution is signal coordination, which considers traffic load at nearby lights, allowing groups of vehicles, known as platoons, to cross intersections uninterruptedly. This method increases traffic volume capacity and uses machine learning algorithms in a centralized system to optimize traffic flow. However, this study suggests that simply modifying green timing and cycle lengths, even while adhering to the Manual on Uniform Traffic Control Devices (MUTCD), is insufficient for optimal network improvement. Coordinated signalization, which considers the topological credentials, offers a superior solution as in urban network when intersections are very close to each other, within 1000 feet as per MUTCD, it is better to use coordinated signal timing.

On the other hand, due to time constraints and budget, neither 24 hours volume count nor OD survey could be conducted, which would have given more accurate results, and the calibration could have been done with better precision. The available data from the Idaho Department of Transportation was also not sufficient to carry out a complete calibrated model. The model was initially calibrated by comparing with through volume with the DHV data of the real Boise downtown collected online from the Idaho Department of Transportation. But 85% of the road segment's volume with a GEH value could not be calibrated to greater than 5%. Moreover, roundabouts are usually used for improving safety in road networks or as traffic calming devices. But this study without considering safety aspects and criteria included the roundabouts which can be excluded.

5.3 Future Research

Just like any other research, this study also has more scope for future research. An operational analysis (intersection capacity or turn bay analysis) of the intersections can be done which can recommend whether to include left turn or right turn movement and optimize the signal controller by adding protected phase movements like 1,3,5, and 7 phases after performing flashing yellow arrow analysis (protected and permitted or just permissive movement) in future and compare with the proposed concepts of topological credentials (*66*). For this a thorough 24-hour traffic counts and turning movement counts for each intersection are needed. Moreover, an OD survey for OD matrix along with traffic count data can be conducted which will help calibrate the model producing more accurate results than mentioned previously. Furthermore, a study on improving the network performance by a combination of signal improvement and lane reconfiguration (directional changes or addition of lanes) using hybrid topological credentials and comparing between the results can be explored in the future. Moreover, with Dynamic Traffic Assignment, a simulated travel time with different time periods can be shown which can be compared with the original traffic condition to produce more real result. In future, roundabouts can be included considering the safety aspect of traffic modeling.

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APPENDICES

APPENDIX A: Ranking of edges using unweighted and edge weighted betweenness centrality values under base condition.

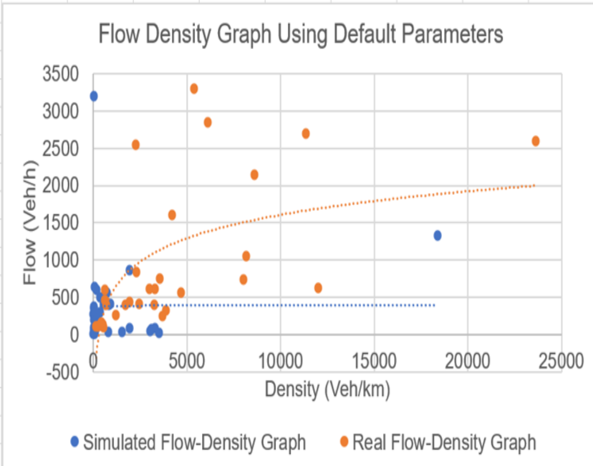
Rank	Edge	Unweighted Betweenness Centrality	Edge	Edge-weighted Betweenness Centrality
1	(18, 19)	0.147	(29, 30)	0.417
2	(14, 18)	0.145	(31, 30)	0.413
3	(8, 14)	0.133	(17, 23)	0.400
4	(20, 19)	0.133	(13, 17)	0.396
5	(8, 9)	0.119	(23, 29)	0.386
6	(11, 21)	0.118	(25, 31)	0.348
7	(25, 24)	0.114	(19, 25)	0.307
8	(18, 24)	0.110	(20, 19)	0.282
9	(9, 10)	0.108	(13, 14)	0.222
10	(17, 18)	0.104	(12, 13)	0.220
11	(25, 26)	0.100	(8, 14)	0.176
12	(15, 20)	0.098	(15, 20)	0.161
13	(2, 8)	0.093	(20, 21)	0.136
14	(23, 24)	0.090	(31, 32)	0.136
15	(13, 17)	0.086	(10, 15)	0.116
16	(20, 26)	0.085	(6, 12)	0.114
17	(10, 15)	0.085	(11, 21)	0.110
18	(2, 3)	0.084	(32, 33)	0.098
19	(17, 23)	0.079	(2, 8)	0.092
20	(20, 21)	0.078	(28, 29)	0.087
21	(1, 2)	0.075	(12, 16)	0.076
22	(7, 8)	0.075	(5, 11)	0.068
23	(21, 27)	0.073	(7, 13)	0.061
24	(3, 4)	0.073	(4, 10)	0.060
25	(19, 25)	0.071	(1, 6)	0.057
26	(12, 16)	0.070	(27, 33)	0.053
27	(10, 11)	0.068	(2, 3)	0.043
28	(6, 12)	0.068	(8, 9)	0.041
29	(4, 10)	0.067	(25, 26)	0.038
30	(24, 30)	0.065	(22, 28)	0.034
31	(31, 30)	0.065	(21, 27)	0.034
32	(7, 13)	0.059	(23, 24)	0.032

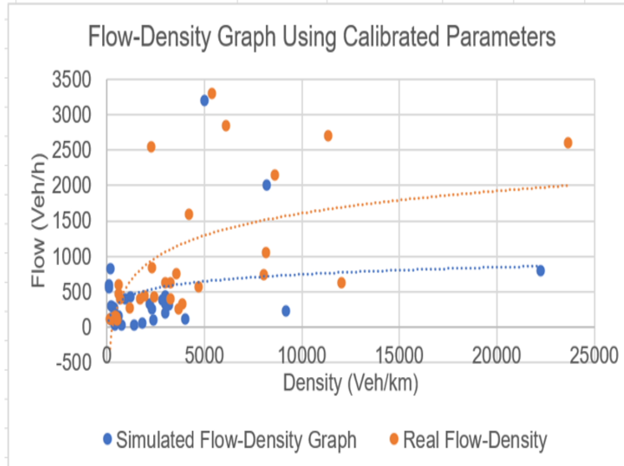
33	(16, 17)	0.059	(17, 18)	0.030
34	(13, 14)	0.059	(18, 19)	0.028
35	(16, 22)	0.058	(25, 24)	0.027
36	(31, 32)	0.058	(16, 22)	0.023
37	(25, 31)	0.057	(3, 4)	0.022
38	(29, 30)	0.055	(9, 10)	0.020
39	(26, 32)	0.053	(4, 5)	0.015
40	(22, 23)	0.053	(20, 26)	0.011
41	(5, 11)	0.053	(10, 11)	0.008
42	(26, 27)	0.053	(22, 23)	0.008
43	(1, 6)	0.052	(26, 27)	0.008
44	(23, 29)	0.052	(1, 2)	0.004
45	(12, 13)	0.045	(26, 32)	0.004
46	(27, 33)	0.042	(18, 24)	0.002
47	(6, 7)	0.040	(6, 7)	0.000
48	(22, 28)	0.037	(7, 8)	0.000
49	(28, 29)	0.035	(16, 17)	0.000
50	(4, 5)	0.033	(14, 18)	0.000
51	(32, 33)	0.033	(24, 30)	0.000

APPENDIX B: Through Volume Calibration

Serial No	Name & Link Segment Distance (ft)	Avg (vehicle/hour)	DHV	GEH	Remarks
1	1: Bannock - 98-131	380	396	1	<5
2	1: Bannock - 1476-1509	21	444	28	>5
3	1: Bannock - 1870-1903	23	564	32	>5
4	1: Bannock - 2625-2633	61	264	16	>5
5	4: 6th - 591-621	440	620	8	>5
6	7: 8th - 591-620	82	100	2	<5
7	9: 10th - 1575-1603	100	114	1	<5
8	10: 11th - 427-451	29	140	12	>5
9	21: 10th - 1608-1608	132	114	2	<5
10	60: 8th - 262-271	310	320	1	<5
11	123: 9th - 1214-1246	113	1600	51	>5
12	124: 9th - 131-140	276	1050	30	>5
13	138: Idaho - 1936-1952	151	400	15	>5
14	139: Idaho - 689-694	301	750	20	>5
15	184: 6th - 394-402	320	400	4	<5
16	185: 6th - 164-172	590	630	2	<5
17	210: Idaho - 656-679	249	620	18	>5
18	272: Capitol - 295-300	550	734	7	>5
19	300: Myrtle - 3609-3629	397	2550	56	>5
20	301: 6th - 558-565	330	420	5	=5
21	331: 9th - 1181-1193	830	840	0	<5
22	341: Grove - 787-806	100	110	1	<5
23	357: 11th - 328-342	420	470	2	<5
24	359: 11th - 197-222	200	250	3	<5
25	374: Main - 984-1008	228	600	18	>5
26	375: Capitol - 1214-1228	144	160	1	<5
27	377: Myrtle - 558-591	789	2850	48	>5
28	377: Myrtle - 1345-1371	288	2700	62	>5
29	380: Front - 787-820	2000	2150	3	<5
30	380: Front - 1148-1181	164	2600	66	>5
31	380: Front - 3182-3188	3200	3300	2	<5

APPENDIX C: Difference in Flow-Density Curve due to Calibration





APPENDIX D: Ranking Based on Unweighted and Edge-Weighted Betweenness Centrality values of Nodes Under Base Condition

Rank	Node	Unweighted Betweenness Centrality	Node	Edge-Weighted Betweenness Centrality
1	18	0.239	17	0.418
2	17	0.237	13	0.405
3	20	0.213	29	0.352
4	13	0.196	23	0.324
5	19	0.174	30	0.313
6	26	0.137	31	0.309
7	8	0.136	20	0.241
8	24	0.133	12	0.182
9	10	0.131	26	0.177
10	23	0.129	25	0.171
11	25	0.120	15	0.155
12	7	0.109	18	0.146
13	32	0.107	32	0.141
14	30	0.106	19	0.135
15	15	0.105	10	0.109
16	12	0.105	14	0.088
17	31	0.103	8	0.084
18	29	0.093	11	0.058
19	16	0.088	6	0.056
20	6	0.083	7	0.055
21	9	0.076	21	0.054
22	14	0.071	33	0.054
23	11	0.065	2	0.031
24	21	0.061	27	0.030
25	22	0.055	16	0.027
26	2	0.053	28	0.026
27	33	0.034	3	0.004
28	3	0.026	4	0.002
29	27	0.023	22	0.002
30	1	0.022	1	0.000
31	28	0.020	5	0.000
32	4	0.013	9	0.000
33	5	0.000	24	0.000

APPENDIX E: Ranking Based on Node Weighted Betweenness Centrality values of Nodes Under Base Condition.

Rank	Node	Node Weighted (Total Maximum Green Time) BC Values	Node	Node Weighted (Maximum Green Time of Phase-2)
1	17	0.730	17	0.714
2	13	0.633	13	0.622
3	23	0.618	23	0.604
4	29	0.590	10	0.587
5	10	0.582	29	0.583
6	18	0.540	18	0.548
7	8	0.528	30	0.511
8	30	0.519	8	0.509
9	25	0.491	25	0.489
10	31	0.477	19	0.478
11	19	0.443	31	0.473
12	14	0.432	11	0.426
13	11	0.421	15	0.416
14	15	0.412	14	0.413
15	12	0.402	12	0.391
16	24	0.373	24	0.387
17	7	0.365	21	0.356
18	21	0.340	7	0.350
19	32	0.317	32	0.316
20	16	0.296	2	0.282
21	2	0.287	16	0.279
22	6	0.280	6	0.267
23	3	0.260	26	0.262
24	26	0.260	20	0.260
25	4	0.258	3	0.255
26	20	0.256	4	0.253
27	5	0.256	5	0.251
28	9	0.256	9	0.251
29	22	0.247	28	0.236
30	28	0.247	22	0.235
31	1	0.224	1	0.210
32	33	0.096	33	0.099
33	27	0.000	27	0.000

APPENDIX F: Ranking Based on Full Weighted Betweenness Centrality values of Nodes Under Base Condition

Rank	Node	Full Weighted (DHV & Total Max Green Time) BC Values	Node	Full Weighted (DHV & Max Green Time of Phase-2) BC Values
1	17	1.000	17	1.000
2	13	0.986	13	0.986
3	29	0.949	29	0.942
4	23	0.932	23	0.923
5	31	0.893	31	0.894
6	30	0.889	30	0.894
7	25	0.825	12	0.820
8	12	0.818	25	0.818
9	14	0.762	14	0.764
10	32	0.753	32	0.752
11	2	0.752	2	0.747
12	7	0.738	7	0.740
13	3	0.732	18	0.734
14	18	0.732	6	0.728
15	4	0.731	3	0.727
16	5	0.730	4	0.726
17	6	0.726	5	0.724
18	8	0.724	8	0.718
19	15	0.702	16	0.701
20	19	0.701	15	0.696
21	16	0.698	1	0.687
22	28	0.696	28	0.687
23	1	0.685	19	0.679
24	26	0.676	10	0.655
25	10	0.667	26	0.649
26	22	0.656	22	0.643
27	20	0.646	20	0.606
28	24	0.584	24	0.600
29	33	0.540	33	0.501
30	11	0.507	11	0.473
31	21	0.429	27	0.370
32	27	0.405	21	0.367
33	9	0.000	9	0.000

APPENDIX G: Ranking Based on Full Weighted values of Nodes Under Disrupted Condition.

Rank	Node	Full Weighted BC Values of 1st Destructed Network	Node	Full Weighted BC Values of 2nd Destructed Network
1	23	1	17	1.000
2	13	0.987	13	0.980
3	17	0.966	25	0.881
4	29	0.889	23	0.876
5	30	0.862	18	0.816
6	31	0.853	12	0.812
7	32	0.832	2	0.759
8	12	0.814	19	0.749
9	14	0.777	14	0.747
10	25	0.772	31	0.745
11	26	0.756	3	0.739
12	2	0.741	4	0.738
13	7	0.740	5	0.736
14	6	0.730	24	0.730
15	8	0.729	7	0.723
16	3	0.722	30	0.719
17	4	0.721	15	0.719
18	5	0.719	29	0.715
19	19	0.719	8	0.712
20	15	0.709	6	0.711
21	16	0.698	26	0.697
22	24	0.696	16	0.694
23	1	0.690	32	0.690
24	28	0.689	1	0.670
25	22	0.654	20	0.668
26	18	0.654	10	0.668
27	10	0.650	28	0.660
28	20	0.644	22	0.633
29	33	0.579	33	0.528
30	11	0.520	11	0.508
31	21	0.455	27	0.429
32	27	0.453	21	0.428
33	9	0.000	9	0.000