MODELING AND ASSESSMENT OF STATE-OF-THE-ART TRAFFIC CONTROL SUBSYSTEMS

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ABSTRACT

Traffic signals are one of the vital control elements of traffic management and control systems under purview of Departments of Transportation (DOTs) nationwide. They directly affect mobility, safety, and environmental parameters of the transportation networks. Traffic engineers in DOTs often face pressure for extracting additional benefits from existing signal control equipment, influenced by evident increase in demand and changing traffic patterns. However, they often face difficulties, usually from the maturity of the field equipment, lack of understanding of currently available equipment capabilities, and multitude of market available equipment. Besides issues in everyday operation, the need for improved decision-making process appears during selection and implementation of the future signal-control subsystems. This thesis is focusing on the issues related with the need for extracting additional benefits and improved planning of signal-control equipment deployment. Presented are several methodologies and techniques for modeling and assessing traffic signal controllers and supporting communication infrastructure. Techniques presented in this thesis include Petri Net modeling language, Software-in-the-loop simulation, and Geographical Information Systems. Specific capabilities of listed techniques are coordinated for maximizing their benefits in addressing specific issues. The intended positive effects reflect in enhanced comprehension, numerical representation, and analysis of state-of-the-art signal control subsystems in focus. Frameworks, methodologies, and example cases are presented for each of the specific issues in identified traffic signal subsystems, along with recommendations for further research.
DEDICATIONS

First, I would like to dedicate this thesis to my parents, Novica and Mirjana, for creating a stimulating environment for my development during my childhood and teaching me to value humanity and moral.

I would also like to dedicate this thesis to my professor, Dr Dušan Teodorović, whose passionate spirit guided me toward my current academic path.

In addition, I would like to dedicate this work to another hard worker, Dr Zoran Dindić, whose character and deeds have inspired my constant self-improvement.

Last but not the least; I would like to dedicate this thesis to all my friends around the world, for their eternal belief in me and numerous joyful moments that we have shared so far.
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1. INTRODUCTION

Increasing constraints for the construction of new road infrastructure are imposing higher performance expectations upon deployed traffic management and control systems. Traffic signals are considered as one of the vital control elements of traffic management and control systems. They directly affect mobility, safety, and environmental parameters of the transportation networks. Transportation agencies nowadays are usually responsible for the increasing numbers of signalized intersections, thus often combining them into a traffic-signal control system. These traffic-signal control systems play an essential role in coordinating individual traffic signals to achieve desired operational objectives of an optimal network-wide traffic control.

Evident changes in traffic demands and patterns on transportation networks are often leading to poor safety, operational, and environmental parameters of traffic signal control system. The situation becomes even more complex when Department of Transportation (DOT) is responsible for managing large traffic-signal control systems that have obsolete technology. This underlines the need and pressure for extracting additional benefits from traffic-signal control systems.

In such a situation, traffic engineers often have to take into consideration many factors for improving system performance. Those factors are originating from specific localized requirements and design elements (e.g., human factors, geometric constraints, etc.). In addition to all these factors, there is one critical system component of traffic-signal control system – the actual control equipment.

Traffic engineers often face difficulties with control equipment. Those difficulties can be on an everyday, operational, basis. In addition to this, issues can be related to planning for the next generation of signal control systems. In order to extract additional benefits from existing or successfully establish future traffic-signal control systems, traffic engineers need a thorough understanding of capabilities and requirements that equipment under their purview has. The focus on the equipment factor becomes even more important since traffic engineers are facing constantly evolving state-of-the-art technology. With this in mind, the list of influencing factors just keeps expanding.

Taking a high-level perspective on this thesis research, the author recognizes three interested parties in the field of traffic signal control: governmental agencies (state or city Departments of Transportation), academic institutions (universities or transportation research institutes), and companies (organizations providing transportation related services or products). These three sides are presented on the Error! Reference source not found., marked as .gov, .edu, and .com, respectively. Those parties have a common goal – to positively affect the performance of signal control. These three sides have their area of cooperative overlap, and for the optimal results the synergy of these all sides is essential. DOTs are recognized as directly responsible for the operation of signalized intersections, but they rely on the equipment provided
by the companies and techniques developed by academia. However, the synergy is not always accomplished in practice. A certain area without proper overlap and cooperation among the three sides appears in some cases. That area of non-overlap affects the capabilities of .gov that operate upon the equipment from .com side. This area is where the focus of this thesis research is, since .edu is recognized as the side that can help in casting a light to the non-overlap area. The need for thorough understanding of signal control equipment and its features is exactly in this area, pointed out in red in the following Figure 1-1.

In order to address the need for thorough understanding and assessment of equipment capabilities and requirements, the research presented in this thesis presents the methodologies and techniques for modeling and assessment of traffic control subsystems. Specifically, this research presents methodologies and deploys advanced techniques for purpose of modeling and assessing of traffic signal controllers and supporting communication infrastructure. The techniques implemented are ranging from Petri Net modeling language, Software-in-the-loop simulation, up to the Geospatial Information Systems (GIS).

1.1 RESEARCH OBJECTIVES

The major objectives of this thesis are:

- To develop a model of ring-barrier control structure implemented in the modern Advanced Transportation Controllers (ATC);
- To develop a methodology and deploy techniques for modeling and evaluation of critical operational features of Advanced Transportation Controllers;
• To develop methodology for assessment of future communication requirements of traffic control systems in the case of upgrade of existing signal control equipment.

1.2 THESIS CONTRIBUTION

This thesis conducts a research on several topics related to subsystems implemented in traffic control systems. Specific, aforementioned needs, for enhanced understanding and evaluation of these subsystems are addressed implementing a range of coordinated techniques. This research, aims to improve the decision making process for day-to-day operation of existing and implementation of next generation signal control systems.

1.3 THESIS ORGANIZATION

This thesis consists of five chapters. Chapter 1 presents an introduction, research objectives, and contribution of this thesis. Chapter 2 presents a novel model of ring-barrier structure used in modern traffic signal controllers. Chapter 3 presents multi-scale procedure for assessing control features of the Advanced Transportation Controllers. Chapter 4 presents geospatially based assessment of communication infrastructure requirements in the process of signal control upgrade. Finally, chapter 5 presents the thesis conclusions and recommendations for further research.
2. MODELING RING-BARRIER TRAFFIC CONTROLLERS USING COLORED TIMED STOCHASTIC PETRI NETS

Abstract
As one of the many techniques used in modeling traffic processes and systems, Petri Nets are recognized as a tool for modeling in traffic signal control. In this paper, ring-barrier traffic signal control structure is modeled using Petri Nets. Colored Timed Stochastic Petri Nets is used in this paper to provide additional modeling capabilities. The proposed model incorporates all the main features of ring-barrier structure and includes the modeling of left-turning vehicles. We also describe and discuss possible control structures, previously developed Petri Net models and implementation issues.
2.1 INTRODUCTION

Traffic engineering is an area of transportation engineering dealing with safe and efficient planning, geometric design and traffic operations of roads, streets and highways, their networks, terminals, abutting lands relationships with other motorized and non-motorized modes of transportation. Urban traffic control, as one of the essential parts of traffic engineering is dealing directly with safe and efficient operations of road networks.

Since 1868, when the first traffic lights were installed, up to now, the role of traffic control in the overall national transportation network and traffic management is constantly increasing. Environmentally conscious traffic management, energy saving models and increased computer application in everyday real-time operation are just one of the many trends in urban traffic control throughout the whole world.

Traffic signal systems have always integrated the conflicting duality reflected in two main control goals: safety and efficiency [1]. These two goals have established all the fundamental principles related to traffic signals. Even in the future, most of these traffic engineering fundamentals are not going to change, but in the process of evolution in the operation of transportation facilities, they will be applied in new ways to meet incoming challenges. Today, traffic control technology is developed continuously in order to expand and increase its capabilities and help traffic engineers in more and more complex issues posed in front of them. On the other side, besides the development in the technology itself, a new modeling and optimization techniques, such as artificial intelligence techniques, knowledge based expert systems, and other various operations research and simulation techniques are under constant improvement and development.

2.2 Petri Net Modeling

Petri Net definition

Petri Net is a particular kind of directed, weighted, bipartite graph with specific graphical representation, consisting of two kinds of network nodes, called places and transitions, and arcs which are either from place to transition or from transition to place [2]. Each place is marked with tokens whose movement through the network are used for representation of modeling processes. From modeling perspective, concepts of conditions/states (using places) and events/actions (using transitions) are represented by the network nodes. In the graphical representation, places are usually represented as circles and transitions as rectangles. The advantage of this modeling technique is that it can be state and action oriented at the same time [3]. Petri Nets play a key role among the modeling techniques for discrete event systems because they are able to capture the precedence relations and interactions among the concurrent and asynchronous events. There are various types of Petri Net, from the most common ones up to a
High-level Petri Nets, which are used to increase modeling capabilities and reduce the size of models of ordinary Petri Nets.

**Petri Nets in Traffic Engineering**

Since the 90’s, Petri Nets had been used for addressing issues in traffic engineering such as traffic light planning, dynamic routing, special vehicle control and traffic flow modeling [4]. Petri Nets are also used in other transportation related fields of study, such as for example in automated guided vehicle system for logistical purposes [5].

One of the first papers on the implementation of Petri Net in the transportation modeling was in 1993 [6]. Some papers in the 90’s have also recognized the potential of Petri Nets for safety-related and modular representation of traffic control systems, along with potentials for large-scale transportation systems implementation [7], [8]. All these papers used basic Petri Nets models in their modeling approach. In these very first papers, the universal issues related to traffic control were also discussed. On the one side are the issue of specified safety rules under which controller has to operate, and on the other hand, the issues of flexibility and serviceability of traffic control process. As it is discussed in these papers, both of these issues can be potentially resolved using Petri Nets.

This paper describes the potentials of Petri Nets application in typical traffic control strategies, with developed subnets for traffic control logic and traffic flow representation. Finally, as one of the important contributions of this paper, besides being one of the first to use Petri Nets in the area of traffic control, is that results of the performance evaluation are compared with analytical approaches from Highway Capacity Manual. Safety related issues such as predefined timed color sequence and impossibility of the occurrence of conflicting movements are successfully resolved using Petri Nets and verified with specified analysis methods that are developed for Petri Nets. Furthermore, Petri Nets as a modeling technique has been proven to have properties for providing enough flexibility for modeling the traffic control process.

After these initial papers, other authors started to develop and expand the possibilities of Petri Nets to model traffic control systems by introducing more data diversity and management capabilities into Petri Nets itself [9]. The research was directed toward specific type of Petri Nets - Stochastic Timed Petri Nets (STPN).

STPN, besides introducing the stochastic element in the traffic control modeling, lead to the significant reduction in the complexity of analysis. Stochastic nature of the time in the traffic process has been one of the main reasons for introducing this specialized type of Petri Net, and those issues are successfully resolved with properties that STPN have. On the other hand, this development did not bring in any improvements in the modularity or initial model complexity reduction.

After this, the following papers such as [4] and [10], brought in the idea of implementation of higher level Petri Nets – Hybrid Petri Nets, with an idea that a transportation network per se is considered to be a hybrid system, including both continuous-time and discrete
event components. The most recent developments have lead to the widening of the area of research into Colored Petri Net (CPN) as a more powerful upgrade of basic Petri Nets[3] [11], [12]. Besides implementation in fundamental traffic control models, other papers, have introduced the possibilities of Petri Nets implementation in the area of transit priority and emergency vehicle preemption [13], [14], or even the implementation in the area of micro and macroscopic modeling of traffic flow [15].

**Stochastic Timed Colored Petri Net**

In this research, Stochastic Timed Colored Petri Nets (STCPN) is selected to be a technique for the implementation. STCPN are chosen as a logical continuum of the previous research done in the area of Petri Net implementation in traffic control. STCPN provides primitives for the description of the concurrent processes synchronization and the supporting programming language provides the primitives for the definition of data types and manipulation of data values.

Each STCPN net used in this research consists of net structure, declarations and net inscriptions. Methodology of modeling timed processes in STCPN is based on global clock, which represents model time, and time stamp, which is associated with particular token. This feature allows modeling of deterministically or stochastically distributed time intervals.

All the previous research has lead to the conclusion that STCPN have several advantages:

- Provides means for clear graphical representation of control logic;
- Provides more relevant information using stochastically distributed time;
- Single token caries more complex information or data and thus reduce the size of the models;
- Can be constructed of hierarchically distributed individual sub-models and thus describe more complex systems;
- Has well defined and compact semantics, allowing formal description, analysis and performing of safety and deadlock control analysis; and
- Has available software tool for the analysis.

Petri Nets can therefore be used in the modeling of traffic control for the following reasons:

- Can express concurrency, competition and synchronization in the actions;
- Can implement mathematically defined analysis techniques for verification of control logic; and
- Can be used as a universal and direct graphical medium for communication.
2.3 NEMA Ring-Barrier Control Structure

In traffic control, phases, with all the related control parameters, are the essential mean for conducting the desired control behavior to the system user. The National Electrical Manufacturers Association (NEMA) provides detailed nomenclature for signal phases definition in order to eliminate misunderstanding between manufacturers and purchasers [16]. This is control type usually referred as ring-barrier-phase control or NEMA phasing and is used in North American traffic control implementations.

In ring-barrier control, controllers have five predefined time intervals – green, yellow, red clearance for vehicle movements and walk and flashing don’t walk for pedestrian movements. Each of these intervals has a specified duration and each phase is assigned to compatible vehicle or pedestrian movements. Each of the phases is assigned to a specific ring and to a specific barrier (Figure 2-1).

The logic behind ring-barrier control, defined in phases having different ring or barrier compatibility is as following:

- Phases assigned to the same ring are timing sequentially,
- Rings times simultaneously, and
- Phases designated to different barriers are timing independently.

![Figure 2-1: Dual-ring eight-phase control defined by NEMA nomenclature](image)

Ring-barrier-phase control logic (Figure 2-2) is the essence of any modern traffic signal controller operational structure. From Figures 1 and 2 it is observable that each movement has dedicated and standardized phase number. This standardized representation of control logic easiness programming, modeling and calculating of signal control parameters. In addition, this standardized representation is enhancing communication among traffic engineers.
Because of the high importance of previously described control structure, there is a need to adequately represent and model its control behavior. For example, the recent development in the new techniques for representing traffic control systems is reflected in the usage of precedence graph models [17]. Proposed precedence graphs are illustrating the interactions among phases, intervals and overlaps, from a simple three-leg intersection up to the example of advance flashing warning signals. The idea of this implementation is, using a structure-modeling approach, to create a representation that is leading up to a better understanding and improved development of signal control logic.

Using the similar idea as one of the basic premises, one of the techniques receiving more and more significance in the area of traffic control throughout the world is Petri Nets. Initially used in various expert areas, such as computer applications, protocol and operational process modeling implementations, this technique has found its place among the other techniques for modeling and simulation of traffic related processes and systems.

**Model Formulation and Development**

All the previous Petri Net models found in the literature are based on the control logic that is not directly used in North American NEMA standard. The model presented in this paper is representing structure that ring-barrier control has. The essential premises behind ring-barrier structure to disable certain conflicting vehicle movements while leaving enough flexibility for efficient control are imbedded in the logic of the Stochastic Timed Colored Petri Net model presented here.

In using Petri Nets to model certain system, modeler usually takes two different perspectives to model the system and its behavior. Those perspectives are based on the features of the modeled system and can be recognized as modeling flow of control or modeling flow of data.
In this particular case, and taking into consideration all the features that NEMA ring-barrier control system has, the researchers have decided to take the approach of modeling the flow of control. Here it also has to be stated that top-down design approach has been applied, in an attempt to break down the system into smaller sub-systems. These approaches consequently lead to specific modeling results.

Analysis of the modeled control system has produced a list of definite system features and components. Besides certain system features and components, that represent real life system, some of the system features are assumed or omitted. Assumption or omission of certain system features is not disrupting general system behavior or its safety related features, since all the features not represented in this model are related to greater system efficiency and flexibility. The premise behind this is that safety features of the traffic control system have primary role over any efficiency related feature.

As previously stated, the model’s intention is to represent the logic imbedded in the traffic signal controller on the isolated signalized intersection. An intersection is considered to be fully-actuated with detection mechanisms located on all major and minor approaches. Separate stop bar detectors are placed in each through and left turning lane. In addition, advance detectors are placed upstream in through lanes (Figure 2-3). This is the usual practice in detector location for fully actuated signalized intersections.

The initial assumption is that the ring-barrier control structure consists of eight signal phases. All the phases are assigned to specific vehicle movements. Vehicle movements considered in this model include both, vehicles going straight through the intersection and vehicles turning left in the intersection.

Vehicles turning right in the intersection receive the same phase timing as vehicles going straight through the intersection since no right turn on red is allowed. This model is the first model to consider representing left turning vehicles. The guiding idea behind this implementation is that omitting modeling vehicles in left turn significantly reduces the validity of the real world model representation and its safety/efficiency related features, thus reducing the model’s fidelity. On the other hand, inclusion of left turning vehicles is significantly complicating the modeling process and the model itself.
One of the assumptions made in this model is that no pedestrian signals exist on the signalized intersection under consideration. This of course does not mean that pedestrian flows do not exist or cannot be served on the intersection, but it means that pedestrian flows are referred to use the vehicle signal indications. Furthermore, because of the previously stated assumption, no pedestrian detectors are assumed to exist on the intersection. Nevertheless, signal timing logic is taking into consideration pedestrian movements in the duration of minimum phase timings.

Another assumption is that both barriers start timing with the phases dedicated for through movements – phase 2 and 6 for barrier 1 and phase 4 and 8 for barrier 2. Through phases in each barrier separately are also defined as dual entry phases. This means that call for any of two groups would also activate the other group signal in the absence of calls on the predefined detectors of non-conflicting groups.

STCPNs used for the model creation, as a discrete modeling technique, support stochastic nature of the traffic process on the signalized intersection. That stochastic nature of traffic process reflects in the distribution of vehicle inter-arrival times, which are assumed as exponentially distributed. Each particular vehicle arrival is assumed that places a call on the detector located in front of the stop bar. A detector call is assumed to be a signal, translated and conducted from particular detector unit to the controller’s processing unit. As previously stated, because of the detector configuration, detector signal for trough and left turning lanes are separated. Vehicle that arrives on the approach and places a call for a specific direction, in the absence of all previous un-served calls (vehicle waiting in the queue) will assure the activation of particular phase and at least duration of minimum green.

Actual phase indication that will appear on the intersection signal head will depend on the simultaneous/asynchronous calls on other phases, previous phase activated, minimum and
maximum duration of a particular phase and moment in system time. System time in the model is represented via global clock that is operating for the complete model. Global clock changes timing in discrete intervals depending on the particular timings in the model nodes. All of the model tokens have their own time represented via time stamp and they define the time steps at which model global clock is changing value.

Signal head indication, as previously stated, is directly depending on the tokens that represent different detector actuations in time and space. Change of the signal status is controlled by safety features of ring-barrier structure and is only possible if all the conditions for change are met. Constraints in the conditions are represented using different combinations of arcs and transitions in the model.

It has to be stated that the model represents only the control logic and not the movement of the vehicles through the intersections. The reason for this is that modeling of vehicle movement through the intersection is not going to directly provide benefit by improving model capabilities or potential outputs. Modeling of vehicle movements through the intersections is planned for future improvements of the model. At this point, the assumption is that modeling of vehicle movements would require modularity of the model that could be also implemented in Colored Petri Net having in mind this modeling technique has the ability to represent such a structure.

2.4 Proposed STCPN Model

Developed model, being a Stochastically Timed non-hierarchical Colored Petri Net is a tuple STCPN = (CPN, R, r0) that is consisting of:
CPN = (Σ, P, T, A, N, C, G, E, I) defined as:
Σ – finite set of color sets
P – finite set of places
T – finite set of transitions
A – finite set of arcs (P ∩ T = P ∩ A = T ∩ A = ∅)
N – node function P x T ∪ T x P
C – color function
G – guard function
E – arc expression function
I – initialization function

All these elements are specific for Colored Petri Net as a modeling technique and the software where model was developed – CPN Tools. In addition, model is consisting of global color set/variable declarations and functions based on Standard Modeling Language. One of the functions is a function for generating inter-arrival times by exponential distribution used on the transitions as a node function.
fun ExpTime (mean: int) =
  let
    val RealMean = Real.fromInt mean
    val rv = exponential(1.0/RealMean)
  in
    floor (rv+0.5)
  end;

Petri Net Construction and Refinement

As previously stated, the top down approach for model development has lead to structural and behavioral analysis of the control structure. Each of the analyzed parts of ring-barrier concept are modeled using specific Petri Net sub-network. Since safety concepts are given a prime role, initial model sub-networks were created to fulfill constraints that ring-barrier logic imposes on the conflicting vehicle movements.

The envisioned model representation of ring-barrier control is based on the control logic presented in the Figure 2-2. General model representation is presented in Figure 2-4. Places B1 and B2 represent state of the control mechanism with activated barrier 1 or barrier 2, depending on the vehicle actuations. Simulation process starts in the barrier 1 but the network configuration should allow transitioning from and returning to initial state. Transitioning between barriers is constrained with a specific set of actions taken and conditions fulfilled.

Figure 2-4: Overall Petri Net model

Further structural development of the model resulted in the several sub-networks. Some of them are presented in the Figures 2-5, 2-6 and 2-7. A sub-network in Figure 2-5 represents inner control structure of barrier 1. The idea for generating vehicle arrivals that are translated
into detector calls, as previously mentioned, is developed and implemented in this sub-network of the model. Stochastic vehicle arrival process is located in the place named Arr. The generation of detector calls for activating phases from barrier 1 and 2 is separated thus resolving the possible issue of conflicting detector calls.

Sub-network is also defined in such way that signal timing is updated each time vehicle is served. Vehicles in the specific lane receive green time until the temporal gap between successive arrivals of detector calls is higher than predefined minimum (gap out) or until the green time reaches maximum allowable timing (max out). Presence of token in one of the places 2+6, 2+5, 1+6 or 1+5 is representing the activation of that specific phase combination. Each token carries information about the duration of phase timing. Dashed transition and arc on the left side of the figure represents the idea that phases 2 and 6 are the first one to be activated in the barrier 1. Dashed transitions T2 and T1 on top and bottom of the picture, respectively, represent the transitioning between barriers.

Furthermore, in the process of control structure analysis, additional sub-networks are created to resolve the issues of asynchronous detector calls (arrival of vehicles) in the same barrier. In the ideal case, simultaneous arrival of vehicles from different approaches would activate specific phase from a specific barrier. Since arrival of vehicles is random, in majority of cases the arrival of vehicles is not simultaneous. Figure 2-6 presents an example how is the issue of asynchronous detector calls for phases 2 and 6 from barrier 1 resolved using network structure. As previously assumed, phases 2 and 6 are dual entry phases.
Additional sub-network is presented in Figure 2-7. The intention of this sub-network is to resolve control priority between phases that serve through and left turning movement. As previously stated, phases controlling through movements on the intersection are timing together and before other phases in the particular barrier. The restrictions are primarily modeled by controlling transition firing.
Model Analysis using Petri Nets techniques

During the control structure analysis and model creation, as previously stated, safety features of the NEMA ring-barrier structure are considered as the most important. Specifically speaking, control structure should not allow simultaneous movement of conflicting vehicle flows, should not deadlock in the specific state, should be able to return to initial state and should allow changes in the control output only when specific conditions are met.

Petri Net, as a modeling technique, has predefined properties that can be related to the expectation of model behavior and that can be investigated using several validation methods. All the validation methods have defined semantic and logic that can be implemented with software used in the model creation. In this particular case, discrete transition-based simulation, as a user-friendly and visually based tool for investigating model behavior, is chosen as an initial validation tool in the process of model development. Furthermore, specific developments of network structure, token colors assigned, and codes accompanying the network itself are introduced to restrict simultaneous movement of conflicting vehicle flows and allow the influence on the control output.

Final model validation using coverability tree method has confirmed that networks created are alive and able to return to initial state, thus preventing the occurrence of deadlock in the system. At the end, investigating the structural model properties it is confirmed that net is bounded, conservative, repetitive and consistent which provides additional real life implementation value to the model.

Figure 2-8: Graphical representation of coverability tree for Petri Net sub-network representing barrier 1
2.5 Conclusion and Future Work

The developed Petri net model is based on the analysis of the ring-barrier control structure. The model captures the current practices in US signal traffic control and includes modeling of 8-phase full NEMA controllers, including left turning vehicles’ phases. The model establishes the groundwork for developing new features in next generation controllers, and provides a mechanism for documenting and communicating these features to other researchers and developers.

There are many possibilities for applying the model and expanding its capabilities. Future work includes further model expansion with the goal of introducing optimization capabilities, testing of the model with the field data and comparison to commercially available simulation software.

References


Abstract
In order to extract additional benefits from a signal control system, traffic operation engineers need enhanced understanding, analytical representation, and verification of traffic signal controller capabilities. This paper proposes methodology for providing in-depth information based on integration of Petri Net modeling and Software-in-the-loop simulation (SILS). These two techniques are recognized as capable to coordinate model and assess control capabilities. The proposed methodology is tested on the market 2070 Advanced Transportation Controller firmware preemption features. Combined analysis from Petri Net discrete simulation and network topology along with testing and verification conducted using SILS is presented. Conclusive findings and possibilities for further research should introduce these techniques as tools for enhanced graphical logic representation, comprehension, and guided testing in the process of assessing unknown traffic signal controller capabilities.
3.1 Introduction

Modern traffic signal controllers are an essential element of signal control subsystem in an Intelligent Transportation System (ITS). As an important element of one ITS, controllers directly affect its safety, efficiency, and environmental parameters. Traffic signal controllers are facing increasing traffic demands and changing traffic patterns. Relations become even more complex when a large number of signalized intersections in the signal control subsystem have obsolete technology. In addition, the desired system operations are often expressed in vague or overly broad functional requirements (FR). In such a system, traffic operations engineers often face issues with underused, improperly used, esoteric, or controller features that fail to work as intended. In such an environment, traffic engineers have to be able to assess both controller hardware and firmware capabilities in order to extract additional benefits from traffic signal controllers.

From the other perspective, rapidly evolving technologies are introducing more technological complexity. Throughout the last two decades, the Institute of Transportation Engineers (ITE), National Electrical Manufacturers Association (NEMA), and American Association of State Highway and Transportation Officials (AASHTO), have supervised a standardization effort in the area of traffic signal controllers. This standardization has introduced the Advanced Traffic Controller (ATC) standard. This standard has clearly defined an area of signal cabinet, controller, engine board, and operating system, with all the modular components. However, the area of signal control firmware has been under high influence of application development competition between third-party software developers. That competition lead to the multitude of signal control firmware that adds to the complexity in assessing the components of a signal control system.

The desire to enhance the utilization of existing controller features obviated an essential need for an assessment of signal controller firmware features. In addition, the assessment should promote development and introduction of novel controller features, consequently leading to the improvement of the system’s and user’s efficiency, safety, and environmental parameters in a specific ITS. In light of all the complexities introduced from the perspective of users and vendors, the research presented here is focusing on improved assessment process. This paper is presenting the methodology and specific techniques for conducting multi-scale controller firmware assessment. This in-depth assessment is considered as essential for obtaining informed, defendable, and ultimately, optimal solutions that would shape current and next generation control system.

3.2 Proposed Framework and Methodology

A developed framework for the assessment of controller capabilities is based upon the need for having significant amount of validated and verified information that would
consequently be used as an input to the defendable decision-making process. At the beginning of the assessment process, traffic engineers with an expertise in signal control should develop FR of desired control system. FR are directly related to specifics of spatial traffic patterns and existing controller features in current implementation. Further, FR translate into technical system requirements, and classify into different groups with respect to specific controller features.

The multi-scale assessment process is based upon four steps: modeling, analysis, testing, and verification of controller firmware capabilities (Figure 3-1). According to the suggested four-step framework, the methodology developed should include a combination of techniques for accomplishing the desired goals. Those techniques should be able to enhance the assessment process by inducing higher understanding, generating additional analytical information, and by revealing possibilities for adjustment or improvement. In addition, specific techniques should also be able to illustrate the dynamic of controller operation. The research team decided to integrate two applicable modeling/simulation techniques – Petri Nets modeling and Software-in-the-loop simulation. The brief description of these techniques and the reasoning for their combined introduction are presented in the next two sections.

![Figure 3-1: Iterative Input to Controller Capabilities Assessment Process](image)

**Colored Timed Petri Net**

Petri Net is a particular type of directed, weighted, bipartite graph with a specific graphical representation that is a network consisting of two types of nodes: places and transitions. There are also arcs that connect nodes from place to transition or from transition to place [2]. Each place is marked with tokens whose movement through the network is used for the representation of the modeling processes. From the modeling perspective, network nodes represent the concept of conditions/states (using places that are represented as circles) and events/actions (using transitions that are represented as rectangles). Petri Nets as a modeling
technique can be simultaneously state and action oriented [3]. Petri Nets already play a significant role among the modeling techniques for discrete event systems because they are able to capture precedence relations and interactions among the concurrent and asynchronous events [18].

There are various types of Petri Nets, but this research selects Timed Colored Petri Nets (TCPN) [3] for the implementation. \textit{Timed} is related to token capabilities to contain the time information, while \textit{Colored} is related to ability to represent specific data set. TCPN provide primitives for the description of concurrent processes synchronization. Supporting functional programming language used - CPN Modeling Language (CPN ML), an extension of Standard ML - provides primitives for the definition of data types and manipulation of data values [18]. Each TCPN consists of three elements: net structure, declarations and net inscriptions. Methodology of modeling deterministically timed processes is based on global clock and time stamps. Global clock represents general time of the model. Time stamps are associated with particular token and their change depends on the firing of the transitions.

Petri Nets have been a proven technique for implementation in traffic related modeling. In the last two decades, Petri Nets have been used for addressing various engineering issues in traffic signal control, dynamic routing, special vehicle control and traffic flow modeling [4, 6-8, 12, 13, 15, 19]. Petri Net would contribute to the modeling and analysis steps of assessment procedure by providing additional understanding of controller features due to several reasons:
- Petri Nets can dynamically express concurrency, competition and synchronization in the actions,
- Petri Nets can provide mathematically defined analysis techniques for compact logic verification,
- Petri Nets are universal communication medium and provide means for clear graphical logic representation,
- Petri Nets can provide relevant information using timed processes.

\textbf{Software-in-the-loop simulation}

Software-in-the-loop simulation (SILS) is a generally known technique implemented in testing procedures in different scientific fields. A system of microscopic traffic simulation model, virtual traffic controller and interface for communication between these two components comprise SILS in its application to traffic simulation [20]. This system combines the advantages of microscopic simulation software and virtual traffic signal controller. Traffic signal controller in SILS bases on the virtual software replica that has the identical operational logic as real controller firmware. The main components of software-in-the-loop emulator used in this research are virtual controller and virtual database editor. Virtual controller is the core of the SILS and consists of Dynamic-link Library that microscopic simulation software uses to simulate signal control logic of ATC 2070 controller. The database editor is a Graphical User Interface that allows viewing, editing and printing traffic signal database of the virtual controller.
Previous research in the field of evaluation of signal features has used mostly hardware-in-the-loop simulation (HILS). HILS is similar to SILS, except it uses controller input through hardware connection [21-23]. SILS, on the other hand, is a part of establishing state-of-the-practice for assessment of generally known controller features and their impact on efficiency parameters [24, 25]. The reasoning behind implementing SILS (compared to HILS) is that it has the same flexibility for different testing scenarios with less application complexity than HILS. The SILS flexibility originates from independence from real-time hardware interfacing.

SILS is the technique able to uncover problems and increase confidence in the defined controller specifications. In this methodology, SILS is an ideal tool for testing and verification of operational usefulness and usability of selected controller features. Information obtained from Petri Net analysis is envisioned to coordinate work with SILS, enhancing the verification process through input of purified information and thus providing analytical depth.

### 3.3 Modeling and Analysis Using Petri Net

Modern traffic signal controllers have over 200 control parameters settings. For the purpose of this research, we are focusing on example cases of ATC firmware Preemption features for emergency vehicles.

**General modeling approach**

Preemption (PE) is defined as a fully guaranteed termination of normal signal traffic control operation and transfer to a special control operation mode, for the purpose of servicing rail vehicle, emergency vehicle, mass transit vehicle passage, and other special tasks (e.g., certain non-intersection locations such as at approaches to one-lane bridges and tunnels, movable bridges, highway maintenance and construction sites, metered freeway entrance ramps, etc.) [26, 27]. FR for PE operation in this example is a need for greater flexibility and maximizing emergency response. Implementation of a system analysis on the PE process identified three distinct stages as Transitioning in, Serving (Dwell), and Transitioning out. Modeling required decomposition and/or abstraction of selected controller features.
In analysis, programmable controller features were distinguished between time-related and phasing-related options, leading the decision to represent phasing options as places and timing options as transitions and their associated delay functions. Each token entering the Petri Net model represents one special vehicle call with a specific priority level. During the analysis of controller features, some of the controller features that are standard for all the controllers (e.g., some clearance times) were disregarded in the model development. PE detection input had check-in/check-out operation mode. The shortening or omission of yellow change or red clearance interval is not allowed during transitioning. Finite minimum/maximum times constraining PE duration are preconfigured in the model settings.

**Petri Net Construction and Refinement**

Specialized software CPN Tools has been used in the actual process of Petri Net modeling [18]. Representation in the software is according to standard Petri Net modeling principles where circles are network places and rectangles are network transitions. The model’s network places are listed in Table 3-1: N.

**Table 3-1: Network Places**

<table>
<thead>
<tr>
<th>Places</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Call generated</td>
<td>Track Clearance</td>
</tr>
<tr>
<td>Re-service Inhibit Same</td>
<td>Track Clearance Extend</td>
</tr>
<tr>
<td>Re-service Inhibit All</td>
<td>Track Clearance Max</td>
</tr>
<tr>
<td>Call Received/Recognized</td>
<td>Start Dwell</td>
</tr>
<tr>
<td>PE activated/Finish Phase</td>
<td>Dwell Extend</td>
</tr>
<tr>
<td>Change Phase Next</td>
<td>Exit Pedestrian Clearance</td>
</tr>
<tr>
<td>Serve Next Phase Min</td>
<td>Exit Yellow</td>
</tr>
<tr>
<td>Give Min Green for Next Phase</td>
<td>Exit Red</td>
</tr>
<tr>
<td>Phase Early Walk to Green</td>
<td>Exit Phase Call</td>
</tr>
<tr>
<td>Exit to Coordination without</td>
<td>Exit to Early Ended Phases</td>
</tr>
<tr>
<td>Force Off violation</td>
<td>Exit to Coordination</td>
</tr>
</tbody>
</table>
Besides places, controller features are represented with transitions. Most transitions have delays assigned, since they are related to controller timing settings. These delays are changing token’s time stamps after the firing from a particular transition. Delay timing settings are set in seconds, and are defined as integer data type. Multiset consisting of token color is defined as colset DATA = with P1|P2 timed. P1 and P2 represent different colors, i.e. different PE calls and timed means they are timed tokens. In this case, DATA is defined color set for tokens used in modeling. Variable \( n \) assigned to network arcs is defined as \( \text{var n: DATA} \). Delays are coded using “@+” operand next to the transitions with the accompanying CPN ML as:

\[
\begin{align*}
\text{val Delay} & = 5: \text{INT}; \\
\text{val Start\_Walk} & = 1: \text{INT}; \\
\text{val Start\_PC} & = 12: \text{INT}; \\
\text{val Track\_Clearance} & = 10: \text{INT}; \\
\text{val Min\_Dwell} & = 10: \text{INT}; \\
\text{val Dwell\_Extend} & = 10: \text{INT}; \\
\text{val Next\_Phase\_Min\_Green} & = 10: \text{INT}; \\
\text{val Exit\_PC} & = 0: \text{INT}; \\
\text{val Exit\_Yellow} & = 0: \text{INT}; \\
\text{val Exit\_Red} & = 0: \text{INT};
\end{align*}
\]

Figures 3-3 to 3-5 show typical graphical representation in CPN Tools modeling window. Figure 3- shows transitioning in process, with places for generation of PE call, decision upon re-service inhibition, call receiving, and activation of PE.

Figure 3- depicts the continuation of transition in with change next phase, serve next phase, phase early walk to green, and track clearance timing.

Figure 3- shows the continuation of the PE process with dwell extend option exit pedestrian, yellow and red clearance. Finally, four transition out options are depicted, as Normal – exit phase call, Next – exit to early ended phase, In Step – exit to coordination, and In Step Programmed – exit to coordination without violation of force off points. The very act of constructing the model leads to new insights into system operation, providing the modeler with more elaborate understanding of the system.
Figure 3-3: Initial part of Transition In process

Figure 3-4: Transition In and Dwell
An initial overview of following figures reveals the role of specific programmable options in the overall PE process. The initial significance these models have is the possibility for utilization as a visual communication medium. This could accompany verbal discussions among engineers, consequently improving the understanding of features, their place in the overall process, and improve the presentation of design ideas.

**Petri Net specific model analysis**

Besides additional insight obtained through the model development process itself, further exploration is based upon: 1) network ability to produce different token timing from discrete transition-based simulation, and 2) network structure topology reflected in the incidence matrix.

Discrete transition-based simulation is performed using CPN Tools in-built simulation engine that has a single step, fast forward and backward simulation capabilities. Firing of tokens at transitions gives the final token marking and provided information on the dynamic of the PE service process. Initial and final marking of the simulation are the states of the tokens in the beginning and at the end of the PE process. The initial marking has been programmed as $1^P1@+20++1^P2@+600$, while final marking obtained at the end is $1^P1@+79++1^P2@+669$. In the code for the initial marking, reading from left to right, $1^P1$ represents one token that is detector call for Priority 1, @ is used to symbolize that token is timed and “+” sign before a number represents time stamp of the token – i.e., token arrival at second 20
of global simulation time. Code “++” adds the seconds token that represents another PE call arriving at second 600 of global simulation time.

The difference of time value in the final marking points out at the difference in the service time of different PE calls, due to shorter amount of service time. Further analysis of controller features is pointing out that critical feature is Change Phase Next, since it introduces the time difference between different PE calls. This control feature should be further tested and verified using SILS.

Incidence matrix is another tool for assessment of controller capabilities. Incidence matrix is converted mathematical representation of the network topology. Incidence matrix \( A = [a_{ij}] \) is an \( n \times m \) integer matrix (assuming that Petri Net has \( n \) transitions and \( m \) places) obtained by equation:

\[
a_{ij} = a^+_{ij} - a^-_{ij}
\]

where \( a^+_{ij} \) is the weight of the arc from transition \( i \) to its output place \( j \) and \( a^-_{ij} \) is the weight of the arc to transition \( i \) from input place \( j \) [2]. This means that incidence matrix columns are network places and rows are network transitions. Each field in the matrix can have the value -1, 0 or 1. If the value is -1 it means that there is an arc going out from that place to the transition. If the value is one, this means there is an arc going from a transition to the place. Zero represents no connection. The rank of the matrix is used as a single number representing the complexity of network topology. This number can be directly related to the greater number of utilized programmable options that should consequently signify greater control capabilities. This can be also used in comparison of different controller firmware. Incidence matrix for this model is presented on the Figure 3-. Calculated rank of this matrix is 20. Petri Net analysis of incidence matrix lead to the emphasis on the Transition Out part of the PE process, since it shows a large number and branching of Transition Out places and transitions.

Utilizing Petri Nets capabilities, as described, does not complete the assessment process. Emphasized unknown programming options – Change Phase next and transition out options in this case – lead the assessment further to SILS, where these features should be tested and verified.

![Figure 3-6: Incidence Matrix for modeled controller PE features](image-url)
3.4 SILS Testing and Verification

SILS is implemented in the next two assessment steps: testing and verification of unknown operational behavior. However, the SILS implementation is not related to the applicability of control options for different traffic patterns, as in previous research. Emphasis of this implementation is on investigating questionable controller firmware capabilities. Testing and verification has been conducted fully utilizing flexibility of virtual traffic simulation environment to trigger control events using various traffic users and situations. Signal control elements have been assumed as constant for finite periods, while the change in traffic conditions was aiming to activate certain control functions. The different behavior observed as a response to imposed traffic conditions is the key information from this part of assessment process.

Virtual traffic signal controller has been integrated within VISSIM microscopic simulation software, with controller resolution of 10 Hz, as implemented in the field controllers. Research team developed coordinated traffic signal control system in the microscopic simulation environment. Single signalized fully-actuated operation was based upon 28 detectors (vehicle, pedestrian, transit, PE, and queue). Different users have been used, for providing the reality component of the testing environment. Users consisted of passenger vehicles, heavy vehicles, pedestrians, bus transit, and emergency vehicles. The input of different user to the simulated traffic signal control system is done in various time steps – from 300 to 1800 seconds, for covering a wider range of traffic conditions. Arrival time for special usage vehicles (transit buses and emergency vehicles) has been set at discrete time points. Based on the schedule, the control system initially operates in Free operation, after which it transitions to Coordinated operation defined by Time of Day coordination pattern and functions events. The testing and verification bases on the features pointed out by Petri Nets analysis – Change Phase Next during Transition In and Transition Out process programmable features.

Simulation Results and Interpretation

Investigation of controller firmware capabilities is based on the graphical representation of signal time table. This table is an inbuilt VISSIM option and intuitively represents the signal time change and detector actuation calls in relation to respective cycle length. The control effects of different firmware options are presented on the Figures 3-7 to 3-10. These figures show emergency vehicle arrival and request for Dwell operation under phase 6 of ring barrier phasing scheme of simulated controller. The placement of call from the emergency vehicle is done on the check-in detector 511, while check-out is through a call on the detector 521.

The first test has been done for Change Phase Next, which is a firmware flag per defined preempt. Figures 3-7 and 3-8 show the control effects of Change Phase Next, in the case it is flagged off or flagged on, respectively. In the case the flag is on, control logic is changing any phase next decision to faster serve the preempt phase. Vice versa, with removing this flag, control logic is not providing modification of phase next decision. The effects of these two cases can be observed on the following figures, where phases 4 and 8 in Figure 3- are shortened to
faster serve the PE call. In addition to this, these figures show how a controller enters Free operation when receiving PE call while in Coordinated operation. They also show the Normal transition out process. Normal transition out option bases on the assigned exit phases, as it is shown in this case those are phases 4 and 8.

Figure 3-7: Change Phase Next flag OFF

Figure 3-8: Change Phase Next flag ON

Beside Normal programmable option for transitioning out, two additional programmable options – Next and In Step, have been represented on the following Figures 3-9 and 3-10, respectively. If PE transition out is flagged as Next, PE will exit to the first phases that follow the phases that were timing when the PE was activated. As Figure 3- shows, transitioning out is performed into phases 2 and 6 as phases that were following the interrupted coordinated phases 3, 4, 7, and 8. On the contrary, In Step transition out flag keeps the local cycle timer counting and performs the transition directly into scheduled point of coordination, as if there was no interruption. The difference between these two transition out strategies is shown in the phases activated after PE phase 6 and in the cycle timer line on the bottom of signal time table representation.
As presented, SILS has successfully incorporated the requirements of in-depth assessment process. However, the immediate deployment of SILS would not result in specific and in-depth information required by proposed framework. The usefulness of this technique bases only upon guiding information obtained from modeling and analysis conducted using Petri Nets.

3.5 Conclusion and Future Work

The desire for extracting additional positive effects from any traffic signal control system lead presented research to the need for enhanced understanding of operational capabilities of Advanced Transportation Controller firmware. The research presented the methodology and practical application of combined Petri Nets modeling and Software-in-the-loop simulation, tools that could model, analyze, test and verify the firmware operation. These dynamic and adaptable techniques have been chosen mostly because of their ability to incorporate specific system constraints and complex operational requirements. The example case of controller firmware assessment presented in this paper focused on Preemption firmware features. The focus of
assessment was on unknown control firmware capabilities that could lead to different control results.

The main contribution of this research is in the novel utilization of readily available tools with focus on multi-scale assessment of unknown controller firmware features. The assessment is intended to enhanced understanding, analytical representation, and assurance in intended control system operation. By generating additional information on firmware capabilities, methodology presented should lead to a better utilization of existing control capabilities for reaching user and system optimum in wider range of parameters.

Finally, further research could go in the direction of utilization proposed combination of techniques for system representation and analysis in other ITS applications, or for stimulating and guiding further development of user specific controller firmware features.

References


4. GEOSPATIAL ASSESSMENT OF TERRESTRIAL COMMUNICATION INFRASTRUCTURE REQUIREMENTS DURING THE PROCESS OF TRAFFIC SIGNAL SYSTEM UPGRADE

Abstract
Departments of Transportation (DOTs) resort to traffic signal control infrastructure upgrades in response to growing traffic needs and obsolete technology. These upgrades are infeasible to conduct instantaneously, and therefore require development of optimal spatial and temporal migration plan. The upgrade of signal control equipment can potentially change requirements of the supporting communication infrastructure. Having the idea of effective planning and improved decision-making process, along with reduction of investments and work duplication among DOT staff, there is a need for an analysis of communication infrastructure during the process of creating migration plan for upgrade of signal control system. This research focuses on the development of framework and methodology for such analysis along with an exemplar problem. Since the issue of telecommunication infrastructure assessment has spatial component accompanying the development of migration plan, the described tool integrates Geographical Information Systems with telecommunication procedures for quality of service analysis. Build on twofold basis of geospatial and communication analysis, proposed tool aims to highly improve the analysis process, relating it to the spatial component of the communication infrastructure. This research thus presents the tool for the identified specific issue along with recommendations for further research.
4.1 Background

Communication infrastructure is an integrated part of any modern Intelligent Transportation System (ITS). This communication infrastructure defines logical and physical connections intended to fulfill communications needs of a Transportation Agency [28]. On the other side, traffic signal control subsystem is an essential and very important constituent of any agency’s ITS. Consequently, the communication infrastructure is a very important part of a particular traffic signal control subsystem.

Growing demand and changing traffic patterns, along with the maturity of technology, greatly affect all the operational capabilities of present traffic control subsystem. This reflects in the negative effects on safety, efficiency, and environmental parameters. In order to address those negative effects and respond to the mature technology, Transportation Agencies have a need for system upgrade to a next signal control generation.

Migration Plan for Signal Control Equipment

Traffic signal control infrastructure can be a very large system for instantaneous upgrade. Because of that complexity, the analysis of this process should undertake an established systems-engineering approach conducted in several steps (Figure 4-1). For creating an optimal migration plan, this process would initially require identification of gaps in system features. In addition, the process would require the evaluation of future control equipment and the development of stepwise migration plan with a long-term replacement perspective. This way the guidance of decision-making process for upgrade of signal control equipment would reflect in a temporal and spatial migration plan. This migration plan would specifically define the points in time and locations for the upgrade of evaluated field equipment. Inside of this high-level process, assessment of communication infrastructure has found its role, as presented on the Figure 4-1. This assessment is directly related to geospatial analysis for migration plan.
Signal control subsystem consists of many elements so developing an optimal migration plan for such system is not a simple task. This complexity is the reason why we need selective analysis of signal control elements. In the hierarchically high-level perspective at migration plan development, requirements of changing traffic demands are the most important issue. This points out to the upgrade of immediate control system elements (such as traffic signal controllers) as a primary in the migration schedule. However, there is the need to observe the other effects of change of this control component. One of the important effects is the effect upon communication requirements of the traffic signal control subsystem. In a logical continuum, after the upgrade of major control components, there is the need for assessment of new communication requirements. The logic of integrated infrastructure management requires that communication system should expand, if needed, along with new signal-control system installation. The idea behind this logic is the intention for improved system components integration, reduction of unnecessary investments, and reduction of work duplication among transportation agency staff.

Research focus and approach

This research is focusing on the idea that changes in information flows and characteristics established by the replacement of existing traffic control equipment would result in the change of required communication quality of service parameters. Essentially, there is a need to provide additional information during the process of migration plan development. Having the idea of effective planning and improved decision-making process, along with reduction of investments and work duplication among DOT staff,
there is a need for an analysis of communication infrastructure during the process of creating migration plan for upgrade of signal control system. The additional goal that this research aims to is providing information to transportation engineers for better understanding of the communication assessment procedure and the effects of upgraded equipment.

The upgrade process of communication elements for support of traffic control subsystem includes systematic and coordinated planning and programming of investments, design, construction, and evaluation of physical facilities, and thus can be classified as an infrastructure management issue [29]. The assessment of communication service parameters in this research focuses on the throughput. Throughput is a prime measurement representing the service capability of particular telecommunication network and thus it directly affects its operational capability. Beside throughput, the research presented here considers also communication network redundancy and reliability. The focus of this research is on guided terrestrial communication media. Other media, such as radio waves and free-space optics are not the topic of this research since their transmission features are different and spatial/communication analysis would require different approach. In addition, this type of equipment is less often deployed for communication inside traffic signal control system.

Considering that communication infrastructure is a physical structure with a wide spatial range, the issue of communication infrastructure analysis is recognized in comparison to previous research as Spatial Data Integration issue [30]. However, there is a need for a specific method that will help in resolving particular points of this issue. Since communication infrastructure has strong spatial component, intuitive cognitive power of decision maker referenced to this spatial component has to be utilized in the analysis. Traditional methods of spatial data analysis isolate the decision maker as the recipient of static information as opposed to analytical actor who is gathering information. Temporal and spatial identification of the data used as the information in the decision-making actions is recognized as one of the critical steps in the process. In essence, there is a need for the ability to manipulate spatial data in different forms and extract additional meaning from them, providing crucial information needed to support the traffic engineers through the process of system upgrade. The set of tools recognized as capable to fit these requirements are known as Geographical Information System (GIS).

4.2 Synthesis of past knowledge and efforts

Related Telecommunication Network Features

By the definition, the basic purpose of telecommunication network is transmission of information from one user/device to another user/device of the network, equivalent to directly-connected devices and with absolute data integrity maintained [31]. There are
some general divisions of telecommunication networks depending on their different network features. Based on signal type transmitted, networks can be analog or digital. Nowadays, digital networks are more often due to their preferred features (e.g., they can transmit signal without degradation due to the noise) [32]. Considering its topology, the network can be Point-to-Point, Star, Ring or Mesh [33]. Based on the direction the information flow, networks can be simplex or duplex. Simplex networks are unidirectional. Duplex networks are bidirectional and can be half or full-duplex. Half-duplex systems are sending information in one direction at a time. Full-duplex systems are transmitting signals in both directions simultaneously. Networks based on guided communication are divided among copper or optic cables as transmission mediums [34]. Copper cables further divide into twisted pair and coaxial cables.

Modern telecommunication analysis bases on standardized Open Systems Interconnection (OSI) model. This model has seven layers: physical, data link, network, transport, session, presentation, and application. Physical layer coordinates functions required to carry a bit stream over a physical medium. Data link layer transforms the physical layer to a reliable link. Network layer is responsible for source-to-destination delivery of a packet, possibly across multiple networks. Transport layer is responsible for process-to-process delivery of the entire message. Session layer establishes, maintains, and synchronizes the interaction among communicating systems. Presentation layer is concerned with the syntax and semantics of the information exchange. Application layer enables the user, whatever human or software, to access the network [35].

**Service capability in telecommunication networks**

Previously mentioned seven OSI layers, with their elements and protocols, directly affect the throughput. Throughput, or data rate, is the number of data elements (bits) sent in 1 second and is a measure of how much information can be sent through a network connection. This data-carrying capacity is expressed in bits per second (bps). In theory, throughput is in direct relation to the bandwidth. Bandwidth is the range of frequencies used for transmission and is the major factor that determines the carrying capacity of a telecommunications channel. In practical applications, the term bandwidth is often used instead of throughput because of their close relationship. In addition to the available bandwidth, throughput depends on the level of signals used, and the quality of a channel (level of noise). The basic equation of Shannon’s capacity, that represents a throughput of a network element, is defined as:

\[ C = \frac{T}{2} \cdot \log_2 \left(1 + \frac{S}{N}\right) \]  

(1)

where:

\( C \) – capacity,
Throughput of the network is the number of packets passing through the network in a unit of time. Beside throughput, other quality of service parameters can be involved in the analysis. For example, redundancy relates to error detection and correction. These processes are usually conducted through introduction of additional information into transmitted data code and this is done in the protocols on different OSI layers. In addition to this, quality of service of communication networks used in ITS is also measured with reliability. Reliability relates to network ability to provide uninterruptable service. This issue is usually addressed with automatic traffic redirection, using algorithms that operate in dynamic load conditions. The routing of data packets through the network is the responsibility of network OSI layer (ex. Internet Protocol).

Telecommunication infrastructure specific to ITS

Specific communication infrastructure related to the ITS bases on a similar layered structure as OSI model and is defined in the National Transportation Communications for ITS Protocol (NTCIP) framework (Figure 4-Figure 4-2). NTCIP defines a group of general-purpose communications protocols and transportation-specific data dictionaries/message sets that support Center-to-field (C2F) or Center-to-Center (C2C) applications [36]. NTCIP standard is guiding and defining most of the telecommunication areas and activities inside ITS. NTCIP has Information, Application, Transport, Subnetwork and Plant level. Information level has standards that define the meaning of data and messages exchanged between Traffic Management Center and field device (C2F) or another Center (C2C). Application level standards define the procedures for exchanging data on the level of application. Transport level standards define procedures for exchanging and routing the data on the network level. Subnetwork level has standards that define procedures for exchanging the data between two devices over some communication media. Plant level represents the actual physical infrastructure. Each of the levels includes specific protocols related to the either C2F or C2C application and consequently those protocols determine the throughput requirements introducing overhead bits.
GIS applications in transportation

As stated under research techniques, GIS is identified as a set of tools to enhance the analysis of communication infrastructure during the development of plan for upgrade of traffic signal control subsystem. GIS integrates hardware, software, and data for capturing, managing, analyzing, and displaying all forms of geographically referenced information [37]. The early benefits of GIS were from its ability to store, retrieve and display spatial information. However, GIS is nowadays frequently a tool to analyze spatial data. The value of GIS is evident in expanding array of disciplines using spatial analysis, spatial modeling and spatial statistics. Visualization, data management and geographical modeling capabilities are the main attractions for using GIS for infrastructure management [38].

Transportation agencies are facing with constant increase of the information scope to support effective decision making on various levels, from engineering of individual projects to statewide planning and management. Furthermore, wide economic and environmental development problems require sharing of data and agency cooperation at all levels [39]. GIS is well adopted to respond to these particular requests and serves in Departments of Transportation (DOTs) as a data, systems and processes integrator. GIS has applications in the area of transportation at different levels:

1. Planning – transportation planning, pavement management, bridge management, capacity management, air quality analysis, etc.
2. Preliminary design – corridor investigation, environmental investigation, etc.
3. Construction – construction planning, detour rerouting, site management, etc.
4. Operations and management – highway inventory, accident analysis, traffic monitoring, etc.

In the research and practical areas of transportation, GIS has been used on different system and management applications. On the operational level, GIS has been integrated with SCOOT Adaptive Traffic Control System [40], used in the network analysis and map manipulation for traffic site impact analysis [41] and for wide-area, real-time interactive transportation system visualization [42]. On the other hand, GIS has also been used in the process of regional transportation planning [43]. Significant number of GIS implementations is also in the area of infrastructure management. GIS-based systems were developed to manage, calculate, and store roadway characteristics to determine rehabilitation methods and estimate immediate and long-term infrastructure investment needs [44]. In addition, a prototype of integrated GPS/GIS/Internet system for the management of utility data along highway networks was developed [45]. Other GIS implementations were for spatial referencing and graphical display for evaluation of truck crashes [46] and transit surveying [47]. All these implementations and research cases have proven that GIS, as a powerful tool for data representation and analysis, can introduce a major difference in proposed approach by significantly enhancing management processes.

GIS applications in telecommunications

GIS applications in the area of telecommunication started with applications for automated mapping and facilities management [48]. Further research introduced GIS for analyzing the adequacy of a regional broadband infrastructure by spatially relating infrastructure facilities with demand (in this case, schools running distance education applications) [49]. This research bases on a need to know (1) what infrastructure facilities are available, and how they are geographically distributed, and (2) what is the nature and location of the demand. Two dimensions relate spatially to reveal gaps between existing infrastructure supply and user’s demand. The most recent research has implemented GIS in WiMax wireless network planning and performance evaluation [50]. However, there is an evident lack of any significant research in the area of spatial analysis of guided communication infrastructure for supporting transportation agencies decision-making.

4.3 Framework and methodology

Framework Development Process

In the development of the framework and methodology, a systematic engineering approach has been undertaken. An infrastructure assessment conducts as the process of
linking infrastructure facility information with application requirement information for revealing a spatial location of infrastructure supply shortage. Furthermore, this framework directly relates to the framework for the migration plan of the signal control equipment, as its extension. Having in mind that the migration plan has temporal and spatial component, assessment tool for telecommunication infrastructure has to incorporate similar logic. As the basis for this tool, the general course of assessment actions is guided by two most important decisions in this assessment process (Figure 4-4-):

1. What are the network expansion requirements levels?
2. Where are the locations of network expansion requirements?

The general course of action consists of two integrated analysis processes. The one part of the process is the calculation of throughput requirements, based on communication analysis. The other part of the process is the spatial data manipulation and visual assessment of network expansion locations, using all the powerful capabilities that GIS can provide.

![Figure 4-3: The framework mechanism for guiding the assessment process](image)

The analysis of the telecommunication requirements is done for the complete existing infrastructure. However, the emphasis is on the locations where the signal control equipment is first to be upgraded to the next generation. This research assumes that the optimal solution for signal control equipment exists before the communication infrastructure assessment. Speaking more specifically, it is assumed that spatial and temporal plan for upgrade of signal control equipment is conducted using some of the
geospatial techniques, such as GIS. Following this logic, the existing geo-referenced database containing information on signalized intersections can be used in the layered structure as a communication points’ layer. Furthermore, it is assumed that the upgrade of the signal control equipment is done on the zone basis, grouping definite number of signalized intersections in the zones by their upgrade priority. Final representation of migration plan for signal control equipment would represent zones with different upgrade priority level. The actual process of defining the zones and calculating the solution on the larger scale is not a part of this research.

Building upon the assumption that analyst has readily available migration plan, the additional layer added before the start of the communication infrastructure assessment is a polyline layer representing the actual location of communication infrastructure in referenced space. This layer, along with data and decisions from the migration plan is used for overall spatial telecommunication infrastructure analysis. The framework constraint is that spatial, geometric and attribute compatibility of objects used in GIS analysis will be disregarded in the methodology development. This includes a large list of incompatibilities, including differences in the measurement techniques, coordinate systems, spatial scale, aerial coverage, data models, data structures, entity sets, attribute measurement scales, as well as temporal coverage. Assumption is that there is available feature data set, which is geo-referenced and ready for analysis having complete spatial representation of communication locations and infrastructure. Figure 4-Figure 4- presents the overall framework flow of analysis.

**Telecommunication procedure for network throughput calculation**

In the first step of the throughput calculation, engineers involved in the process must be aware of all of the devices deployed in the system. Information on the communication requirements of each device is essential, with the key differences being the frequency of communication, and the amount of data transferred. These factors are used in the calculation to determine the amount of required throughput. The process of
assessment is essentially an iterative process with each element having very specific standards and requirements, usually defined by NTCIP. The key to an efficient communications system is a creation of a concise system operations and a set of system requirements based on their clear understanding. Finally, for the actual process of throughput analysis, it is important to gather and consider the relationship among the following key variables:
- Transmission bit rate;
- Transmission method;
- Transmission latency;
- Response delay of the field device;
- Application message size;
- Data element format;
- Frequency of communication; and
- Number of devices sharing the same line or channel;

Throughput analysis bases on previous key variables and has the following steps:
1. Estimate messages exchange frequency;
2. Estimate Application, Transport and Subnetwork Protocol size;
3. Estimate timing factors (delays);
4. Estimate number of drops per channel;

The required throughput is generally computed as:

\[
\text{Bandwidth} = \frac{\text{size of exchange} \cdot \beta}{(1 - \text{latency})}
\]

Where:
- size of exchange – the number of bits application is sending along with overhead protocol bits;
- latency – the summation of all the timing factors that delay the instantaneous data transmission.

Throughput is calculated for each application in the system, as an integrated part of the infrastructure assessment process. This throughput is the actual required throughput that particular application has. Furthermore, the assumption is that information about each particular telecommunication network element a minimal throughput exists. Determination of the all the throughput requirements has to follow the calculation procedure determined by NTCIP layered structure standards and protocols.

**Assessment steps**

The procedure developed will require the procedure similar to the process of design of communication systems, having the perspective “from the ground up”. The first
step is the identification of communication points, which would be in traffic control system, signalized intersections or ramp metering points. The second step is identification of field devices at communication points. Third step is the identification of bandwidth requirements for each of the communication devices. Fourth analysis step is the identification of bandwidth requirements of communication devices planned for future traffic signal control subsystems at specific communication points. Fifth step is the identification of spatial locations of existing communication infrastructure. The sixth step is the identification of features and network element’s throughput for that communication infrastructure. In the seventh step, analyst should group communication infrastructure elements with similar communication capabilities inside the same communication drop. In the eighth step, analyst should determine the adjacency of communication points to the linear communication infrastructure. The ninth step is the calculation of difference in existing and required future throughput. The final step of analysis is the representation and identification of the communication structure affected by the system upgrade and introduction of new control equipment. These 10 steps are grouped and presented on the following Figure 4-

Figure 4-. The procedural steps are grouped based on the side of analysis where they relate – either geospatial or communication analysis.

4.4 Example application

This section demonstrates a practical example (with similarities to the one provided in the NTCIP guide [36]) of a spatial analytical tool that can improve the
process of the telecommunications infrastructure assessment in the process of signal system upgrade. The system under analysis is serving as a verification of framework and methodology developed.

**Description of hypothetical communication system**

The hypothetical system assumes traffic control system under operation of DOT with developed distributed communication infrastructure. The system includes signalized intersections currently operated by type 170 controllers. The existing communication infrastructure fulfills the requirements of the present system. The control system is about to be upgraded with newer controllers, type 2070. This upgrade is assumed to have higher transmission bit rate requirements due to increase of communication overhead introduced by higher operational capabilities of 2070 controllers.

All the signalized intersections are connected in the C2F system controlled by the central computer located in the Traffic Management Center (TMC). Operation is divided into communication between TMC computer and master controllers, and between master and local controllers. This communication accomplishes using Application layer services that convey the requests to access and modify values of master and local controller objects. The actual message consists of set of data elements or objects and a specific application layer protocol.

The critical operation is communication between modems in master (primary device) and local controllers (secondary device). This type of operation is multicasting (one-to-many) polling. Primary device is the initiator of a session and determines the use of a communication channel at any given time. The master controller sends “time hack” to controllers and polls for available data frame from all field units connected to the communications drop. The master controls the local controllers through broadcast of different data frame (if local controller is not in Free or Flash). Local controller transmits status, database, and system detector information, and receives system commands and data transmission. The assumed system operation is as following:

- **System commands that local receives on once per minute basis are:**
  - Coordination pattern,
  - Command for Coordinated, Free, standby or Flash mode
  - Time and date,
  - Request for local status,
  - Special function command (added in the upgraded system)

- **Local controller is polled by commands once every 1 second with time hack and query for database/status data:**
o Cumulative volume and occupancy for each detector in the last sample period,
o Average speed for each speed detector in the last sample period,
o Green and yellow status for all phases and overlaps,
o Walk and pedestrian clearance status for all phases,
o Vehicle and pedestrian detector status,
o Phase termination status,
o Local time,
o Coordination status,
o Conflict flash status,
o Local flash status,
o Automatic flash status,
o Local Free,
o Preempt activity and calls,
o Status of user-defined alarms;

• Controller stores data until polled and must respond within 20 ms;
• System operates in overlap full duplex mode;

Routable connection in the network is between TMC and master controllers. Partial NTCIP-based layered structure is as following:
• Application level - SNMP protocol (without using Traps);
• Transport level – UDP/IP;
• Subnetwork level – Point-to-point;
• Plant level – two pairs per channel dial-up telecommunication line (V-Series modems).

Non-routable connection is for sending dynamic objects from master to local controllers. Partial NTCIP-based layered structure is:
• Application level – STMP protocol;
• Transport level – T2/NULL;
• Subnetwork level – Point-to-multipoint;
• Plant level – two pairs per channel twisted pair (FSK modems).

Data circuit-terminating equipment in the non-routable part of network is analog modem, connected to controller over RS232 cable. The modem converts controller digital output to analog format voice frequencies. As required by modem specifications, the port may be configured as Half or Full Duplex asynchronous, over a physical switch for controller port 3B. Each controller has assigned unique IP address, according to
Transmission Control Protocol/Internet Protocol (TCP/IP) standard “dot notation”. This IP address is used to identify each particular controller in the system. The address must be assigned from the same subnet as the other network devices. If the controller is connected to an IP router, the address must be valid for that router. In addition, controller might have the ability to choose NTCIP standardized or proprietary protocol, but in this example we assume NTCIP is used.

The controller software can support valid bit rates of 1200, 2400, 4800, 9600, 19200, 38400, and 57600 bps, although this is dependent on the controller Computer Processing Unit (CPU) and the modem being used [51]. For example if 2070-6A module is used it can support 1200 bps and if 2070-6B module is used it can support 9600 bps. Model 400, the standard modem for use with 170 controllers, only supports 1200 bps communications. Modulation used to connect modems in the cabinets to central control computers is Frequency Shift Keying (FSK) for speed below 9600 bps. For higher speeds, Phase Shift Keying (PSK) and Quadrature Amplitude Modulation (QAM) are used.

**Spatial analysis combined with telecommunication analysis**

As emphasized before, spatial-temporal migration plan has to be available as an input to this infrastructure analysis. Spatial communication infrastructure analysis localizes the area where immediate analysis of communication infrastructure is needed. Localized infrastructure analysis has in mind the zones selected for having the highest priority for upgrade in the migration plan. Example spatial migration plan for signal control equipment is presented on the Figure 4-

The data presented in this figure is obtained from publicly accessible District of Columbia GIS web site (http://dcatlas.dcgis.dc.gov/catalog/) and is used just for illustrating migration plan for signal control equipment on a larger area. In the Figure 4: Hypothetical migration plan for traffic signal control system in the area, the priority of upgrade for each zone is assigned as number from one to five, with zones having one as those having the highest priority for upgrade and vice versa. Any further analysis should initially focus on the network parts providing communication service to the signalized intersections having the highest upgrade priority.
In the first step, we identify the locations of the communication points. These locations are represented in GIS as a point layer (Figure 4-). Then we identify communication devices at those points. In this case, they are defined as in the description of this hypothetical system. In the third step, we identify the existing communication requirements, which result in 800 bps for the present system features. The future system features result in the communication rate of 900 bps, due to the upgrade to controllers having standard with higher data exchange. Next, we identify the location of existing communication infrastructure, which is a polyline layer on the Figure 4-. Both layers presented on this figure are under common geographical framework.
The features of communication points and infrastructure are included as attributes of GIS layers. The main information that these layers contain is the information on throughput requirements. Attributes assigned to the controller layer features consist of $X$ coordinate, $Y$ coordinate, Signal_Number, Zone_ID, Upgrade_Priority, Min_Throughput_Existing and Min_Throughput_New. $X$ coordinate and $Y$ coordinate are related to GPS coordinates of the intersection controller. Signal_Number is referring to internal DOT identification number for the traffic signal controller. Zone_ID and Upgrade_Priority are attributes originating from migration plan, showing zone for upgrade and upgrade priority level for the particular signalized intersection. Min_Throughput_Existing and Min_Throughput_New are attributes providing information on the throughput required by the existing or introduced signal control equipment. Attributes of communication infrastructure layer are Object_ID, Shape_Length, Media_Type and Existing_Throughput. Object_ID is DOT identification number for telecommunication network segment. Shape_Length is providing additional spatial related information. Media_Type is providing information related to transmission medium. Existing_Throughput is the throughput that specific communication network segment has.

At this point, engineer needs to determine communication point’s location in relation to upgrade priority. This is done using Upgrade_Priority attribute of the layer of communication points. Those points that have Upgrade_Priority value of one are the first to be included in the analysis. GIS Selection by attribute tool selects the points with the value of this attribute equal one, through Structured Query Language (SQL) relation. In the next step, the analyst obtains the information on telecommunication infrastructure for the selected communication points. All the previous information related to the telecommunication infrastructure features are used for the calculation of throughput required for each communication point. These values are assigned to attributes Min_Throughput_Existing and Min_Throughput_New of the communication point layer.
Further spatial analysis identifies linear segments related to communication points under investigation. These segments are defined and grouped by the location of routing/switching points, i.e. the smallest network segment that can be separately investigated. All the network segments are copper-based since we assume that fiber optic infrastructure usually do not have throughput problems when used for signal control applications. In addition, the throughput capability of each separate communication network segment is provided. Value is assigned to attribute `Existing_Throughput` and in this example all the communication network segments have transmission capability of 9600 bps.

In the next step, we create a new layer. This layer is a combination of two separate spatial datasets – communication points and communication infrastructure lines and their attributes. New layer is polyline having the summary of attributes values from the point’s layer. In essence, the features of one dataset falling within spatial extend of another dataset are combined and summed. Attribute values are summarized using SUM operation. In reality, the coordinates of communication points and polyline representing communication infrastructure might not overlap. The option of selecting points that are closest to the polyline can overcome this issue. This way, all the points are assigned to specific closest polyline and their attributes are summarized creating attributes of a new layer. Attributes of different layers and their relations are presented on the following Figure 4-Figure 4-. This layer is where we conduct the calculation of difference in existing and required future throughput of network segment.

![Figure 4-8: Content of final overlap layer originating from the overlap analysis related to communication points and communication infrastructure layer](image)

Values of attributes `Min_Throughput_New` and `Existing_Throughput` have been used for calculation and creation of joined output layer attributes. After the “Join”
operation and removing of unnecessary layer attributes, new layer has attributes Object_ID, Zone_ID, Upgrade_Priority, Sum_Min_Band, Sum_Throughput and Available_Throughput. Sum_Min_Throughput is the summation of the attribute Min_Throughput values from the points closest to a specific line structure. Sum_Throughput is the actual throughput required by all the devices that are sending the data to the center over that communication network segment. Available_Throughput is the difference between Sum_Throughput and Existing_Throughput values for specific linear network segment. Available_Throughput is used at the end as a representative value showing network element transmission capabilities.

Analysis results and improvement recommendations

Figure 4-10 is a graph, obtained from GIS graphical representation tool, showing the values of Available_Throughput after the final calculation using spatial analysis. We can observe that Available_Throughput of network element with Object_ID 14 has negative value. Consequently, this means that this network segment has no enough extra throughput left after the system upgrade.

For the spatial representation of assessed critical network infrastructure, we use GIS tool Selection by attribute (Figure 4-Figure 4). SQL query of Available_Throughput attribute of ≤ 0 bps indentifies the information on the critical network segment. In theory, communication link could hypothetically allow no overhead throughput available, thus allowing the value of 0 bps of Available_Throughput. In practice, we need overhead throughput because of the requirement for round trip communication time reduction, signal attenuation, signal-to-noise ratio, and latency induced by a device to properly
format and send a response. These are all the reasons why available overhead throughput less or equal to 0 bps is unacceptable in practical applications.

Finally, the analyst can identify the specific network element that does not have required throughput to support communications after system upgrade (Figure 4-11). The linear structure requiring expansion of transmission capabilities is marked on the map in blue and its features are recognized.

![Figure 4-11: Selection by Available_Throughput attribute](image)

Furthermore, the information on potential throughput problem leads to the recommendations for improvement. Improvements in communication infrastructure for signal control system could be introduced on any of NTCIP layers. Finding solutions
starts with redefining system settings or improvement and replacement of different system components, iteratively inside the layered structure of NTCIP. The recommended first approach is to try modifying upper layers then look for improvement in modifying elements in lower NTCIP layers.

For example, the improvement could be obtained through introduction of IP over Ethernet with replacement of second-by-second polling architecture with the one based upon Simple Network Management Protocol (SNMP) using trap commands. SNMP is the application level protocol, based on manager/agent relations. Manager is the host station that runs SNMP client program. Agent is the router that runs SNMP server program. The server checks environment and if it notices something unusual it can send a warning message (SNMP trap) to the manager. Manager checks an agent by requesting information that reflects the behavior of agent – object defined by agent. Manager forces an agent to perform a task by resetting values in the agent database. An agent contributes to the management process by warning the manager of an unusual situation. Essentially, using SNMP trap commands, field device is asynchronously initiating communication only when it has something to send, thus significantly reducing throughput requirements.

In addition, the change could be usage of synchronous instead of asynchronous modems since they do not introduce overhead bits. In addition, change from FSK to PSK/QAM could increase throughput without increase in signaling frequency. In addition, the replacement of analog with digital modems is also one of the possible solutions. Finally, the changes in the requirement of frequency communication (e.g., gather detector data on the clock time basis – every minute or signal cycle) could lead to the reduction of throughput requirements of the upgraded system. As a final resort for this example, would be the investment into Synchronous Optical Network (SONET) fiber optics cable for replacement of existing copper cables. Fiber optics throughput capabilities can resolve all issues related to the communication in one ITS and they are usually utilized as an ultimate solution. Any of the decisions for improvement bases on the previously developed Communication plan upgrade projects and its planned expansion.

4.5 Conclusion and further research

This research guides the need for assessment of communication infrastructure during the upgrade of traffic signal control system. Research presented develops a framework and methodology for the analysis of telecommunication infrastructure using geospatial tools. This leads to the integration of communication analysis with geospatial capabilities to develop a coordinated tool for implementation in the process of signal-control equipment upgrade. The process of infrastructure analysis has twofold basis: requirement analysis of communication system along with implementing GIS as a tool that highly improves the process. Selection of GIS is due to its ability to integrate data.
and processes related to spatial entities. GIS is utilized to improve the decision-making process by employing intuitive human reasoning of space.

Framework and methodological steps for infrastructure analysis presented base on aforementioned twofold basis. Example provided aims to prove the established framework and developed methodology through the ability of GIS to manipulate spatial data and extract additional value from it. In addition, the example itself, as the whole research process presented here, is taking a perspective adjusted for transportation engineers, providing deeper understanding of the related elements. One of the points of this research is providing knowledge and guidance for similar implementation cases. The final product is a tool that can be potentially utilized in the process of identifying existing infrastructure gaps and development of recommendations for DOT’s Communication Plan.

Finally, having the role of initial research in this field, this paper opens a field for numerous possibilities for advances and development in the area of telecommunication infrastructure analysis and assessment related to transportation infrastructure. One of the first expansions of this research could go toward the area of wireless communications utilized for traffic signal control systems.

References


5. SUMMARY OF FINDINGS, CONCLUSIONS AND RECOMMENDATIONS

This thesis is trying to address the need for enhanced understanding and decision-making for improved operation and planning of traffic signal control subsystems. This need is recognized as an essential for improving the operational capabilities of traffic control system in general. The approach guiding this research is that better comprehension of subsystem capabilities and requirements would lead to better utilization of existing equipment and improved decision upon the next generation of signal control system. For addressing some aspects of this issue, this thesis deploys several techniques for modeling and assessing of traffic signal controllers and supporting communication infrastructure capabilities and requirements.

5.1 Findings

Chapter 2 of this thesis presents the development of Petri Net model for the representation and analysis of the RBC structure. The focus to modeling RBC structure is originating from its importance as a core of any modern Advanced Transportation Controller. Developed model is in accordance with current practices in NEMA based 8-phase signal controllers. The modeling and analysis process is aiming towards better understanding of RBC and ATC. The true value of this model is that it provides a mechanism for documenting and communicating controller features to other researchers and developers.

In chapter 3, this thesis focuses on the need for enhanced understanding of operational capabilities of Advanced Transportation Controller’s firmware. It is observed that controller firmware is not under direct standardization and a number of features are under influence of third-party software developers. This often leads to unknown or improperly used controller features since traffic engineers in DOTs do not have sufficient information on them. The need for enhanced understanding is addressed through combination of Petri Nets modeling and Software-in-the-loop simulation. Trough integrated multi-scale operation, these tools lead to enhanced understanding, analytical representation, and assurance in intended control system operation. Generating additional information on controller capabilities, methodology presented should lead to a better utilization of existing control capabilities, thus reaching user and system optimum in wider range of parameters.

Chapter 4 guides this research towards assessment of change in requirements of communication infrastructure during the upgrade of traffic signal control system. Since communication infrastructure is considered as integrated part of traffic signal control
system it needs to be upgraded along with the upgrade of signal control equipment. The desire originates from the need for improved decision-making process, along with reduction of investments and work duplication among DOT staff. Research presented in this chapter develops a framework and methodology for the analysis of communication infrastructure based on Geographical Information Systems. Hypothetical example provided aims to prove the developed framework and methodology through the ability of geospatial tools to manipulate spatial data and extract additional value from it. In addition, the research presented, utilizes a natural comprehension of space and transportation engineers’ perspective to the issue, providing deeper understanding of the related elements and providing knowledge and guidance for similar implementation cases.

5.2 Recommendations for further research

The RBC Stochastic Timed Colored Petri Net model is establishing groundwork for further development of new features in the next generation controllers. This model along with the methodology presented in chapter 3 could successfully stimulate and guide further development of user-specific controller operational features. Methodology from chapter 3 has potential for implementation in the analysis of various other market controller firmware features, thus leading to improved knowledge base for their evaluation. In addition, integration of Petri Net modeling and Software-in-the-loop simulation could be implemented in defining and developing customized control features. In the area of communication infrastructure related to signal control systems, there is a potential for further research toward the area of wireless communications used for signal control. Presented methodologies and techniques could be useful in modifying current approaches for addressing issues and assessment of other subsystems and specific implementation cases in signal control and traffic engineering, in general. Finally, presented research has potential in developing curriculums for academic institutions and transportation agencies that are interested in educating traffic signal control specialists.