FLORIDA INTERNATIONAL UNIVERSITY

Automation of Traffic Signal Plan Modification Decision in Response to Non-Recurrent Congestion

2020 TRANSPORTATION TECHNOLOGY TOURNAMENT

Authors

Rajib Saha
Mosammat Tahnin Tariq
Hector Mata
Kamar Amine
Raihanul Bari Tanvir
Etty Chris Emmanuel

Academic Advisor

Mohammed Hadi, Ph.D., P.E.

Industry Advisors

Daniel A. Smith
Nicole L. Forest, CSM, FCCM
Giri Jeedigunta, P.E., PTOE
Aidin Massahi, Ph.D.

May 15, 2020

Automation of Traffic Signal Plan Modification Decision in Response to Non-Recurrent Congestion

Saha, R., Tariq, M., Mata, H., Amine, K., Tanvir, R. & Emmanuel, E.

Florida International University

May 15, 2020

Abstract

Congestion on arterial networks continues to become a major challenge for all road users, policy-makers, and traffic signal maintenance agencies around the nation. Most agencies still use Time of Day (TOD) based signal timing plans to manage traffic signal operations. These TOD plans are prepared using historical traffic data collected for different times of the day and fine-tuned based on field observations. As such, these plans are unable to address traffic congestion due to a sudden increase in demand or a drop in capacity during non-recurrent conditions. Some Traffic Management Centers (TMCs) around the nation have assigned traffic signal engineers/experts to manually modify signal timing plan in response to non-recurring congestion to provide additional capacity to the congested movements. Such modifications require human intervention resulting in a reactive, time-consuming, and expensive process that necessitates observing the traffic network conditions, designing new timing plans, and then implementing the new plans. Another concern is that the expert signal engineers/expert operators may change jobs, causing an important loss in the acquired knowledge and experience. The experts also do not usually provide the service 24 hours a day/7 days a week at the TMC. The above discussion indicates that there is a need to automate the decisions to change the signal timing plans during recurrent congestion. The Concept of Operations (ConOps) in this report describes the development and characteristics of an application to automate the decision-making process of traffic signal engineer/expert operators. The proposed solution utilizes a combination of machine learning algorithms consisting of a decision tree and fuzzy rule-based system to recommend modifications to signal timings during non-recurrent events, including incidents, construction, a surge in demands, and device malfunctions. The ConOps was developed in observance of the System Engineering Process (SEP), which implied focusing on the stakeholder involvement for all the steps of the process. The ConOps describes the functional, physical, and enterprise architecture of the developed system and its interaction with the existing systems. In addition, the cost for the implementation and the anticipated benefits are also incorporated into the report. This application has the potential to benefit agencies by improving the efficiency of the process used to address non-recurrent congested conditions. The main advantage of this application is that the signal maintaining agencies or the TMCs will be able to implement this application utilizing their existing operational platform without requiring any infrastructural upgrades while reducing the dependence on expert staff in making the decisions.

Contents

List of Figures

List of Tables

List of Acronyms and Abbreviations

AMP Arterial Management Program. 1, 2

ATCS Adaptive Traffic Control Systems. 2, 9

ATMS Advanced Traffic Management Systems. 2

ConOps Concept of Operations. i, 2, 7

FDOT Florida Department of Transportation. 2, 4, 10

ITS Intelligent Transportation Systems. ii, 2–6, 10, 11

NOCoE National Operations Center of Excellence. 2, 10

SCPDS Signal Control Plan Development System. 5, 7, 10

SEP System Engineering Process. i, 2, 10

TMC Transportation Management Center. i, iii, 2, 4, 5, 8, 9

TOD Time of Day. i, 1, 2

TSM&O Transportation System Management and Operations. 1, 4

1 Background

Congestion on arterial networks continues to become a major challenge for all road users, policymakers, and traffic signal maintenance agencies around the nation. Figure 1 shows that more than fifty percent of congestion occurs in unexpected times and places due to non-recurrent events such as incidents, special events, work zones, and bad weather [1]. User delays due to non-recurrent conditions result in economic loss, increased fuel consumption, and emission.

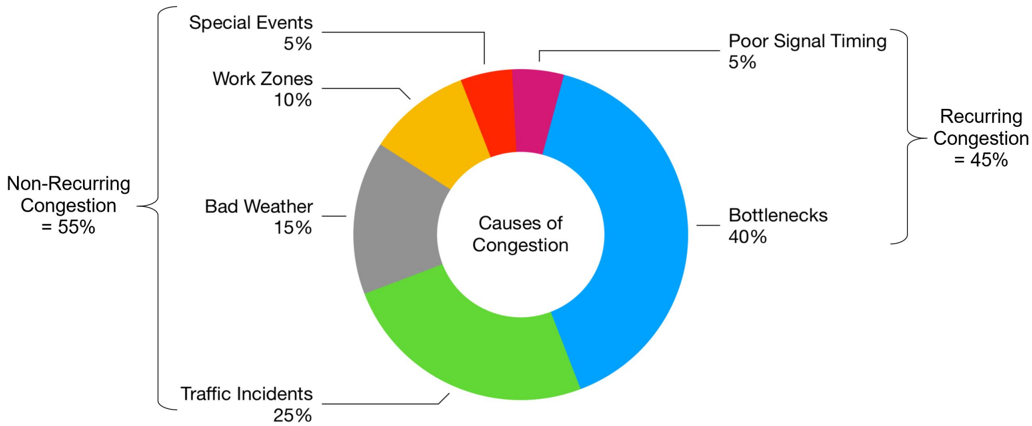


Figure 1: Causes of Congestion in the U.S. [1]

Due to non-recurrent events that cause reductions in capacity or increases in demand, congestion can extend to upstream intersections from the bottleneck location. Under these conditions, the vehicle queues continue to grow from cycle to cycle, as a result of insufficient green times that cannot meet the demands or because of blockages that prevent traffic from efficiently using the assigned green times (Figure 2). In such cases, the queue spillbacks result in significant impacts on upstream intersection operations.

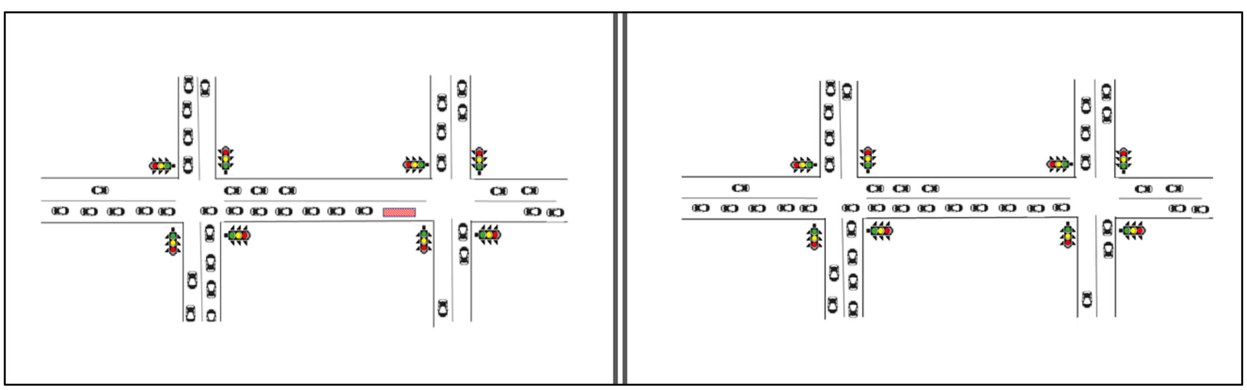


Figure 2: Queue Spillback Due to Non-Recurring Congestion.

In recent years, the Transportation Departments have started to focus on Arterial Management Program (AMP) strategies to manage the performance of the arterial streets under the flagship of Transportation System Management and Operations (TSM&O) initiatives. The activation of special traffic signal plans during non-recurrent events is an essential component of AMP and can provide significant benefits in managing congestion. Most agencies around the nation predominantly use Time of Day (TOD) based signal timing plans to manage traffic signal operations. TOD plans are initially developed utilizing historical traffic data collected for different times of the day. The developed plans are subsequently fine-tuned based on field observations. Usually, the development of TOD plans involves gathering data under normal traffic conditions in the absence of non-recurrent congestion due to incidents, lane blockage events, and surges in demand due to special events. However, the non-recurrent events can create queue spillbacks during both peak and off-peak periods resulting in significant delays and spillbacks. Adaptive Traffic Control Systems (ATCS) have been developed and implemented to react to unanticipated traffic variations occurring from cycle to cycle, and therefore, can operate more efficiently than TOD-based systems. It has been reported that ATCS can reduce delays during incidents. However, the ATCS performance under incident scenarios, as well as when the signalized intersections become congested with long queues, has not been proven to be beneficial yet. Moreover, the ATCS systems are associated with additional costs of installation and maintenance; therefore, they are deployed only on small subsets of the arterial networks.

This report states a high-level Concept of Operations (ConOps) of a solution for activating special signal plans that correspond to the non-recurrent events. This solution can be considered as traffic responsive and has been proven by our team using simulation to mitigate non-recurrent congestion. The demonstration of the application of this solution in Broward County, FL (the Fort Lauderdale area), is being done in collaboration with the Florida Department of Transportation (FDOT) District IV for the "2020 Transportation Technology Tournament" organized by the National Operations Center of Excellence (NOCoE). The ConOps is developed following the guidelines of the System Engineering Process (SEP) as described in ITS ePrimer by the U.S. Department of Transportation.

2 Current Practice by Agency

Some Traffic Management Centers (TMCs) have assigned traffic signal engineers/experts to respond to non-recurring events as part of the AMP practice by modifying the timing plans to mitigate the impacts of non-recurrent congestion. Such a process is initiated by the identification and validation of the existence of non-recurrent events utilizing different Intelligent Transportation Systems (ITS) based systems, as shown in 3. The signal timing experts update the signal plan based on observations such as the conditions of the main and side streets, comparison of the queue spillback situation with historical queues, and the effects of queues on the upstream intersections. The new plan is downloaded to the field controllers utilizing the existing central software at the TMC (e.g., ATMS.now).

Figure 3: Workflow of the Current Special Signal Plan Activation by the Expert at the TMC

3 Problem Statement

The process of changing the signal timing by an expert operator at the TMC poses several drawbacks. The process is time-consuming and needs special training in traffic signal operations. It requires human intervention, making it prone to errors not to mention that agencies on a limited budget sometimes cannot afford to hire specialized personnel, and even when hiring them, the personnel cannot be available 24/7. These experts may also leave their positions resulting in losing valuable experience.

4 Vision, Goals and Objectives

The vision, goals, and objectives were defined during the concept exploration stage of the system engineering process. They were developed to reflect multiple viewpoints from various stakeholders. Figure 4 shows the defined vision, goals, and objectives for our project.

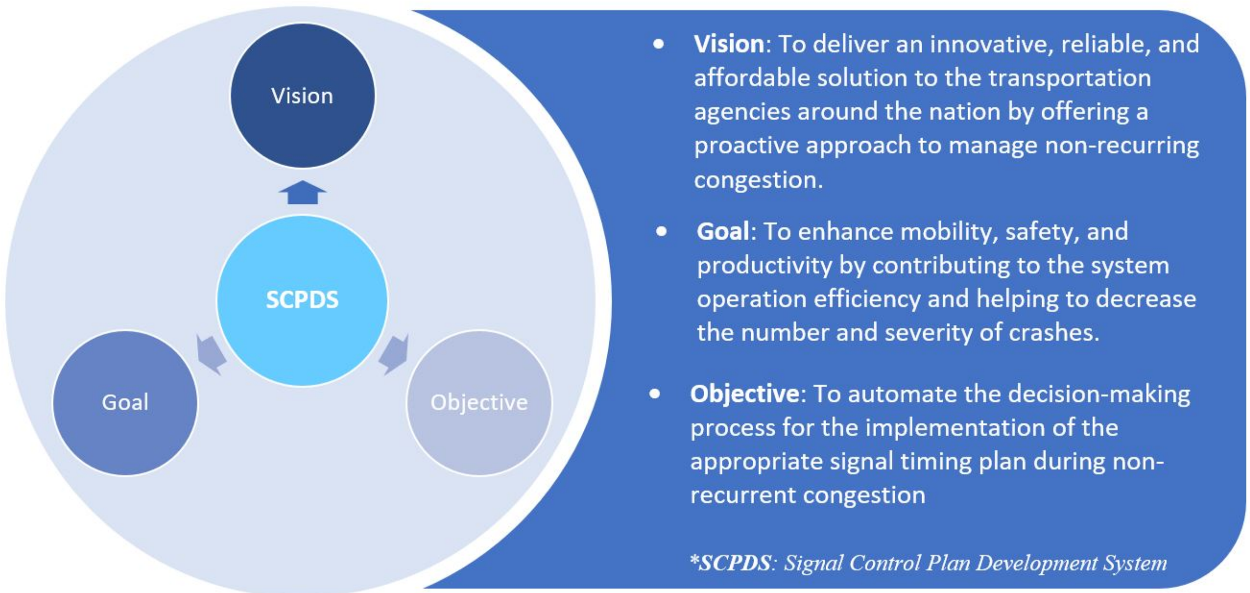


Figure 4: Defined Vision, Goal and Objectives.

5 Proposed Solution

The team is proposing a viable solution that can be easily implemented utilizing the existing system without significant additional resources. In developing the solution, the team harnessed the power of machine learning and a plethora of data obtained from different ITS tools deployed by the agency in conjunction with a compilation of the experts' decisions throughout a year of traffic activity. The following paragraphs provide a description of the tasks associated with this solution.

5.1 Automation of the Expert Decision

Data analytics was utilized to associate the historical expert decisions with their corresponding traffic status in the network. The resulting data serve as the basis for developing the model. The development team utilized a combination of Recursive Partitioning and Regression Decision Tree and Fuzzy Rule-Based System to model the complex decisions made by the traffic signal engineers/experts [3]. A comparison of the developed model with the experts' decisions showed that the model achieved high accuracy in replicating the expert decisions and thus recommending the new signal plan. The development team assessed the effect of the new signal plan using simulation and showed a significant reduction in non-recurrent congestion delays. The results of the model are shown in Table A.1 in Appendix A.

5.2 Automation of the Decision Generation Process

The team will develop a user application/software interface for an easy implementation of the model. The application will run the developed machine learning model in the backend and generate plans in real-time based on simple user inputs about the traffic conditions. The application interface is easy to use and is compatible in format with the existing system used by the agency. The working procedure mimics the current practice by the agency except for the inclusion of the automation software instead or in support of the signal timing experts shown in Figure 3.

6 Stakeholders

There are multiple stakeholders that have been identified for this project. The Florida Department of Transportation (FDOT) District IV TSM&O program and TMC play a central role as a stakeholder considering that the model and application are developed based on the data provided by this agency and will be used by their operators. Broward County TMC that maintains the traffic signals will play an important role in coordinating with the FDOT on the plan implementation. Other stakeholders will include third-party data providers, the maintenance and construction management department, the emergency management center (EMC), the system operators, and the facility users.

7 Operational Concepts

7.1 Functional Architecture

The functional architecture of the ITS project describes the abstract of the functional elements and their logical clustering of processes and interactions to fulfill the system requirements and perform the stated objective of the project. The project's functional architecture includes the functional processes and the dataflow between the processes that enable the project to operate as an integrated system. Considering that the developed application is related to traffic signal control during the non-recurrent events, the proposed architecture includes multiple service packages from the Architecture Reference for Cooperative and Intelligent Transportation or ARC-IT [2]. These service packages are the "Traffic Signal Control", "Traffic Incident Management System", "Integrated Decision Support and Demand Management", "Work Zone Management", and so on. Figure 5 represents the functional architecture (process specification and data flow) of the overall system of the automation of signal timing modification during non-recurrent congestion.

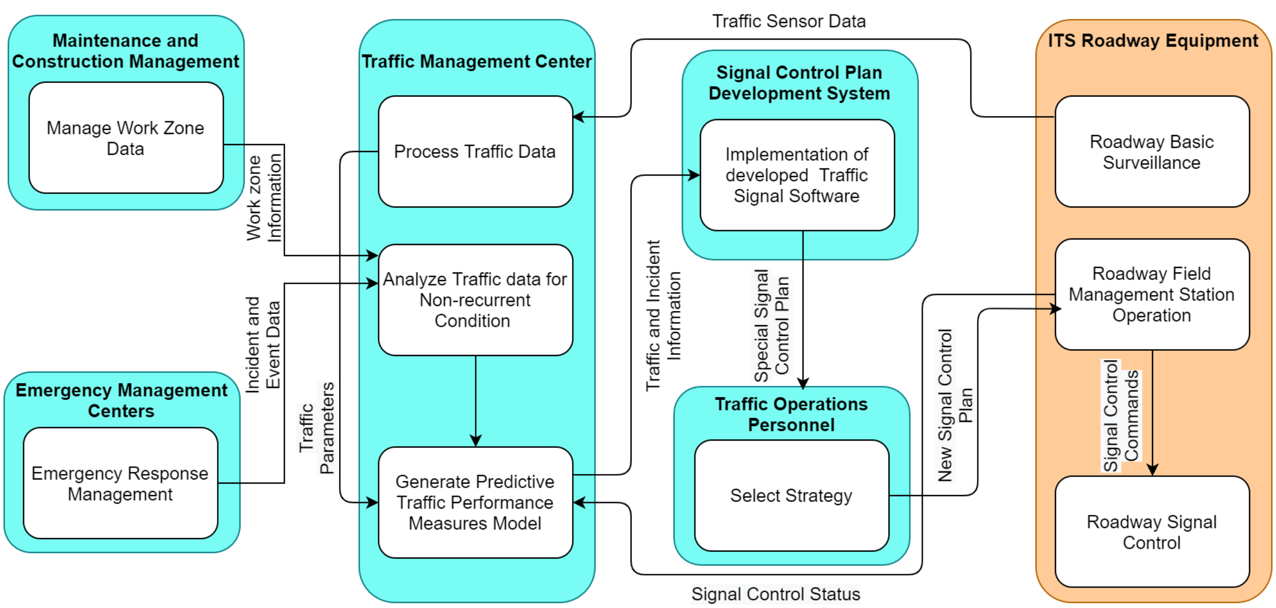


Figure 5: Elements of the Functional Architecture of the System.

7.2 Physical Architecture

The physical architecture comprises of physical objects that provide the ITS functionality for performing a task or a group of tasks. Each physical object may have one or more functional objects and is connected with other physical objects through information flows. The physical architecture of the proposed system is shown in Figure 6, and it displays the different ITS based equipment and systems that are already in place as well as the proposed application labeled as Special Signal Control Plan Development System (SCPDS). As shown by the information flows depicted in Figure 6, the new system can operate as a stand-alone system, receive data from the TMC system, and deliver control plans to the TMC. Finally, the TMC system implements the signal plan in the controller through roadway ITS equipment.

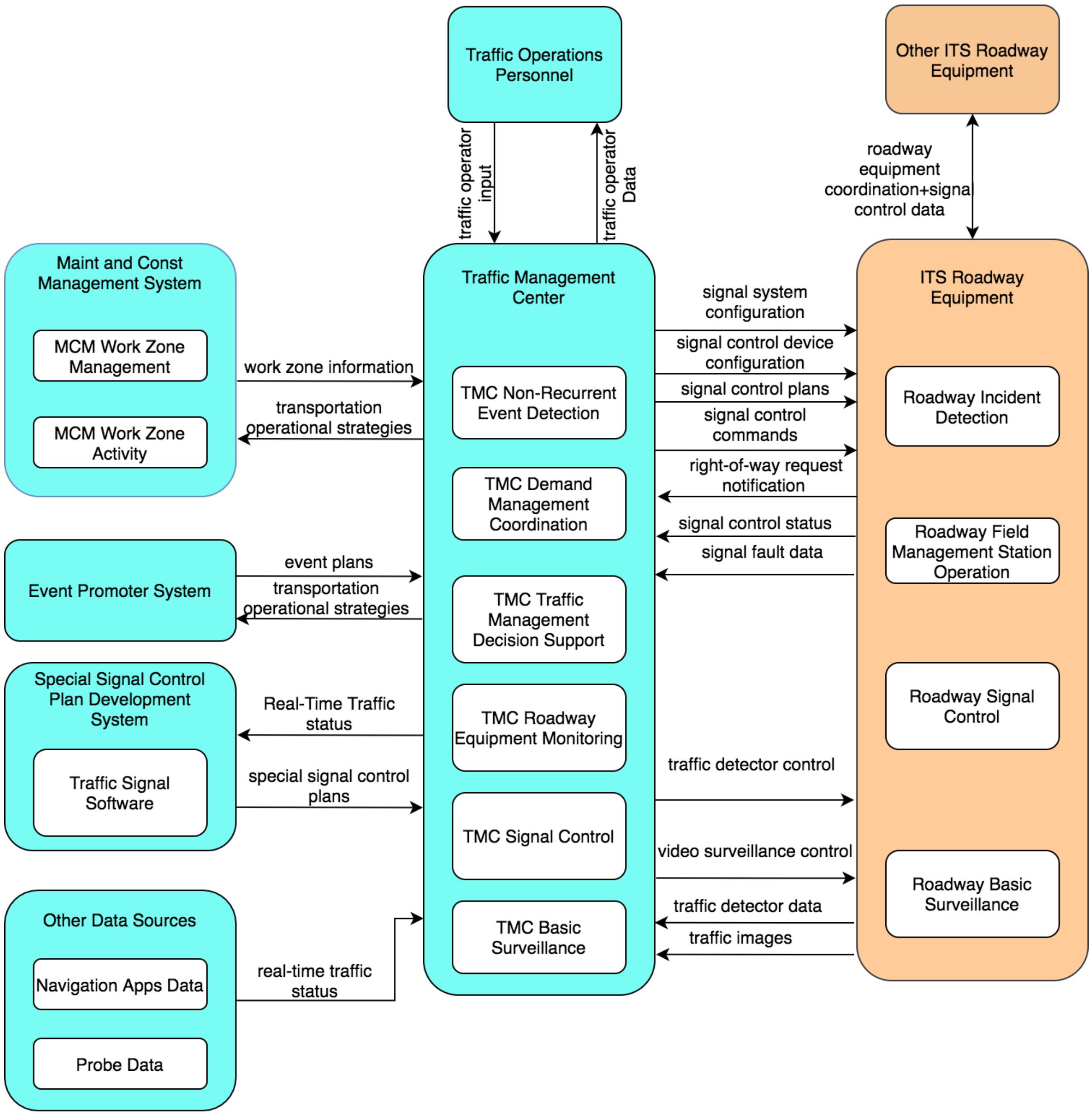


Figure 6: Elements of the Physical Architecture of the System.

7.3 Enterprise Architecture

The Enterprise architecture depicts the relationships between the existing enterprise objects and the role that they perform within a given domain in the ITS environment. The relationships between the enterprise objects are also defined by the enterprise architecture in terms of who is responsible for what, and how the objects interact with ITS. Figure 7 shows such interactions as well as the role/relationship of each one of the enterprise objects in this project. As it can be noted, many of the objects represented in Figure 7 are stakeholders that participate and have interactions with other enterprise objects in the ITS environment. Also, the physical objects are depicted and referred to as resources.

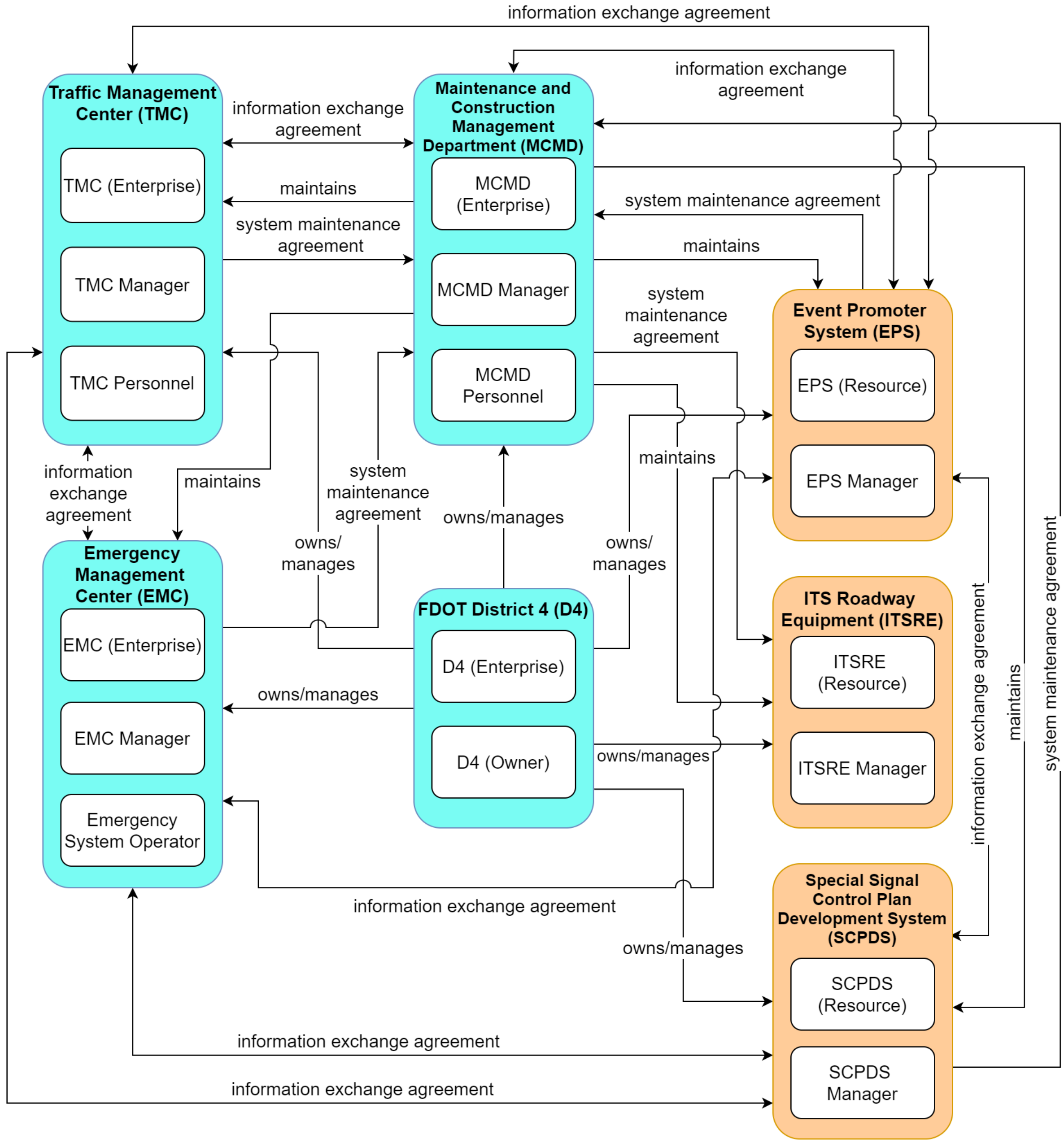


Figure 7: Elements of the Enterprise Architecture of the System.

7.4 Signal Control Plan Development System.

The special Signal Control Plan Development System (SCPDS) is the proposed new system in this ConOps for automatically developing new signal plans in response to non-recurrent congestion. The system is mainly composed of software that will generate new plans based on the inputs. The stages of software development process are shown in Figure 8.

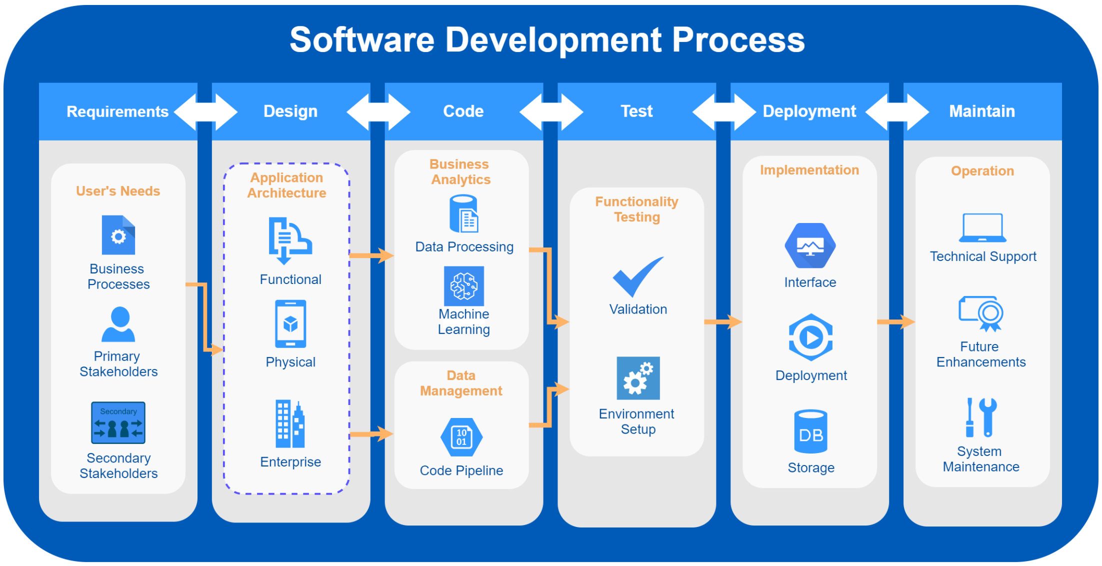
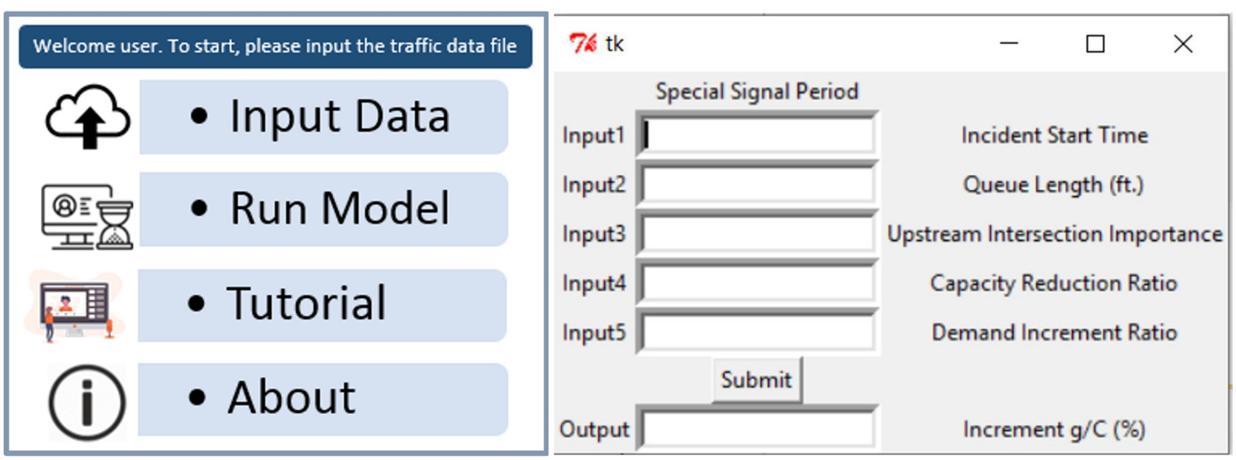


Figure 8: Process of Signal Control Plan Development Systems.

The team is currently working on the coding of the software. The conceived main page of the software, the input window is shown in Figure 9. One of the vital parts of the software is to collect the required inputs based on the identified events and traffic status. A data dictionary table is developed (Table A.2, Appendix A) to guide the users for providing appropriate inputs. Moreover, a tutorial is also embedded in the software to inform the users about the basic features of the software.



(a) Welcome Page

(b) Input Page

Figure 9: The Wireframe of the Application.

7.5 Cost Breakdown

Since most of the required systems are already in the operation at the TMC, the new system development cost will be minimal. The cost breakdown considering a $50 average hourly rate of the developer is given in Table 1.

Table 1: Item Wise Estimated Cost.

Concept	**Description**	**Amount**
Development	Software Creation, Front-End and Back-End Development	$38,000.00
UI/UX Design	User Interface Design	$5,000.00
Quality Assurance	App Testing	$1,000.00
Project Management	App Monitoring	$10,000.00
	Project Cost	**$54,000.00**
Maintenance and Updates	Bug Fixing, New Features, Development, Improvement, and Performance @30% of the Project Cost	$16,200.00
Overhead Cost	@10% of the Project Cost	$5,400.00
	Total Cost	**$75,600.00**

7.6 Implementation Timeline

A system engineering process consisting of six important stages is used for developing and implementing the software. Since the machine learning model has already been developed, the software coding will be done in a short time, while the testing and integration will require more time. However, it is important to point out that it is possible to achieve the implementation in a period as short as six months. Figure 10 shows the tentative implementation deadline, considering starting activities in the early days of June 2020.

	Task Name	Duration	Start	End
1	Software Coding	45 days	06.15.20	07.31.20
2	Unit Test	30 days	08.01.20	08.31.20
3	Integration Test	30 days	08.15.20	09.14.20
4	System Test	30 days	09.15.20	10.14.20
5	Acceptance Test	30 days	10.01.20	10.31.20
6	Operations and Maintenance	5 Years	11.01.20	10.30.25

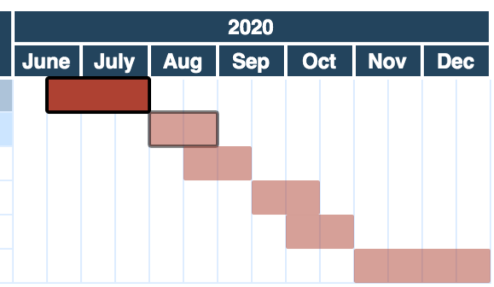


Figure 10: Software Development and Implementation Timeline.

7.7 Potential Benefits

This application will ensure a better and more proactive response to non-recurrent conditions, improving mobility, safety, and environmental impacts. The application will benefit agencies with limited resources by reducing their reliance on the expert and add efficiency to the process of addressing non-recurrent congested conditions.

7.7.1 Operational Benefits

By not requiring complicated algorithms or high-resolution data to produce a signal timing plan, the application provides a practical, flexible and fast solution that is available at any time of the day/week, rather than counting on the availability of experts at the time of need. The application's user-friendly interface provides a solution to any emergency at any time through almost any user with access to the required input. It also offers a proactive approach to managing non-recurrent congestion as the model has the capability to predict the queues on the horizon. As the software can work as a stand-alone application, other agencies (e.g., Police) who deal with the signal control can also use this application and generate appropriate plans.

7.7.2 Safety and Environmental Benefits

The reduction in the time needed to react to non-recurrent congestion (caused by incidents in specific) and reducing the associated queues are expected to reduce secondary crashes and thus improve safety. On the other hand, the reduction in the total and average delay leads to a decrease in fuel consumption and, consequently, a reduction in emissions.

7.7.3 Mobility Benefits

The new signal plans generated by the application were found by the research team based on simulation to decrease average delay, mitigating non-recurrent congestion, and queue spillbacks. The delay benefits are presented in Table A.3 in Appendix A.

7.7.4 Economic Benefits

The flexibility of this application provides agencies or the TMCs the advantage of implementing it on existing operational platforms without requiring any infrastructural updates or expert staff to manage traffic operations, providing a cost-effective comparative advantage over existing ATCS systems. As the application is accessible by almost any user, rather than experts, this tool has the potential of reducing the staff cost. The project has the potential to generate a high return on investment. Considering only the mobility benefits, Table 2 shows that the project can generate a 20:1 Benefits-to-Cost ratio. The data used in the calculation was obtained from the expert and simulation as presented in Appendix A.

Table 2: Benefit-to-Cost Ratio.

Concept	**Parameter**	**Parameter Value**	**Yearly Estimate**	**5 Years Estimate (P/A, 6%)**
Benefit	Event Description	One lane blocked out of three	$ 607,464.00	**$ 2,558,638.00**
	Number of Events	14 per month		
	Average Queue Length	3245 ft		
	Average Vehicle Length	18 ft		
	Value of Lost Time in Queue	$ 13/hr		
	Total Reduction in Average Delay	96 sec/veh		
Cost	Initial Project Cost	$ 59,400.00	$ 75,600.00	**$ 127,634.00**
	Recurrent O&M Cost (From Table 1)	$ 16,200.00		
Benefit / Cost Ratio = 20:1				

7.8 Challenges of Implementation

7.8.1 Deployment in other Jurisdiction

One of the crucial challenges of the software is the use in other areas. The application is developed considering one area, and the model in the backend of the software is trained by using decision from one expert only.

To make the application universal, the inclusion of more study areas and expert decisions are recommended. In addition, the existing model can be tested in other jurisdictions, and accuracy can be measured against expert decisions working in that area.

7.8.2 Regional ITS Architecture, Policy, and Capability Maturity

Regional ITS architecture, policy, and maturity poses another challenge as it may differ from agency to agency in different regions. The capability maturity and resources of the agencies differ, and their ITS system as well. The policy and operational guidance and procedures of the agencies concerning signal timing design also differ. The proposed software need to be evaluated and demonstrated under different conditions. The implementation of the appropriate signal timing plan should follow the agency policy and capability maturity. Therefore, there is a need for reviewing the existing policies and operational guidance and procedures or updating the existing ones using a combination of the best practices and careful consideration of the environment.

8 Conclusion

This study introduced a concept-of-operations for the development and implementation of a special Signal Control Plan Development System (SCPDS) that automates expert decision-making in implementing the appropriate signal timing plan during non-recurrent conditions. The proposed solution utilizes a combination of machine learning algorithms such as decision tree and fuzzy rule-based system to recommend modifications to signal timings during non-recurrent events, including incidents, construction, a surge in demands, and device malfunctions. The solution was developed in observance of the System Engineering Process (SEP) which implied focusing in the stakeholder involvement for all the steps of the process to make sure that the stakeholder needs are properly addressed by taking into consideration the several viewpoints of diverse stakeholders as well as the consideration of multiple operational scenarios to understand how the application will operate under different conditions. Moreover, some limitations were also analyzed, for example, the challenge associated with the signal timing policy, operational guidance, and procedures, and capability maturity of different agencies and recommendations are presented to review and if necessary to update the policy and procedures based on the best practices prior to the implementation of the SCPDS. Finally, one of the most important aspects of the solution is its expansion capability for use in other areas. The easy interpretability of the inputs and outputs makes it a viable option for use by other agencies who deal with traffic control. The minimal resource requirements also make the solution attractive to agencies with limited resources.

9 Acknowledgement

The team offers their sincere gratitude to the Southeastern Transportation Research, Innovation, Development and Education (STRIDE) Center for funding the project. The team also extends their acknowledgment to the FDOT District IV Officials: Mr. Daniel A. Smith, PMP; Ms. Nicole L. Forest, CSM, FCCM; Mr. Giri Jeedigunta, P.E., PTOE; Dr. Aidin Massahi for their sincere effort to produce this document. The team is in debt to their Academic Advisor, Dr. Mohammed Hadi, P.E., for his continuous guidance, support, and suggestions throughout the process. The team is also grateful to the National Operations Center of Excellence (NOCoE) for arranging such a wonderful tournament.

10 References

[1] Federal Highway Administration. (2020). Efficient Use of Highway Capacity Summary Report to Congress. Accessed on May 6, 2020. Retrieved from:
https://ops.fhwa.dot.gov/publications/fhwahop10023/chap2.htmn8

[2] U.S. Department of Transportation. (2019). ARC-IT, The National ITS Reference Architecture. Accessed on May 6, 2020. Retrieved from:
https://local.iteris.com/arc-it/html/servicepackages/servicepackages-areaspsort.html

[3] Tariq, T. M., A. Massahi, R. Saha, and M. Hadi. (2020). Combining Machine Learning and Fuzzy Rule-Based System in Automating Signal Timing Expert's Decisions during Non-Recurrent Congestion. *Transportation Research Record: Journal of Transportation Research Board*

A Appendix

A.1 Model Validation Results

Predicted increase in g/C ratio (numerical value)	True increase in g/C ratio (numerical value)	Predicted increase in g/C ratio (linguistic term)	True increase in g/C ratio (linguistic term)	Validation
60	69.23	Large	Large	Correct
10	26.67	Small	Medium	Incorrect
100	102.63	very large	very large	Correct
31	34	Medium	Medium	Correct
31	30	Medium	Medium	Correct
60	68	Large	Large	Correct
0.1	0	No change	No change	Correct
31	22.39	Medium	Small	Incorrect
100	100	very large	very large	Correct
10	11.49	Small	Small	Correct
10	26.67	Small	Medium	Incorrect
31	28.57	Medium	Medium	Correct
0.1	0	No change	No change	Correct
		Accuracy of the model		**77%**
		Mean absolute error		**5.38%**

* Source: Tariq et al., 2020

A.2 Input Data Dictionary

Input Parameters	Description	Range	Input value
Congestion or Incident Start Period	It is a categorical variable taking the values 'morning'(between 7:00 am and 10:00 am), 'midday' (between 10:00 am and 4:00 pm) and 'evening'(between 4:00 pm and 7:00 pm).	Morning, Evening Peak Midday	1 2
Upstream Intersection Importance	The score of the upstream intersection cross street's importance ratio ranges from 1 to 3, where 3 indicates the highest importance.	Not Important Important Very Important	1 2 3
Capacity Reduction Ratio	It is calculated based on the capacity adjustment factors for incident zones suggested in the Second Strategic Highway Research Program (SHRP 2) L08 project deliverables.	No Blockage One lane Blockage Two-Lane Blockage	0 0.26 0.49
Demand Increment Ratio	Demand increment ratio is calculated as the ratio of the increase in the hourly demand compared to the normal day hourly demand.	None Small Medium Large	0 1-1.35 1.33-2.00 1.95-3.20
Queue Length(ft.)	The queue length is the length of the queue of a congested movement due to non-recurrent congestion.	Small Medium Long	0-600 550-6000 5550-9000
Percentage Increment in g/C ratio	Percentage increment of $\frac{g}{c}$ ratio $= \frac{Modified\frac{g}{c}ratio - Normal\frac{g}{c}ratio}{Normal\frac{g}{c}ratio}$	No Change Small Medium Large Very Large	0 6-26 25-55 53-85 80-120

A.3 Delay Impact of Updating the Green Time based on Model Output

Event	**Change in delay (sec./veh)**				
	subjected direction (EB)	**opposite direction (WB)**	**Cross street (SB)**	**Cross street (NB)**	**Total change in average delay**
One-lane blocked out of three lane road	-96	-3.1	1.6	1.6	-96
Two-lane blocked out of three lane road	-111.9	11.8	7.7	6.5	-86
Demand increment ratio 1.54	-130.2	7.2	6.5	6.6	-109.9

* "-" sign indicates a reduction in delay

** Source: Tariq et al., 2020