DEVELOPMENT OF FRAMEWORK FOR NETWORKING AND SYNCHRONIZATION OF TRAFFIC SIGNAL AT ROAD INTERSECTIONS

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CERTIFICATE

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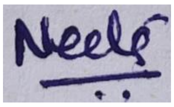

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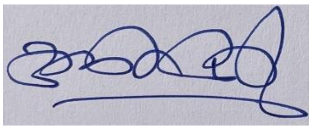

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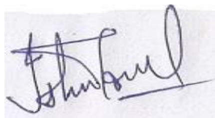

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ABSTRACT

Intelligent transportation systems (ITS) intends to deliver novel services linked to various railways, road and off-road modes of transport. ITS improves real-time decision making operations of the entire transport system. It also addresses the complex issue of effective control and management of traffic at road junctions, signalling and train control systems. Numerous traffic light management systems have been developed to improve the real-time traffic flow at junctions, but none of them have resulted in real-time traffic synchronization or networking of the traffic signals of a region. The complicated architecture of traffic systems does not coordinate/link the timings of traffic signals with the average daily road traffic, which leads to congestion at the intersections. Also, the current systems used for signalling, monitoring and train control systems have various drawbacks related to fault of traction power supply system, train delays, security etc. Thus, there is a need of an adaptive method which resolves the issues of real time traffic signal control and metro railways infrastructure. The objective of this thesis is to suggest robust and effective frameworks to control congestion at intersections and to improve the functionality, efficiency and usefulness of signalling and train control systems. The contributions presented in this thesis are outlined below:

- We propose an intelligent and secure framework for networking and synchronization of traffic signals using traffic information extracted from sensors using Programmable Logic Controller (PLC). The proposed method focuses on calculating the timings of traffic lights on the basis of current lane densities and the densities of peer junctions at various levels using Supervisory Control and Data Acquisition) SCADA for the smooth flow of traffic at intersections and for reducing the congestion at neighboring intersections.
- We propose a solution for facilitation and prioritization of emergency vehicle transit in metropolitan environments. In this technique, sensors are used

along with PLCs to learn and extract traffic information from all the directions at a road intersection. The proposed method is efficient in giving preference to the road with presence of high priority vehicles like VIP, police, ambulance and fire brigade etc. so that they can cross an intersection at their maximum speed.

- We propose the development of real time monitoring and control strategies for metro railways infrastructure. A simulated prototype of an automated metro train system operator has been developed that uses PLC and SCADA for the real time signalling, monitoring and control of the metro railways infrastructure.

Experimental analysis has been done extensively to prove the efficacy of the developed solutions.

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List of Abbreviations

ITS	Intelligent Transportation Systems
CBTC	Communication-based Train Control
V2V	Vehicle-to-Vehicle
V2I	Vehicle-to-Infrastructure
V2X	Vehicle-to-Everything
TUC	Traffic Response Urban Control
GMM	Gaussian Mixture Model
WSN	Wireless Sensor Network
VTL	Virtual Traffic Light
SPaT	Signal Phase and Timing
BSM	Basic Safety Message
DSRC	Dedicated Short Range Communication
CV	Connected Vehicle
VDOT	Virginia Department of Transportation
RSU	Road-Side Units
AIM	Autonomous intersection management
RL	Reinforcement Learning
MARL	Multiagent Reinforcement Learning
GA	Genetic Algorithm
PSO	Particle Swarm Optimization
FCD	Floating Car Data

LGLR	Long Green and Long Red
LoRA	Long Range
FSM	Finite State Model
ATC	Air Traffic Control
CTM-UT	Cell Transmission Model for Urban Traffic
SM	Surrogate Method
OBUs	On-Board Units
BSS	Basic Safety System
D2D	Device-to-Device
TSC	Traffic Signal Control
EtherCAT	Ethernet Control Automation Technology
PLC	Programmable Logic Controller
SCADA	Supervisory Control and Data Acquisition
TJI	Traffic jam/congestion indicator
IPR	Inductive Proximity Sensors
ICS	Industrial Control Systems
DCS	Distributed Control Systems
OCC	Operational Control Center
CATC	Continuous Automatic Train Control
TPSS	Traction Power Supply System
HMI	Human-Machine Interface
RTU	Remote Terminal Units
MTU	Master Terminal Unit
OHE	Overhead Equipment

CCTV	Video Surveillance and Control
IDS	Intrusion Detection System
RVE	Remote Video Engine
VCC	Video Control Centre

Chapter 1

INTRODUCTION

1.1 Need for Traffic Signal Control at Road Junctions and Associated Challenges

The primary goal of an intelligent transportation system (ITS) is to provide better and safer services to multiple modes of transportation and traffic management transportation networks. It improves real-time decision making operations of the entire transport system. ITS address the complex issue of effective control and management of traffic at junctions. Since 1912, traffic light systems have been used to regulate traffic at junctions, pedestrian overpasses, and other locations. For ensuring vehicular traffic safety and consistent flow of traffic, traffic signal control and management at road junctions is a challenging problem in the transportation system. The increase in traffic bottlenecks on a daily basis causes us to run into several problems. Due to the large number of vehicles on the road, transportation infrastructure and distribution system deficiencies are the main causes of traffic congestion. Today's traffic congestion issues negatively affect the metropolitan transportation system and even cause issues for several nations. The development of very congested driving conditions remains a serious issue, especially at major intersection hubs, even after the growth of automated traffic systems.

Intersections are the points where two or more routes interact with each other. Intersections are where crossroads, pedestrians, vehicles, and bikes change their direction. Intersections act as an obstruction/barrier for smooth traffic flow within the urban areas because of the large number of vehicles traveling from one place to another. This leads to traffic interruption, congestion, and poor control and management of the traffic [1,2]. The intersection delay affects the signal control logic and the travel efficiency of road users [3]. According to a study, over 10% of the traffic delays all over the world are due to the fixed traffic signal delays. It was found that over 295 million traffic hours of delay was observed on major road intersections in the United States [4]. Therefore, precise estimates of time-dependent delays are needed at junctions on metropolitan roadways for traffic control and management.

Researchers have been working on the use of numerous approaches for optimizing traffic signal techniques. Various traffic signal management systems have been developed to improve the real-time traffic flow at junctions, but none of them have resulted in a smooth and continuous traffic flow for dealing with congestion at road intersections. Intersection monitoring is required for vehicle/pedestrian classification, traffic monitoring, vehicle counting, security and surveillance, incident prediction and detection etc. An intersection management system consists of applications like monitoring, control and analysis of traffic, data source, target, communication and implementation. Railway systems also play a vital role in today's constantly growing transportation sector. Metro railways deliver fast and convenient travels in the metropolitan cities to the daily commuters. The importance of signaling and train control systems in accomplishing these goals cannot be overstated because they ensure the entire safety of train movements, increased efficiency, and lower operational costs. However, in the course of their study and management, a number of challenges abound as stated here below:

1. The majority of traffic monitoring technologies at junctions rely on high-cost cameras and sensors that are difficult to install and maintain.
2. The complicated architecture of traffic systems does not coordinate/link the timings of traffic signals with the average daily road traffic, which leads to congestion at the intersections.
3. Numerous traffic light management systems have been developed to improve the real-time traffic flow at junctions, but none of them have resulted in real-time traffic synchronization or networking i.e. available methods for traffic signal control do not synchronize the traffic signals of a region.
4. Most of the studies have used complex and costly methods for traffic signal control at road junctions.
5. Existing road traffic controllers do not have any provision for emergency vehicles.
6. Current communication-based train control (CBTC) systems used for railway signalling and train control systems have various drawbacks related to fault of traction power supply system, train delays, security etc.

1.2 Real-time Signalling and Control Systems and Its Issues

Traffic signal control and management at road junctions is a challenging problem in the transportation system. One of the primary causes of the severe traffic congestion in urban areas is the use of conventional traffic signal controllers. Therefore, the growing volume of traffic on urban roads necessitates the implementation of effective traffic control measures, particularly at intersections where mixed traffic and turning movements cause congestion [5]. A crucial safety problem is also the facilitation and prioritization of emergency vehicle transit in metropolitan environments. Traditional methods do not take into account the direction that vehicles are moving, changes in traffic over time, collisions, the passage of emergency vehicles, or pedestrian crossings [6]. Traditional traffic signal controllers do not consider the presence of emergency vehicles into account while determining the light sequences. When more vehicles approach an intersection, the response times and risk of accidents of emergency vehicles also increases because emergency vehicles approach junctions quickly at a very high speed. It is imperative to speed up emergency response times, especially for health and fire-related situations. Therefore, synchronizing the signals over the specific route cannot be addressed.

Earlier, Track circuits and transmission based systems were used for signaling & train control systems in metro railways. With advancements in telecommunications and information technology, the CBTC systems has now been used for railway signaling and train control systems. But these systems have various drawbacks related to fault of traction power supply system, train delays, security etc. Most of the existing algorithms have mostly concentrated on energy-efficient train scheduling and single-train optimum control. Without energy storage devices, the former cannot guarantee the proper application of regenerative energy on the metro lines because it ignores the synchronization of moving and stopping trains. The latter involves planning rail operations to synchronize moving and stopping trains for greater regenerative energy consumption. It is required to take dispatching steps in order to maintain line capacity in the undersupplied area during the power supply shortage brought on by the malfunction of the TPSS in the metro line.

1.3 Problem Statement

There is continual research geared towards studying and management of real time management of public transport system in tasks like real time road traffic management, traffic signal control at road intersections, priority based emergency services, traffic light networking and synchronization, signalling, monitoring and control of metro railways infrastructure. The main objective of this thesis is to develop a framework for networking and synchronization of traffic signals at road intersections. The specific problems addressed in this thesis are as follows:

i. One of the primary causes of the severe traffic congestion in urban areas is the use of conventional traffic signal controllers. Most traffic signal control methods work on the traditional fixed time cycle. This is a challenge for traffic signal control in real time.

ii. A crucial safety problem is also the facilitation and prioritization of emergency vehicle transit in metropolitan environments. Traditional traffic signal controllers do not consider the presence of emergency vehicles into account while determining the light sequences. It is imperative to speed up emergency response times, especially for health and fire-related situations.

iii. The significance of nearby junctions has not been studied in the existing approaches which are used to control congestion at intersections. These works are restricted to one intersection only, which makes the problem appearance more complex and extensive in scope.

iv. Around the core issue of improving the signalling and train control systems, many researchers have focused on the CBTC techniques. Due to unreliable wireless communication and frequency handover, CBTC systems have a significant impact on the functionality, efficiency and usefulness of the train control system. They have a large attack surface. They can be subjected to multiple hacking attacks like network intrusion, data tampering which eventually lead to security hazard.

v. Most of the algorithms proposed in the literature have concentrated on energy-efficient train scheduling and single-train optimum control. It is required to take dispatching steps in order to maintain line capacity in the undersupplied area during the power supply shortage brought on by the malfunction of the TPSS in the metro line.

vi. A majority of traffic management methods do not perform well when tested on large network of roads. Some are not able to distinguish vehicles that are coming from the nearby junctions.

1.4 Scope and Objectives of the Thesis

Automation is required in diverse fields of scientific and technological applications specifically in real time control and management of public transport system applications. Automation assures the improved monitoring and control and also enhances the quality of work performed by control systems. Real time control systems play a key role for multiple uses such as road traffic management, traffic signal control at road intersections, prioritising emergency services, traffic light networking and synchronization, signalling, monitoring and control of metro railways infrastructure. etc. Some of them are briefly discussed below:

- **Traffic signal control.** In studying real-time traffic flow at junctions, various tasks carried out that include communication, vehicle counting, lane identification, intersection classification and analysis of traffic. These tasks are based on explicit and implicit attributes of traffic. Sensors and cameras play a crucial role extracting the attributes and automating the stated tasks. Various traffic signal management systems have been developed to improve the smooth and continuous traffic flow for dealing with congestion at road intersections.
- **Synchronization of traffic signals.** Delay caused by the status of one light at a crossroad impacts the flow of traffic at neighboring intersections also. Networking and synchronization of traffic signals requires exploration on the significance of nearby junctions. The regular traffic system must be upgraded in order to alleviate traffic congestion and minimize waiting times and travel time as well as maximize vehicle safety, efficiency, and economic benefits. More efforts are made in order to obtain maximal modeling, control, and monitoring of several synchronized junctions.
- **Signalling and train control systems for metro railways.** These systems ensure the entire safety of train movements, increased efficiency, and lower operational costs. Earlier, track circuits and transmission based systems were used for signaling & train control systems in metro railways. With advancements in telecommunications and information technology, CBTC

systems are used nowadays for railway monitoring, signaling and control systems. These systems are used for tracking fault of traction power supply system, train delays, security etc. More concentration is needed on energy-efficient train scheduling and single-train optimum control.

Real time control and management of public transport system is required for various reasons and challenges associated with getting the information at real time have been discussed in section 1.1. The following are the objectives of the thesis:

- ❖ For controlling congestion at intersections, it should first be considered the significance of nearby junctions. Thus, an intelligent and secure framework is required for networking and synchronization of traffic signals at road intersections that is efficient in determination of traffic light timings on the basis of current lane densities and the densities of peer junctions at various levels.
- ❖ Some of the major challenges associated with intersection management is the facilitation and prioritization of emergency vehicle transit in metropolitan environments. Traditional traffic signal controllers do not consider the presence of emergency vehicles into account while determining the light sequences. Therefore, there is need to develop techniques to speed up emergency response times (especially for health and fire-related situations) that are robust in the presence of the challenges.
- ❖ Due to unreliable wireless communication and frequency handover, CBTC systems have a significant impact on the functionality, efficiency and usefulness of the train control system. Efficient methods are needed especially when working with signalling and train control systems where there is possibility to multiple hacking attacks like network intrusion, data tampering which eventually lead to security hazard.
- ❖ Energy-efficient train scheduling and single-train optimum control are prime attributes of signalling and train control systems that are challenging to undertake. It is required to take dispatching steps in order to maintain

line capacity in the undersupplied area during the power supply shortage brought on by the malfunction of the TPSS in the metro line.

1.5 Contributions in the Thesis

The problems mentioned in section 1.3 informs our motivation to come up with their solutions which are presented in detail in this thesis. In this thesis, effective solutions have been put forward to address the challenge of real time road traffic management, congestion control at road intersections, priority based emergency services, traffic light synchronization, networking of traffic signals of an area, improved PLC & SCADA based control systems for public transport i.e. metro railways. The main contributions of the work done in this thesis are as follows:

1. An insightful discussion has been done on several traffic light synchronization research papers to highlight the practicability of networking of traffic signals of an area for the smooth flow of traffic at intersections and for reducing the congestion at neighboring intersections.
2. We developed an intelligent and secure framework for networking and synchronization of traffic signals at road intersections. Traffic information at a particular intersection has been extracted from sensors using PLC which are in turn used to train the real time control system with help of SCADA. We focused on calculating the timings of traffic lights on the basis of current lane densities and the densities of peer junctions at various levels.
3. An emergency vehicle management technique is designed that is efficient in giving preference to the road with presence of high priority vehicles like VIP, police, ambulance and fire brigade etc. so that they can cross an intersection at their maximum speed. In this technique, sensors are used along with PLCs to learn and extract traffic information from all the directions at a road intersection.
4. Real time monitoring and control strategies have been developed for public transportation. In these techniques, a simulated prototype of an automated

metro train system operator has been developed that uses PLC and SCADA for the real time signalling, monitoring and control of the metro railways infrastructure.

1.6 Outlines of the Thesis

The thesis layout is as follows:

1. **Chapter 1: Introduction**

   Chapter 1 discusses nature and significance of real time management of public transport system along with various traffic signal control strategies used at road junctions, signaling and control systems for metro railways and challenges associated with them. Contributions and thesis layout are also discussed.

2. **Chapter 2: Literature Review**

   Chapter 2 discusses the related works used in various tasks and processes pertaining to real time management of public transport system. The approaches focus on traffic signal control at road intersections, real time road traffic management, priority based emergency services, traffic light synchronization, signalling, monitoring and control systems for metro railways. It also highlights the practicability of networking of traffic signals of an area and provides potential directions for further research in this area.

3. **Chapter 3: Design & Development of Technique for Synchronization of Traffic Signals at Road Intersections**

   This chapter presents a technique for developing a framework for networking and synchronization of traffic signals at road intersections to decrease waiting time of vehicles and improve traffic flow in large cities. Traffic light timings are determined using PLC on the basis of current lane densities and the densities of peer junctions at various levels. Chapter is concluded with results and comparative analysis with the related work.

4. **Chapter 4: Design & Development of Technique for Emergency Vehicle Management at Road Intersections**

   The chapter presents a technique using PLC for emergency vehicle management which gives preference to the road with presence of high priority vehicles. The method utilizes the traffic density information collected from sensors or cameras.

5. **Chapter 5: Real Time Monitoring and Control Strategies for Public Transport**

   This chapter discusses a PLC and SCADA based methodology adopted for developing real time monitoring and control strategies for public transport infrastructure. A simulated prototype of an automated metro train system operator has been proposed here for the real time monitoring and control of the metro railway systems.

6. **Chapter 6: Conclusion & Future Directions**

   In this chapter, the brief summary of all the ideas, observations and contributions of each objective are presented in summary. Also, future work is outlined.

Chapter 2

LITERATURE REVIEW

2.1 Introduction

The design of an intelligent traffic light control system and railways monitoring and control systems is an active research topic. Many researchers are working on the design and development of intelligent traffic signal control systems to solve this stressful issue. New methods and advanced systems based on artificial intelligence, fuzzy logic, swarm intelligence, evolutionary algorithms [7], image processing, neural network, data fusion, and linear programming etc. have been proposed by the researchers to solve this TSC problem. The categorization of existing literature on techniques used for signalling and train control systems and congestion control at road intersections has been done in this chapter. Figure 2.1 presents the year-by-year trend of the papers published in the area between 1990 and 2021.

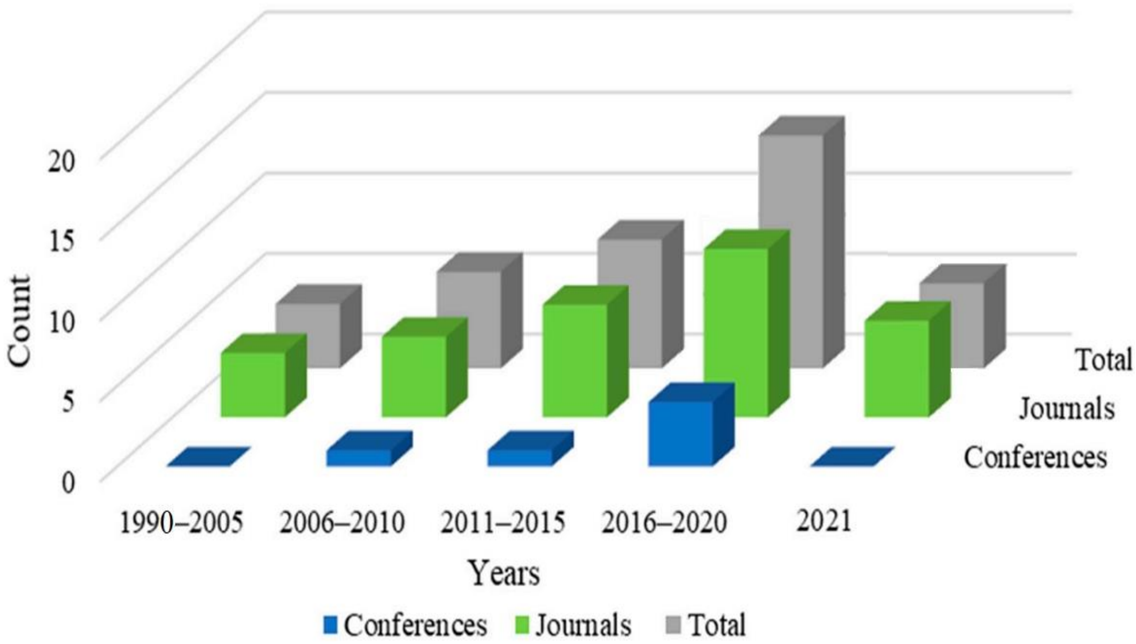


Figure 2.1. Number of papers published in TSC domain from 1990 to 2021

2.2 Background of Traffic Signal Synchronization for Intelligent Vehicles

The development of traffic signal synchronization for intelligent vehicles is derived from the traffic light control technology. To better understand the synchronization of traffic lights concept, this section outlines the traffic light control technology and analyzes the advantages of synchronization of traffic lights.

Numerous traffic light management algorithms have been developed so far to improve the real-time traffic flow at junctions, but none of them have resulted in real-time traffic synchronization or networking. The rising trend reflects the increasing popularity in the subject and emphasizes the importance of current research. Intersection monitoring is required for vehicle/pedestrian classification, traffic monitoring, vehicle counting, security and surveillance, incident prediction and detection etc. Table 2.1 illustrates the classification of components and applications of intersection management. An intersection management system consists of applications like monitoring, control and analysis of traffic, data source, target, communication and implementation. Application includes functions like traffic monitoring, control and analysis. Data can be captured from the infrastructure and vehicle side. Target includes the different types of objects that interact at an intersection for e.g. pedestrians and vehicles. Communication part allows the sharing of information between vehicles and infrastructure entities using Vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I) and vehicle to everything(V2X) communication approach using several protocols and standards. Implementation and evaluation can be done using simulators, making functional prototypes or scale-models.

Table 2.1. Classification of components and applications of intersection management

Application	Data Source	Target	Communication	Implementation
Monitoring: • Recognition • Detection • Tracking Control: • Traffic control • Warning advertisement • Traffic rules supervision Analysis: • Traffic flow • Path analysis • Context and behavior	Infrastructure: • Presence sensors • Range sensors • Image sensors • RFID and wireless Vehicle: • Position • State • Travel information	• Pedestrians • Bicycles • Motorcycles • Small Vehicles • Large Vehicles	• V2V - Vehicle to vehicle • V2I - Vehicle to Infrastruc-ture • V2X - Vehicle to anything	• Real • Simulation • Augmented Reality • Dataset • Scale-model

2.2.1 Traditional Traffic Control Methods

Various traffic management techniques have been used for a long time for traffic monitoring and control to reduce delays at junctions. SCOOT [8], SCATS [9], OPAC [10], RHODES [11], PRODYN [12], and MOTION [13] are examples of adaptive traffic control systems that were designed and implemented in several cities in recent decades. SCOOT [8] and SCATS [9] are adaptive traffic control strategies. These systems use loop/magnetic detectors for gathering traffic data. However, the limitation in these methods is that they do not provide the vehicle's speed, heading, and position. While SCATS is a fully computer (microcomputer, regional computer, and central computer)-based system, it is very expensive to use. Unlike SCOOT and SCATS, PRODYN [12] is not based on cyclic settings.

PRODYN addresses the global traffic problem using a two-level iterative computation structure after decomposing the enormous initial optimization problem into multiple smaller problems answered via Dynamic Programming.

These adaptive traffic systems generate a "green signal" for large vehicle flow by optimizing the network's traffic signal offset values according to the current traffic demand. Both real-time and predicted traffic arrivals are used in these systems to optimize the objective functions. These systems have significant drawbacks in terms of cost and functionality because they use cameras and loop/magnetic detectors to track vehicles. The initial implementation cost of the system is around $30,000/junction having a cost of $28,800 per mile/year [14]. Moreover, these systems need a large communication infrastructure that is capable of supporting a centralized control with a high data rate. As a result, many cities across the world have developed systems with high implementation cost.

The Webster procedure was used for fixed signal control at isolated junctions [15] for operation based on measured flows. In this method, the cycle length of every intersection is calculated using Webster's equation. The highest cycle length will act as the cycle length of the whole system. This modified demand-based strategy is viable for real-time undersaturated traffic conditions. In fact, the Traffic Response Urban Control (TUC) technique may be utilized to eliminate the predetermined static signal control sequence, which may lead to more successful outcomes than the original TUC approach. However, the issue is that this technique is quite complex.

2.2.2 Vision-Based Traffic Control Methods

A video camera was utilized to predict and monitor real-time traffic using a dynamic Bayesian networks technique in [16]. In this computationally light method, the distribution of spatial interest and spatiotemporal interest points is classified using the Gaussian mixture model (GMM), and then, the dynamic Bayesian approach is used.

Feature-based approaches [17] and neural networks [18] are also used to recognize and track vehicles coming toward an intersection. Feature-based methods track the features less sensitive to partial occlusion. This approach was ineffective for real-time TSC due to its low accuracy and large storage requirements. In these feature-based methods, binarization, rule-based logic, cameras, and road conditions are used to identify vehicles, which makes the process complex and tedious.

Indu et al. [19] proposed a simple but expensive adaptive traffic signaling system that uses video camera data to provide equal green light timings and then allocates enough time using a fair weight and optimal weight calculation algorithm. Vehicle tracking and image segmentation algorithms become ineffective for real-time operations because of the computational complexity and longer execution time. However, some are not able to operate effectively at night or in variable weather conditions. Zheng et al. [20] use neural networks to predict the upcoming traffic volume from a 15-min daylight traffic flow on an expressway. As a result of the high complexity and memory needs, this approach is unsuitable for real-time systems.

2.2.3 Sensor-Based Traffic Control Methods

Sharma et al. [21] presented a method that assigns equal green signal duration and arrange fair lane departure at an intersection using the GPS data of the users. Wang et al. [22] proposed a data fusion approach that collects the data on the speed, position, and direction of the vehicles approaching junctions with the help of GPS sensors in vehicles. This method only improves the traffic flow on a road network; it does not control the traffic signal timing.

Other strategies such as detectors [23], on-board GPS, and big data technologies [24,25] are also used to monitor the arrival and departure of vehicles at a junction to reduce the congestion in urban areas. For monitoring the local traffic in a region, sensors and traffic servers are also used. Embedded technology [26] records the GPS data of vehicles and sends it to the traffic monitoring system through GSM/GPRS. This method has a very high implementation cost.

Coll et al. [27] introduced an adaptive system based on linear programming that controls the traffic lights and reduces the waiting time at intersections. This method uses the data gathered from the real-time sensors placed at every intersection.

TSC systems based on Wireless Sensor Network (WSN) have also been used at isolated intersections in [28,29]. Rida et al. [28] proposed a time-fragment based control mechanism that splits the time and calculates the percentage of green ratio. Yousef et al. [30] proposed a connected vehicle-based algorithm for isolated junctions that uses vehicle proximity for releasing vehicle platoons.

2.2.4 Connected Vehicle -Based Traffic Control Methods

Another technique to adaptive decision making is the Virtual Traffic Light (VTL) approach [31], which is a Vehicle-to-Vehicle traffic control system with enormous potential, since it may increase traffic flow by more than 30% while eliminating the usage of expensive traffic signals. VTL makes use of V2V communication using the Signal Phase and Timing (SPaT) message and Basic Safety Message (BSM) from the Dedicated Short Range Communication (DSRC) radio for traffic management at intersections. The drawback of this approach is that it requires full penetration of DSRC technology in vehicles, which is not possible at the present time. Furthermore, V2V communications in VTL could come across non-LoS conditions, which makes rapid decision making extremely challenging [32].

A connected vehicle (CV) initiative [33,34] was established by the Virginia Department of Transportation (VDOT) to focus on different V2V and Vehicle-to-Infrastructure (V2I) applications. This program intends to lower the cost of infrastructure for roadside guidance signs and traffic lights by using DSRC technology. However, the complete penetration of the DSRC is required for the connected corridor setup.

Tonguz et al. [35] presented a DSRC-based traffic management method for road intersections. Roads with DSRC-equipped automobiles are given precedence under this system. Even if a small number of vehicles have DSRC technology, this strategy can be effective in reducing the average waiting time on each traffic light. When compared to alternative TSC systems that use detectors, sensors, and cameras, this technique provides a cost-effective solution for traffic management in urban areas by simply using DSRC Road-Side Units (RSUs).

Dresner et al. [36] describes autonomous intersection management (AIM) utilizing multiagent systems, in which drivers and junctions are considered as autonomous entities. Intersections employ a completely new reservation-based technique based on a detailed communication protocol in this mechanism.

2.2.5 Learning Based Traffic Control Methods

Many studies have recommended using reinforcement learning (RL) to regulate traffic lights and reduce traffic congestion [37,38]. Unlike traditional TSC systems, which depend mainly on predefined models, RL may learn immediately from input. Every junction in RL is portrayed as an agent that optimizes its input-based travel time from the surroundings when the action (i.e., the traffic lights) is set [39].

Zheng et al. [40] suggested a FRAP model based on phase competitive modeling, which achieves invariance in traffic flow flipping and rotation conditions. In complicated traffic situations and multi-junction configurations, this system discovers better solutions and delivers greater performance than prior learning methods.

To overcome the fixed traffic signal problem, ref. [41] proposes a novel MARL (Multiagent Reinforcement Learning) approach called Co-DQL, which stands for co-operative double Q-learning. The overestimation problem that affects traditional independent Q-learning is avoided with Co-DQL. TSC simulators are used to test various traffic flow conditions. MARL provides a new reward allocation mechanism for boosting agent stability and resilience.

Joo et al. [42], WeiHua et al. [43], and Zhang et al. [44] investigated some recent improvements in RL techniques that may be applied to solve difficulties with traffic signal regulation. They describe the usage of PPO, A2C, and ACKTR algorithms to handle the problem of partial vehicle detection.

For TSC, Zhang et al. [45] proposes a deep Q-learning approach with partial vehicle identification using DSRC. This system has the benefit of being able to identify cars utilizing different detection technologies such as LTE/5G, BLE 5.0, and RFID.

2.2.6 Miscellaneous Traffic Control Methods

Dezani et al. [46,47] used genetic algorithm (GA) to optimize traffic signals in real time and determine the optimal paths for cars. With the use of a basic neighborhood algorithm, Sabar et al. [48] enhanced GA by using a local search strategy that lowers the average delay in traffic even more than feasible.

In a nine-junction network, Li and Sun [49] suggested a multifunctional GA for traffic optimization. However, this method did not use real-time traffic data. For traffic light scheduling, refs. [50–52] employ a particle swarm optimization (PSO) technique to regulate traffic lights to minimize the waiting time at intersections so that vehicles can reach their destination in the minimum feasible time. Other swarm intelligence algorithms used for TSC include Ant Colony Optimization [53,54] and Harmony search [55,56].

Milanés et al. [57] presented a V2V communication-based method for reducing traffic congestion at intersections by utilizing the speed and location of autonomous vehicles.

Bi et al. [58,59] presented a type-2 FLC system to solve the coordination and complicated uncertainty issues in heavy but organized traffic. (based on fuzzy and Q learning). Firdous et al. [60,61] developed a real-time control system based on fuzzy logic to reduce vehicle waiting times at intersections. Table 2.2 illustrates the categorization of existing literature on techniques used for congestion control at road intersections.

Table 2.2. Categorization of existing literature on techniques used for Congestion control at Road intersections

Reference Number	Objective/ Context	Type of Intersection			Traffic Signal Control Strategies		Source of Data Collection			Comments
		Isolated	Single	Network	Real Time	Fixed Time	Sensors/ Detectors	Field Cameras	GPS/DSRC	
[8]	Split Cycle Offset Optimization Technique (SCOOT)			✓	✓		Detectors			• Minimize stops and delays at intersections by synchronizing adjacent signals. • Disadvantage: Increased overhead during heavy traffic in large complicated network
[9]	Sydney Cooperation Adaptive Traffic System (SCATS)			✓	✓		Sensors			• Monitors real-time traffic signals and a volume of traffic. • Reduces average waiting time, travel time and fuel consumption
[10]	Optimized Policies for Adaptive Control (OPAC)			✓	✓		✓			• Calculates signal timing by minimizing total delay and stops performance function. • No special features for priority/pre-emption on the system level. • No explicit features for pedestrians or oversaturation conditions.
[11]	Real-Time Hierarchical Optimized Distributed Effective System (RHODES)			✓	✓		✓			Decomposition of traffic network by modules that individually deal with sub-problems
[15]	Traffic signal control of road	✓				✓				Based on Webster procedure

	networks in real time									
[16]	Traffic monitoring and prediction on roads		✓		✓			✓		• Uses dynamic Bayesian networks approach • Real time prediction and classification of the state of a road • Improvement of travel and transit information.
[17], [18]	Travel time prediction framework	Freeway			✓		Robust Travel Time framework			• Based on State-space Neural Network • Based on Bayesian combined Neural network
[19]	To reduce waiting time of vehicles at road intersections		✓		✓			✓		A video-based adaptive traffic signalling system
[21]	Assign equal green signal durations and arrange fair lane departure at an intersection			✓	✓				GPS	Adaptive traffic signal timings and lane scheduling
[22]	To enhance the flow of traffic on current road network using a data fusion approach			✓	✓				GPS	• Using floating car data (FCD) • Improve traffic flows on roads
[23]	Traffic signal control system		✓		✓		✓			• Using two-stage fuzzy control system • Reduces the average vehicle delay
[27]	To minimize the waiting time at a crossroad			✓	✓		✓			• Using a linear programming model, • Minimize the queue length of vehicles waiting at intersections.
[28], [29]	WSN based traffic light control systems			✓	✓		✓			• Low cost installation to existing traffic road infrastructure, • Self-configurable, Easy installation of

										new traffic sensor nodes
[30]	TSC at signalized intersections	✓			✓		V2V Communicatio n			• Using connected Vehicle technology • Minimize average delay
[31]	V2V traffic control for traffic management at intersections		✓		✓				DSRC	Virtual Traffic Light phenomenon based on DSRC
[33], [34]	Removal of intersection traffic signal infrastructure			✓	✓				DSRC	• Connected and autonomous vehicle program (CV) • V2V and V2I applications
[35]	Intersection traffic control scheme				✓				DSRC	Based on DSRC-Actuated Traffic Control
[36]	Autonomous intersection management (AIM)			✓	✓		Simulator			• Operate both human-driven and autonomous cars • Prioritises emergency vehicles.
[40]	Reinforcement Learning based traffic signal control			✓	✓		Mathematical Model			• FRAP (Flipping and Rotation and considers All Phase configurations) model • Gives priority to the road with high traffic density. • Better performance in complicated traffic situations and multi-junction environment
[41]	Traffic signal control at a very large scale using Multiagent reinforcement learning (MARL) technique			✓	✓		Simulator			• Using cooperative double Q-learning (Co-DQL) • Stable and robust

[45]	Deep Q-learning algorithm based system for partially detected intelligent vehicles			✓	✓				DSRC	• Minimize the vehicles waiting time at junctions (even if the detection rate of vehicles in low) • Can be used with different detection technologies like LTE/5G, BLE 5.0 and RFID.

2.3 Development Status of Synchronization of Traffic Lights

Synchronization of traffic signals across a city is supported by traffic light control frameworks. When automobiles pass through a junction network, these frameworks lower the amount of time they have to wait. To enhance traffic flow efficiency at high-density junctions, Hu et al. [62] employed a long green and long red (LGLR) technique for synchronizing the traffic lights of an area. For smoothening the traffic flow across the city, ref. [63] employed a real-time system for the synchronization of traffic lights using multiagent fuzzy logic and the Q-learning approach.

Amogh et al. [64] presented a method for improving traffic synchronization efficiency by dynamically modifying timing settings. This system uses traffic cameras to obtain vehicle density at each intersection and then uses OpenCV to conduct operations on the pictures.

Khan et al. [65] proposes a self-organized TSC system based on sensors. It improves the efficiency of traffic flow and reduces the waiting time at intersections. In comparison to traditional traffic management systems, this technology gives more information and prioritizes the road with a large number of cars at an intersection first. However, this approach does not synchronize the traffic lights of all the intersections.

V2I connectivity was utilized in [66] for the networking of junctions and other road signs. It is used to transmit information on infrastructure such as speed restrictions, road alterations, and traffic light information to smart cars.

Sirikham et al. [67] presented a traffic light synchronization system that used two control boards, a sender and receiver. These control boards use the NodeMCU V.2 (2.4 GHz WiFi) to synchronize the control signals by ESP-NOW protocol. However, this system works only for single-lane traffic control.

Kumar et al. [68] proposed a synchronization method for two traffic signals using the Long Range (LoRa) module. It uses the time division algorithm to get the traffic information so that the rerouting of vehicles can be done during the peak hours. This concept helps the vehicles reach their destination in the shortest possible time by taking the fastest route.

A synchronization scheme for traffic light controllers based on an explicit finite state model (FSM) is presented in [69]. FSM is modeled using Verilog HDL, and the coding is done using Xilinx Spartan-6 XC6LX16-CS324 FPGA. The machine is merely simulated with six states, which are selected using the traffic control method. Each state provides the appropriate delay, and the requisite traffic signals are turned ON/OFF for that delay. For example, just two routes are picked, and a control algorithm controls the traffic lights on those roads. This study introduced a flexible architecture that uses a clock divider to give a delay in a certain state and discusses the difficulty of modeling the FSM. The topic of selecting a state-encoding technique was also discussed.

A self-synchronization mechanism for aerial vehicles and air traffic control (ATC) systems was introduced in [70] for avoiding collision. It assists in obtaining a unique path for each aircraft in order to reduce conflict, but if this is not possible, the system gives an optimum option to utilize other shared resources.

An adaptive, flexible, and robust distributed TSC method based on spontaneous synchronization was introduced in [71], which occurs when local interaction leads to a stable state. In this method, every junction is represented by a phase-oscillator model. The global coordination is achieved by synchronizing these phase oscillators to maintain the platoons flow.

Adacher et al. [72,73] proposed a distributed algorithm for solving the synchronization problem of urban traffic signals. They calculated the weighted sum of delays at signalized intersections by CTM-UT; i.e., (Cell Transmission

Model for Urban Traffic) via simulation. A surrogate method (SM) based on an online and stochastic control scheme has been used to synchronize the traffic signals.

An IoT-based traffic signal synchronization method was proposed in [74] to reduce the traffic congestion at road intersections. This method allows the vehicles to travel a long distance by minimizing the number of STOP and GO occurrences by adapting the traffic light phases at the road intersections. This method reduces the average travel time up to 39% using traffic simulator SUMO in comparison to the other fixed time and non-synchronized traffic control strategies.

Nesmachnow et al. [75] introduced the synchronization of traffic lights using a parallel evolutionary algorithm for Bus Rapid Transit systems by considering various features such as real maps and mobility data and analyzing these features for optimization. This method improves the average speed of public transport up to 15.3% and other vehicles up to 24.8%. Using this method, different priorities can be assigned to buses and other vehicles using a multi-objective optimization analysis.

A model for synchronizing the traffic lights at road intersections is presented in [76]. This method uses a hybrid metaheuristic approach that combines variable neighborhood search and Tabu search into one algorithm. The method incorporates a memory structure into an iterative local search, allowing for a wider range of solutions. Certain changes such as modification of a mixed integer linear model's constraints and the generalization of some bounds for integer variables were made to the MAXBAND in this algorithm.

In [77], the decentralized spatial decomposition of a network has been used for the synchronization of traffic signals at the road junctions. This method uses the platoon model to calculate the weighted sum of delays induced by signalized crossings. To get a spatial breakdown of the network, distributed consensus approaches were utilized. Using the distributed communication architecture, each semaphore distributes information with its neighbors in a totally dispersed manner, hence removing the need for a central authority. A surrogate technique is used for synchronizing the traffic signals given the subnetwork.

A self-synchronization paradigm for connected vehicles in traffic networks has been used in [78] to solve the coordination problem at junctions. For safe spacing between cars moving on the same route, coordinating safe crossing at junctions with competing flows, a multilayer decentralized control method is utilized. The Kuramoto equation is used to synchronize the phase and frequency of the network's agents (vehicles). This approach considered the vehicles as oscillating agents instead of the traffic lights. This technique is classified as a decentralized approach since it is interconnected to achieve network-wide synchronization. It combines the advantages of coordinating vehicle crossings at particular crossroads with synchronizing flow from nearby junctions in this way.

In [79], floating car data (FCD) was used to synchronize the traffic signals at intersections. This approach used the penetration rate of "instrumented" vehicles to obtain synchronization in adaptive traffic light systems based on floating car data (FCDATS) in competition cooperation. This technology increases the traffic safety and energy efficiency of transportation systems.

Yang et al. [80] used cellular automaton for synchronizing traffic signals by building a network model of two intersections. By changing the signal duration and green time offset, the synchronization of the signals is investigated, and results are obtained in MATLAB. An optimal signal scheme reduces the overall delay and increases the traffic flow at road junctions. Next, the network's essential features, such as fundamental and time–space diagrams, are addressed.

Li et al. [81] introduced a time synchronization method among VANET devices, claiming that On-Board Units (OBUs) can synchronize with other OBUs or RSUs on their own initiative. This technique lowers the synchronization error to less than 0.3 ms when there is no center node in the Basic Service Set, which fulfills the accuracy criterion of the VANET specification. In the Basic Safety System (BSS), a time-synchronization mechanism is introduced in which there is no central node, resulting in a more stable network. This method can achieve nanosecond precision while avoiding estimate errors. This method can correctly implement time synchronization in a BSS. In addition, there is a topology for the whole VANET in order to achieve time synchronization among RSUs. As a result, the amount of handoff done by OBUs can be drastically decreased. It can also greatly increase the system's stability.

A survey of the synchronization techniques is presented in [82], which addressed various situations and current cellular network generations while reviewing synchronization standards and approaches for V2V and Device-to-Device (D2D) enabled cellular networks. They looked at the major channels, entities, and signals that V2V and D2D enabled cellular networks employ for synchronization in various circumstances. Furthermore, to highlight current developments and give future perspectives, the focus is on synchronization in V2V and Vehicle to Everything (V2X).

Du et al. [83] presented a rule-based algorithm for V2X speed synchronization at road junctions. Vehicles entering from separate lanes form a virtual platoon. When traffic is light, this system allows for fewer unnecessary stops, resulting in energy savings and an increase in average speed. As a result, speed synchronization is no longer effective, as the volume of traffic increases and cars must come to a halt. Virtual platooning is expanded here by introducing some principles that enable a virtual platoon to dynamically modify its whole behavior in response to traffic flow growth while maintaining safety. This technique is extremely efficient in boosting average speed while maintaining the intersection's high capacity. Despite the previous research in this domain over the last five decades, improved traffic signal control framework administration is still required.

2.4 Monitoring and Control of Metro Railways

D. He et al. [84] proposed a mathematical approach for energy conservation in metro trains on the basis of regenerative braking. This approach used the control theory of matrix and calculus to improve the renewable energy utilization ratio and energy efficiency. Mouna et al [85] analyzed the vulnerabilities and security risks in monitoring and control of railway systems.

W. Carvajal-Carreño et al. [86] proposed a fuzzy logic-based tracking algorithm for energy-efficient operation of CBTC equipped metro trains. They used the actual attributes of automatic train operations system which uses the coast command to save energy and accounts for the ambiguity around the previous train's speed.

Using information from the 3-axis accelerometers in cellphones, Wang et al. [87] developed a data-fusion strategy for the speed estimation and position calibration of metro trains in an underground scenario. The lateral, longitudinal and vertical accelerations of a train are measured using multiple cellphones placed in various train cars. The observed accelerations are then converted from the smartphone coordinate systems to those of the metro train.

J. Yin et al. [88] suggested a technique to reduce operational costs and waiting time on metro lines. This method used a Lagrangian relaxation (LR)-based heuristic algorithm [89] to reduce the computational complexity. A. Carrel et al. [90] proposed a framework for studying train operations control decisions that incorporates service and passenger movement data. On the basis of automatically gathered data, a technique was used to analyze metro line operations to highlight potential weaknesses in particular operations control tactics.

Bai et al. [91] presented a paradigm for cooperative control of multiple trains in real-time using cooperative co-evolutionary algorithm. Using this method, one can find out the current status of metro trains on the extents of locations of train operation mode switches, braking of train acceleration and station stopping. In order to reduce net energy consumption, it seeks to determine the best locations throughout inter-station runs to switch between train operation modes and the degrees of driving and braking for various trains. A cooperative control strategy has been used in [92] to deal with the problem of fault in TPSS in metro rail system. This approach used the imaginary section method and space-time-speed (STS) network methodology so that the line capacity can be maximized during disruption.

2.5 Conclusion

Numerous approaches for optimizing traffic signal techniques have been studied in the literature. Various traffic signal management systems have been developed to improve the real-time traffic flow at junctions, but none of them have resulted in a smooth and continuous traffic flow for dealing with congestion at road intersections. The significance of nearby junctions has not been studied in the above cited research works. These works are restricted to one intersection only, which makes the problem appearance more complex and extensive in scope. More efforts should be made in order to obtain maximal modeling, control, and monitoring of several synchronized junctions. We also studied about different track circuits and transmission based systems which were used for signaling & train control systems in metro railways. Current communication-based train control systems used for railway signalling and train control systems have various drawbacks related to fault of traction power supply system, train delays, security etc. Therefore, we need efficient the real time signalling, monitoring and control strategies for the metro railways infrastructure.

Chapter 3

DESIGN & DEVELOPMENT OF TECHNIQUE FOR SYNCHRONIZATION OF TRAFFIC SIGNALS AT ROAD INTERSECTIONS

3.1 Introduction

This chapter presents an intelligent and secure framework for networking and synchronization of traffic signals at road intersections using PLC and SCADA. The whole operation is regulated with the help of OMRON (NX1P2-9024DT1) PLC and OMRON's Sysmac studio programming software is used for developing the ladder logic of PLC. SCADA is used for the visualization of the whole automated process operation using Wonderware InTouch SCADA software. Traffic information at a particular intersection is extracted from sensors using PLC which are in turn used to train the real time control system with help of SCADA. In this chapter, a SCADA based traffic simulation model is built for the visualization of a traffic signal synchronization operation where the whole operation is regulated with the help of PLC. For a duration of 9-hours, 300 vehicles are deployed randomly across 81 linked intersections to compare the conventional fixed time traffic control system with the proposed PLC and SCADA based traffic control system using this simulator. The traffic jam indicator and average waiting time of the entire journey is recorded for all 300 vehicles and 81 intersections. This chapter focuses on determination of traffic light timings on the basis of current lane densities and the densities of peer junctions at various levels. It explores the key role of real-time traffic signal control (TSC) technology in managing congestion at road junctions within smart cities.

3.2 Related Work

For ensuring vehicular traffic safety and consistent flow of traffic, traffic signal control and management at road junctions is a challenging problem in the transportation system. ITS address the complex issue of effective control and management of traffic at junctions. Intersections are the points where two or more routes interact with each other. Intersections are where crossroads, pedestrians, vehicles, and bikes change their direction. Intersections act as an obstruction/barrier for smooth traffic flow within the urban areas because of the large number of vehicles traveling from one place to another. This leads to traffic interruption, congestion, and poor control and management of the traffic. The intersection delay affects the signal control logic and the travel efficiency of road users [3]. There should be a balance in between safe and effective traffic control at the intersections in order to allow the maximum vehicles to move through while maintaining safety.

Nowadays, traffic-light signaling is used to regulate traffic at crucial junctions/crossings by distributing the same green light timings to all routes [93]. The complicated architecture of traffic systems does not coordinate/link the timings of traffic signals with the average daily road traffic, which leads to congestion at the intersections. Various metropolitan cities such as New Delhi, Bangalore, and Mumbai are going through this imbalanced/uneven traffic flow scenario in cities because the majority of working people live in the neighboring areas. The traffic imbalance is generally seen during the peak hours (morning and evening) when people drive from their jobs and residency. Numerous traffic light management systems based on artificial intelligence, fuzzy logic, swarm intelligence, evolutionary algorithms [7], image processing, neural network, data fusion, and linear programming etc. have been developed to improve the real-time traffic flow at junctions, but none of them have resulted in a smooth and continuous traffic flow for dealing with congestion at road intersections. As a result, metropolitan cities require an updated traffic signal control mechanism/technique that updates traffic signal timing and synchronizes the traffic signals at the road intersections on the basis of real-time traffic information.

Synchronization of traffic signals across a city is supported by traffic light control frameworks. When automobiles pass through a junction network, these frameworks lower the amount of time they have to wait. Despite the previous research in this domain over the last five decades, improved traffic signal control framework administration is still required. For large-scale TSC, synchronization provides a number of advantages. Synchronization is not reliant on any network design or set of rules. This is perfect for network traffic management. When the system's most comparable entities synchronize, it is called synchronization. When traffic signal timing and traffic conditions at nearby intersections are comparable or matching, adaptive and smooth traffic signal coordination can be achieved.

3.3 Problem Statement

Delay caused by the status of one light at a crossroad impacts the flow of traffic at neighboring intersections also. Networking and synchronization of traffic signals requires exploration on the significance of nearby junctions. The regular traffic system must be upgraded in order to alleviate traffic congestion and minimize waiting times and travel time as well as maximize vehicle safety, efficiency, and economic benefits. More efforts are made in order to obtain maximal modeling, control, and monitoring of several synchronized junctions. For controlling congestion at intersections, it should first be considered the significance of nearby junctions. Thus, an intelligent and secure framework is proposed in this chapter for networking and synchronization of traffic signals at road intersections that is efficient in determination of traffic light timings on the basis of current lane densities and the densities of peer junctions at various levels. This chapter also provides an insightful discussion on traffic light synchronization to highlight the practicability of networking of traffic signals of an area.

3.4 Synchronization of Traffic Signals

The proposed system decreases average waiting time of vehicles at junctions and enhance traffic flow by applying various processes to traffic lights, without any significant modifications in the infrastructure. In this method, the whole operation is regulated with the help of PLC. Every PLC works on Ethernet or serial communication like RS 242 or RS 485, but the PLC used in this process i.e. OMRON (NX1P2-9024DT1) works on EtherCAT which provides high speed, low latency/delay and incredible synchronization. The proposed PLC and SCADA systems framework is intelligent and secure because SCADA is more secure as compared to other systems because other systems in the literature have a large attack surface. They can be subjected to multiple hacking attacks like network intrusion, data tampering which eventually lead to security hazard. Whereas, there is no such kind of problem with SCADA systems. There are less subjected to multiple hacking attacks like network intrusion, data tampering.

3.4.1 EtherCAT

EtherCAT (Ethernet Control Automation Technology) provides more fast and effective communication based on Ethernet. An EtherCAT is system a with high performance industrial network that can support up to 65,535 devices. By sending Ethernet frames at a faster rate, each node is able to maintain a rapid communication cycle time. EtherCAT is a distinct protocol which has strong general-purpose application. EtherCAT uses common Ethernet technology for the physical layer. Furthermore, EtherCAT's efficiency can be fully leveraged in all small, medium and large control systems that need fast processing and better system integrity. EtherCAT provides the following features.

- Flexible topology
- Network performance
- Integrated Safety
- High-speed Communications at 100 Mbps
- Onboard diagnostics with fault localization,
- Suitable for both centralized and decentralized system architectures
- Low-cost and Functional safety
- Scalable I/O performance from 100Mbps to 10Gbps

There has been a significant reduction in the I/O response time between signal input and output. It is feasible to efficiently transmit a large amount of information by completely utilising the optimized Ethernet frame bandwidth. EtherCAT sends Ethernet frames via all slave nodes on the network rather than sending data to specific slave nodes individually. The EtherCAT master continuously transmits Ethernet frames through each EtherCAT slave as shown in figure 3.1. Before returning to the EtherCAT master, the last slave returns all the frames so that they can pass through each slave. High speed and real-time data transmission are ensured by this mechanism.

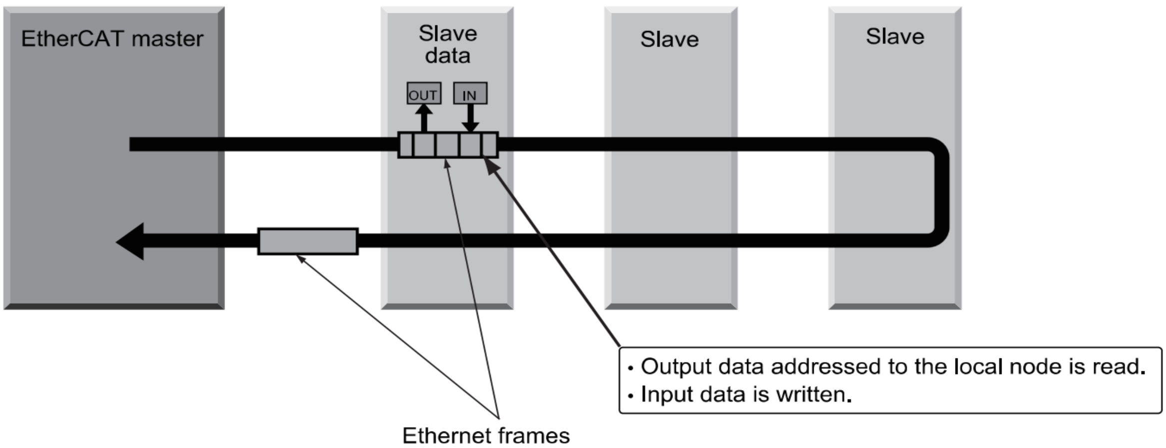


Figure 3.1. Communication in EtherCAT [94]

EtherCAT has the following features in the NJ/NX-series CPU Units.

- Synchronization of processing period of CPU and EtherCAT communication cycle
- Accessing data with device variables without considering addresses
- Optimum functionality and ease of operation based on unified specifications

The CPU motion and sequence processing cycle correspond to EtherCAT's process data communications cycle. As a result, motion and sequence control with a steady set period are made possible. Additionally, the NX701 CPU Unit enables the division of the slaves to be synchronised into two groups with various process data communication cycles. This implies that the processing of slaves is done separately for the group that requires high-speed connectivity. Device variables assigned to the Input-output ports of the EtherCAT slaves are used to access the slaves' EtherCAT ports. Structure-type Axis Variables that have been set up in advance are used to access various forms of data in the servo drive and encoder input slaves. This makes slaves on EtherCAT accessible without respect to addresses.

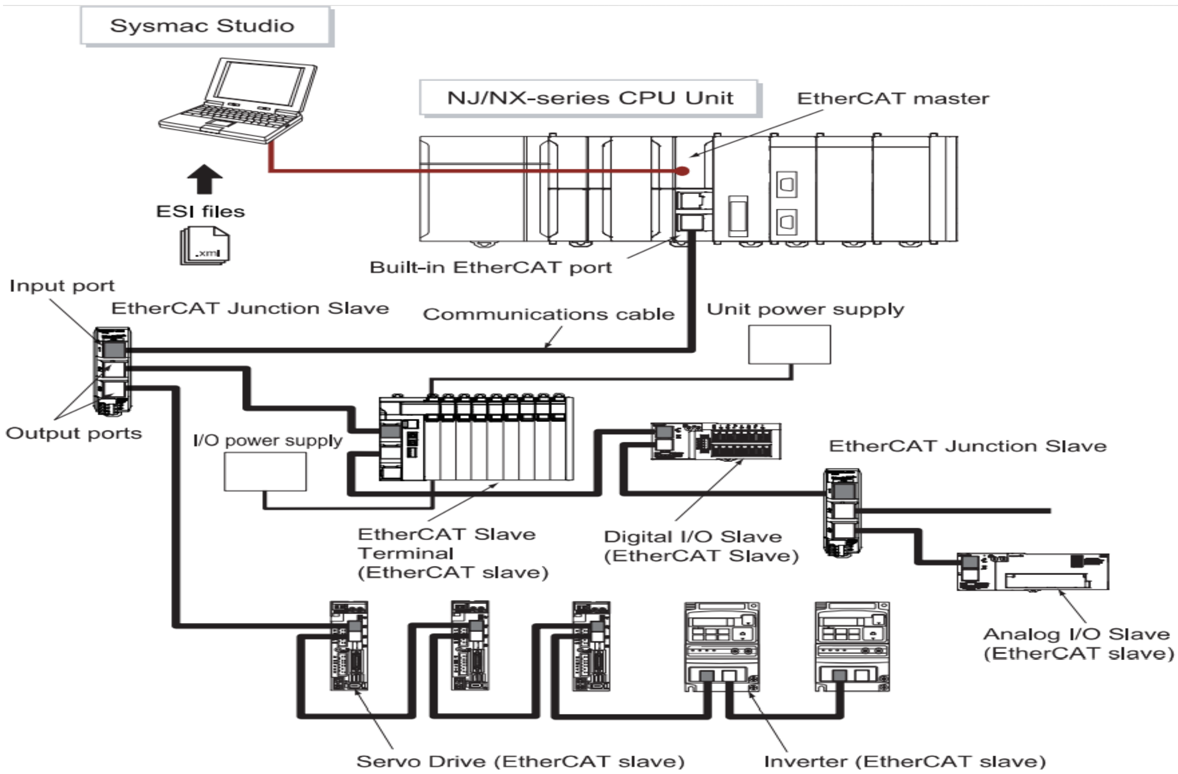


Figure 3.2. EtherCAT network configuration and configuration devices [94]

The devices used to configure the EtherCAT network are displayed in Fig. 3.2. The EtherCAT master controls the network, keeps an eye on the condition of the slaves, and communicates I/O data to the slaves. Data for EtherCAT connections is sent to other devices via the output port. The output data that each EtherCAT slave got from the EtherCAT master is sent out via EtherCAT network. Additionally, it transmits input data through EtherCAT network to EtherCAT master.

To obtain maximum capability and ease of use, we combine the NJ/NX-series machine automation controllers with Sysmac components and the Sysmac studio automation software. EtherCAT slaves and other OMRON control parts with the same communications and user interface requirements are together referred to as "Sysmac devices." Here, OMRON's Sysmac studio programming software is used for developing the ladder logic of OMRON (NX1P2-9024DT1) PLC and SCADA is used for the visualization of the whole automated process operation using Wonderware InTouch SCADA software. Table 3.1 shows the specifications of Omron NX1P2-9024DT1 PLC.

Table 3.1. Specifications of Omron NX1P2-9024DT1 PLC [94]

S. No.	**Specifications of Omron NX1P2-9024DT1 PLC**	
1.	DC Supply voltage	20.4V-28.8 V
2.	Scan cycle time	2ms
3.	Number of digital inputs	14
4.	Number of digital outputs	10
5.	Input type	NPN/PNP
6.	Output type	PNP
7.	Maximum number of expansion units	8
8.	Maximum number of remote I/O nodes	16
9.	Communication port(s)	EtherCAT Master, EtherNet/IP, Ethernet TCP/IP
10.	Number of Ethernet ports	2
11.	Communication option(s)	Serial RS-232C, Serial RS-422, Serial RS-485
12.	Real-time clock	✓

3.4.2 Methodology of Framework for Synchronization

Instead of a single intersection, the proposed system continuously receives updated traffic information for the entire traffic network by which the current traffic condition of a junction and the key routes which are affected by the situation of the neighbouring intersections can be determined. The junction decides itself by considering the volume of traffic and priority of vehicles at the neighbouring intersections and organize the traffic flow accordingly to reduce waiting times and congestion throughout the network. The proposed framework for synchronization comprises of mainly three stages:

1. Evaluating the current status of each lane,
2. Counting the number of vehicles at each traffic light,
3. A controlling mechanism that takes into consideration the impact on the entire traffic network, rather than simply the intersection itself.

1. Phase 1: Evaluate status of each lane

Traffic lights are used to regulate traffic at junctions. Most intersections have four or less traffic lights, each with a number of lanes and both forward and backward directions. A unique ID is assigned to every lane at the traffic lights to identify the intersection, lane and direction. Traffic light IDx consists of horizontal, vertical, directional identities i.e. IDx = HVD, which represents the traffic light allocation as shown in Fig. 3.3. The IPR sensors are installed along both sides of the roads from where they send the density of every horizontal, vertical road as shown in Fig. 3.3. Later PLC handles the identification of lanes using the allotted traffic light identity IDx with the input output mapping while programming the PLC. The driver does not have to enter the lane details in the system. It will be automatically updated in the system.

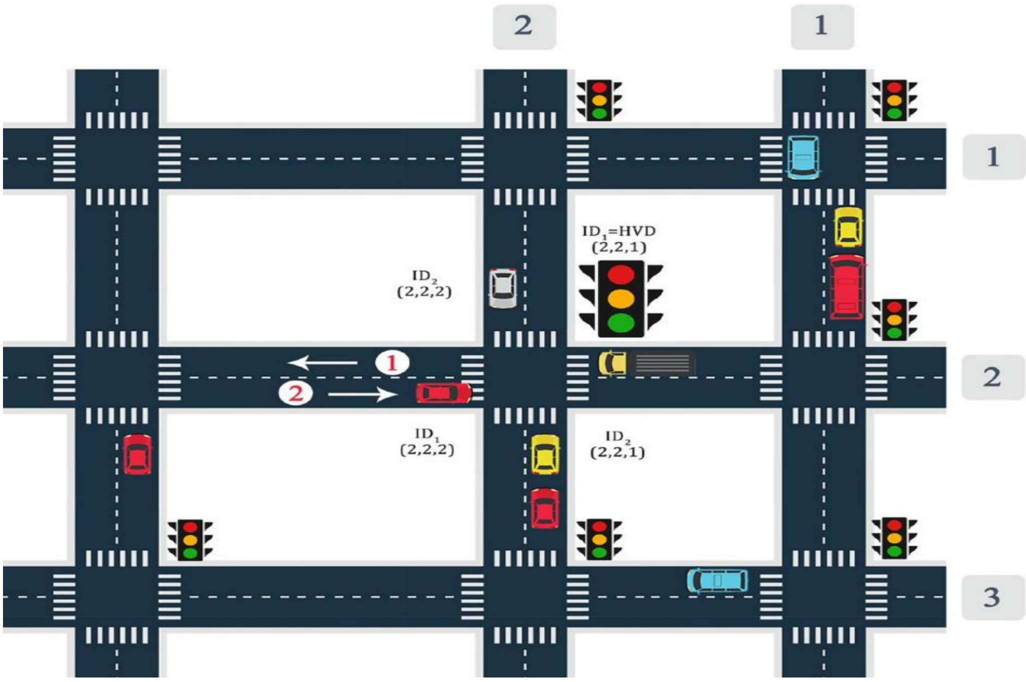


Figure 3.3. Unique ID assignment to every lane at the traffic lights of junctions

Each route is given a number (1, 2, 3, n). Consequently, each intersection has a path number for both the horizontal and vertical directions. There are two ways to take each path (forward direction i.e. 1 and backward direction i.e. 2). For example, an HVD's ID is (3,3,1). The second number denotes the third vertical path, the first number denotes the third horizontal path, and the last number denotes the direction. Since all intersections with a similar horizontal or vertical index are considered to be influenced, therefore, the HVD can be used to indicate leading or affected lanes. On the other hand, the following will be included in IDx for no-interference movement flow.

- the traffic light IDx consisting of horizontal, vertical, location and directional identities.
- IDx = HVLD, which represents the traffic light allocation in terms of horizontal and vertical path number, location/movement, forward and backward direction.
- Every junction has four no-interference movements as shown in table 3.2 with four distinct locations (p, q, r and s), as depicted in Fig. 3.4.

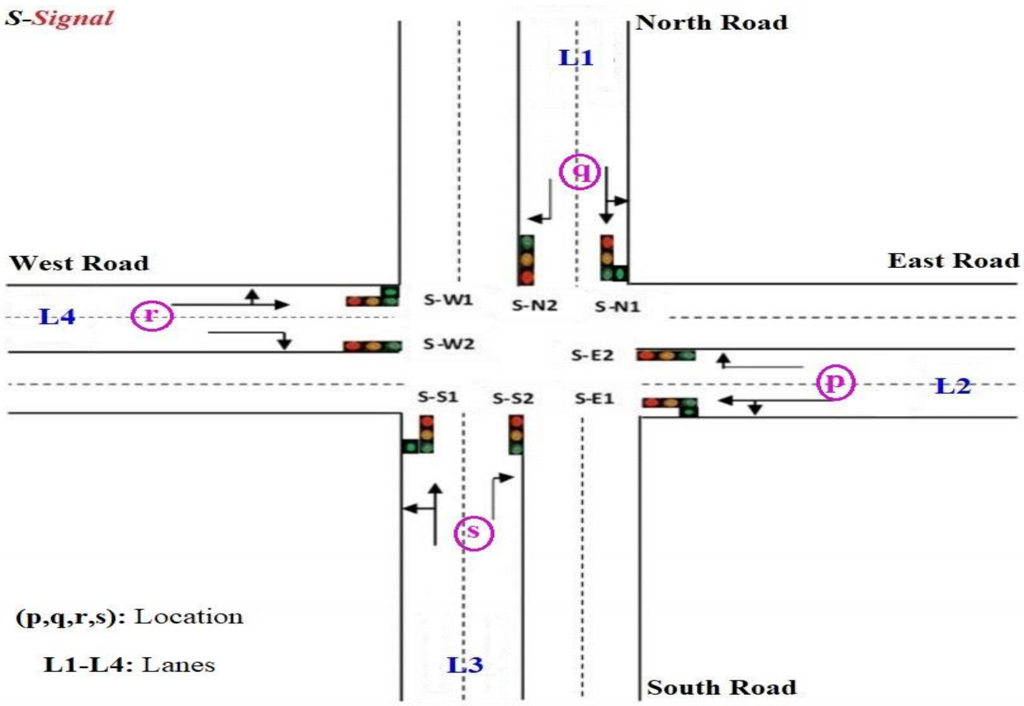
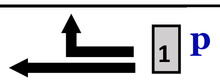
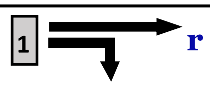
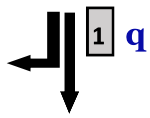
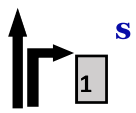
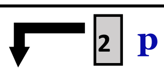
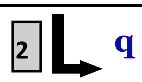
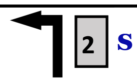


Figure 3.4. Traffic light switching according to lane density and no-interference movement flow

Table 3.2. Four no-interference movements with HVLD

Horizontal	Vertical	Location	Direction	
Movement (1)		p	1	
		r	1	
Movement (2)		q	1	
		s	1	
Movement (3)		p	2	
		r	2	
Movement (4)		q	2	
		s	2	

2. Phase 2: Counting the number of vehicles at each traffic light

Information gathering will be done at each traffic signal. The described traffic counting method will be used to determine how many vehicles are present at each traffic signal. To get the proper density of the vehicles, photo-reflective IR sensors are used with camera and capacitive proximity sensors are planted at particular locations along with timer mechanism. To ensure precise vehicle counting, this method relies on the placement of photo-reflective IR sensors with controlled timers at a distance of 2m just at the level of traffic signal.

Line-of-sight communication is used to send infrared signals from the permanently active infrared transmitter to the ground-based detector. Throughout the time the detector has been receiving the IR signal, no vehicles are allowed to join the stream. Traffic jam is caused more by long vehicles instead of normal/standard length vehicles. Therefore, the total vehicle density moving through a junction is calculated by determining the vehicle's speed and traffic density length. Fig. 3.5 illustrates the process for counting the number of vehicles passing through an intersection.

When any vehicle interrupts the primary photo-reflective IR sensor's connection, two timers will be turned on: t_0 and t_b. The time interval t_0 denotes the time interval/difference in between the first and second connection disruption (spaced 2m apart) which is used to calculate speed of vehicle using Eq. (3.1). The timer t_b is the time of broken connection which is used to measure the length of a vehicle by keeping track of the time between the disruption of the second connection and the reestablishment of the first connection. Every time the time required to complete a broken connection exceeds the amount of time required by a standard-length vehicle, then the number of vehicles will increase by a factor k while speed remains constant.

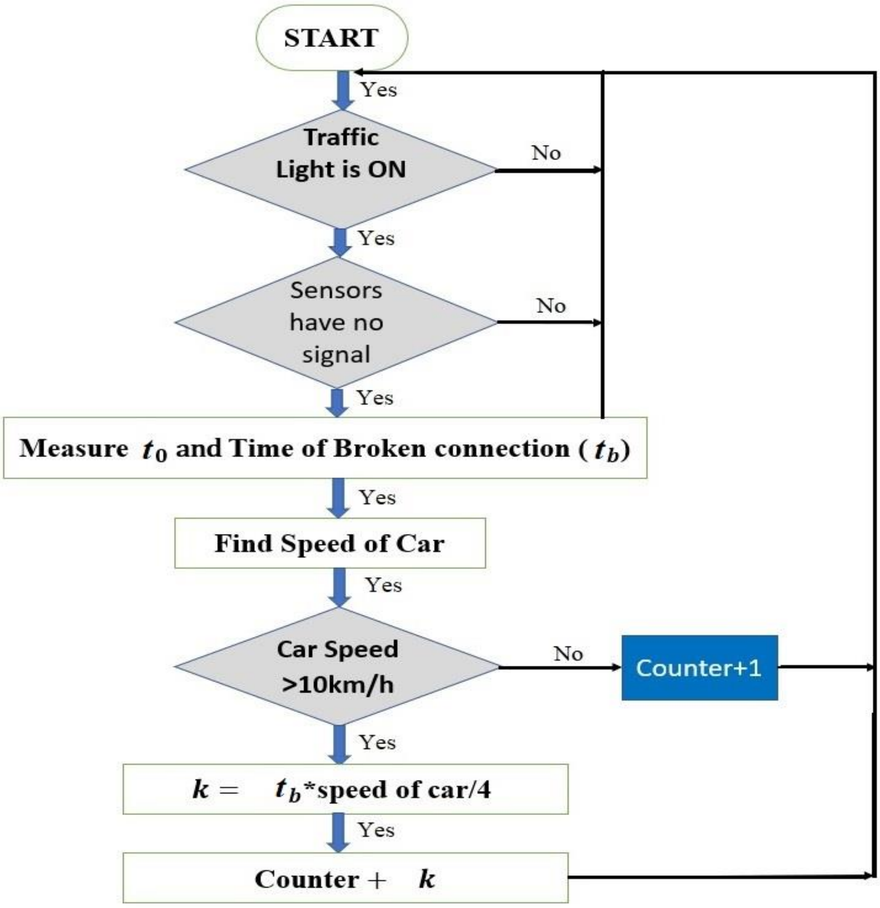


Figure 3.5. Flow chart for determining the number of crossing vehicles crossing an intersection

$$Speed\ of\ Vehicle(m/sec) = \frac{Distance\ between\ the\ sensors}{Time}$$

$$Speed\ of\ Vehicle(m/sec) = \frac{2m}{(t_0 - t_b)}$$

$$Speed\ of\ Vehicle(km/hour) = \frac{2m/_{1000}}{(t_0 - t_b)/_{3600}}$$

$$Speed\ of\ Vehicle(km/hour) = \frac{2m}{(t_0 - t_b)} \times \frac{18}{5} \qquad (3.1)$$

If a vehicle is moving slowly with a speed of less than 10 km/h, then the counter will change once only (there is only one increment in the counter). But for vehicle speed>10km/h, length of vehicle is calculated using the equation given below.

$$Length\ of\ Vehicle\left(\frac{km}{hour}\right) = Speed\ of\ Vehicle \times t_b \qquad (3.2)$$

In order to account for traffic volume in the data, the counter for vehicles over 4m in length needs to be increased using the algorithm provided below in Eq. (3.3).

$$k = \frac{Length\ of\ Vehicle}{Average\ Length\ of\ vehicle} \qquad (3.3)$$

3. Phase 3: Control mechanism for entire traffic network

Every road junction has an OMRON (NX1P2-9024DT1) PLC installed in the middle of traffic signal intersection. The Junction PLC gathers and quantifies traffic density data from sensors and cameras installed in each lane. After receiving the information from sensors, PLC determines the density of road as low, medium, high and alarming density and then determines the phase which has highest priority to get green signal as shown in Fig. 3.6. After that, PLC arranges road segments for green signal and red signal, accordingly. There will be no cases of occlusion in the proposed system because we have used cameras for the front view sensing at a junction and sideways sensing is done with the help of sensors. In case a car got occluded by a big truck, then sideways IPR sensors are already there to give the traffic density count to PLC.

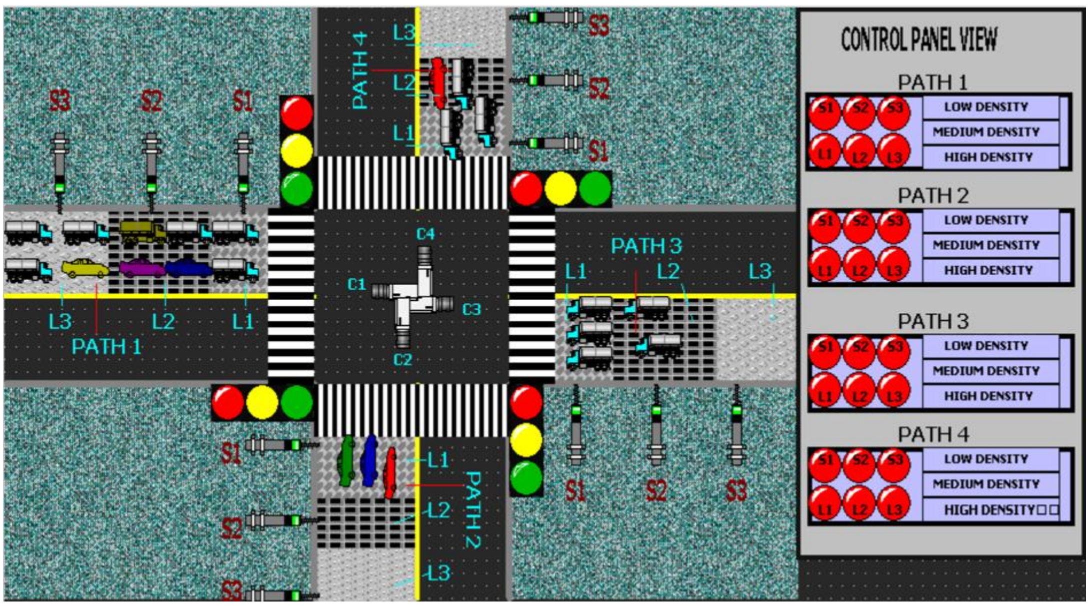


Figure 3.6. Overview of a junction in SCADA Wonderware Intouch software

Using the data from PLCs, we differentiate each horizontal, vertical, directional (HVD) identities schedule on the basis of traffic light weight, traffic congestion indicator, order of traffic light, number of green cycles, time of present state and next state. The intersection controller receives the calculated weight of traffic light i.e. $W(IDx)$ where IDx is the identification number of a traffic light consisting of horizontal, vertical, directional identities i.e. IDx = HVD, which represents the traffic light allocation. Traffic jam/congestion indicator (TJI) is obtained from the sum of previous HVD weights that will drive/lead traffic to the current HVD and the subsequent HVD weights that will be impacted by the current HVD vehicle flow in all directions as shown in Eq. (3.4). In short, TJI for the current HVD depends upon previous HVDs. We also consider the weight of movement while calculating traffic jam/congestion indicator at an intersection as shown in Table 3.3. TJI indicates the summation of the weights of the vehicles at any crossing and summation of weights directly depends upon number of vehicles. This indicator shows the flow of traffic at various intersections.

$$T_{in} = \sum_{H-i}^{H+i} W(IDx) + \sum_{V-i}^{V+i} W(IDx) + Weight\ of\ movement(index) \qquad (3.4)$$

where T_{in} is the Traffic Jam Indicator, H and V represent the number of vehicles moving in horizontal and vertical path (we have taken i = 9 in this work).

Table 3.3. Calculation of Weight of Movement

Weight of Movement (index)	**Equation**
Movement (1)	W(HVp1) + W(HVr1)
Movement (2)	W(HVq1) + W(dVs1)
Movement (3)	W(HVp2) + W(HVr2)
Movement (4)	W(HVq2) + W(HVs2)

Higher traffic jam/congestion indicator will result in a higher order for the traffic signal. Let us assume that green signal is for 40s, red signal is for 90s and we take 3seconds as a safety buffer between change in the status of traffic light. Additionally, it is assumed that the average number of vehicles that can be passed through a green signal in 40seconds is *'p'* (approximately 15 cars on average, i.e. *p*=15). Therefore, the minimum number of green signal cycles (N_{GSC}) required for the passing of total number of vehicles (V_n) through any junction is computed using Eq. (3.5).

$$N_{GSC} = \frac{V_n}{p} \qquad (3.5)$$

Higher value of TJI indicates that V_n is higher. Due to this, the number of green signal cycles will be more. Thus, the total time of green signal cycles (T_{GSC}) at any junction depends upon N_{GSC} and is determined by using Eq. (3.6).

$$\boldsymbol{T_{GSC}} = \sum_{\boldsymbol{i=1}}^{N_{GSC}} green\ signal\ time\ (i.e. 40s) + N_{GSC} \times 3 \qquad (3.6)$$

The time after which the status of the signal changes is equal to T_{GSC} . It indicates that this is the minimum time required to change the status of the signal at any junction. Each PLC controls each traffic signal at a road intersection using an observer-oriented decision-making process with the help of SCADA. Every second, the density data is sent to the main server i.e. a central database authority which monitors the traffic density at each junction and helps vehicle users to take an alternate route to their destination during the peak hours. The traffic at an intersection is controlled by the PLC switching the traffic lights depending on local synchronization (as shown in Fig. 3.7).

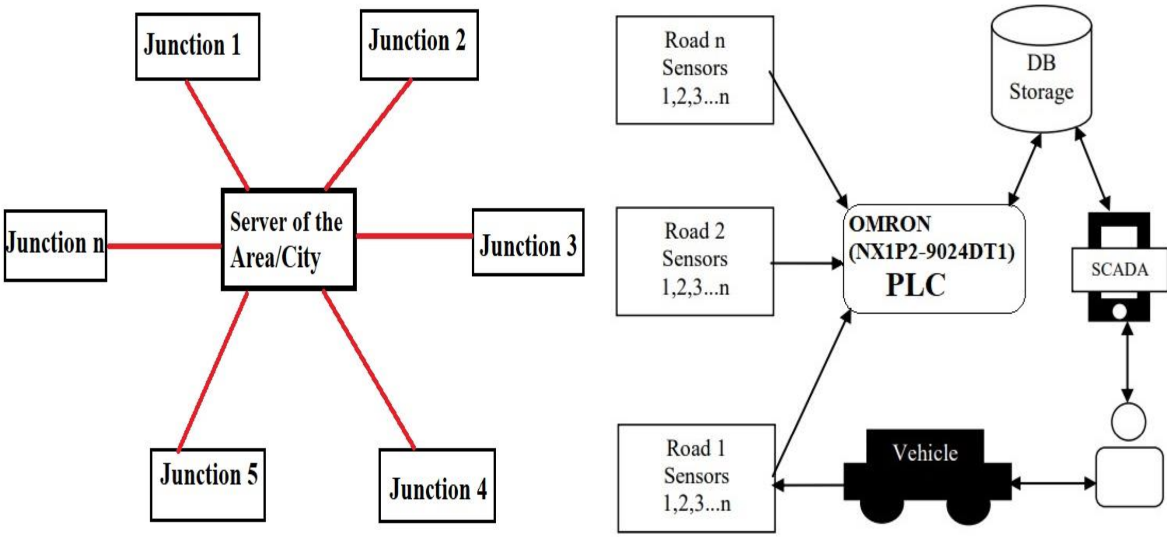


Figure 3.7. n-Junctions connected with the server of a city/area

The traffic signals of a junction are switched according to the traffic density of all the four lanes. They work in the same way as regular traffic signals, with the exception that the traffic lights switch on the basis of density rather than pre-defined time-based switching, dynamically determining the green signal time for each lane. Table 3.4 shows the four-phase sequence in accordance with the green signal and red signal.

PLCs of every intersection sends the traffic density of every lane along with the junction ID of that junction to the central server for the synchronization of traffic signals of an area as shown in Fig. 3.8.

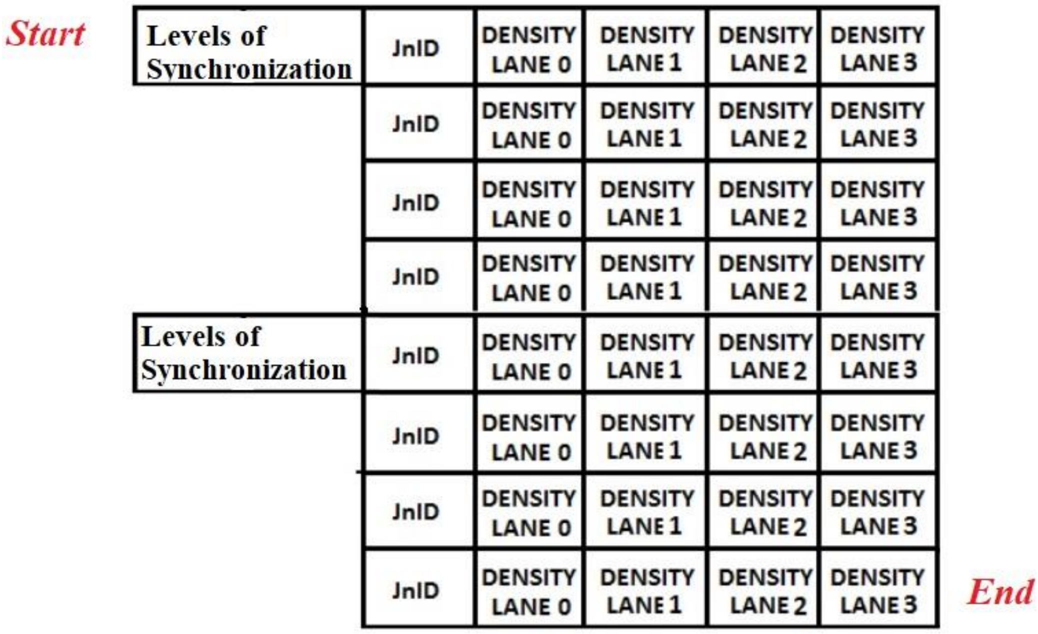


Figure 3.8. Levels of Synchronization along with the junction ID and lane density

Table 3.4. Four Phases or States in accordance with the green signal and red signal.

Phase sequence	Green signal ON	Road segment and Lane	Allowed direction	Red signal ON
Phase-1	S-N1 S-S1	ROAD N-Lane 1 ROAD S-Lane 1	STRAIGHT AND LEFT STRAIGHT AND LEFT	S-N2, S-E2, S-E1, S-S2, S-W2, S-W1
Phase-2	S-W1 S-E1	ROAD W-Lane 1 ROAD E-Lane 1	Straight and left Straight and left	S-W2, S-S1, S-S2, S-E2, S-N1, S-N2
Phase-3	S-N2 S-S2	ROAD N-Lane 2 ROAD S-Lane 2	Right Right	S-N1, S-E2, S-E1, S-S1, S-W2, S-W1
Phase-4	S-E2 S-W2	ROAD E-Lane 2 ROAD W-Lane 2	Right Right	S-W1, S-N2, S-N1, S-E1, S-S2, S-S1

Traffic signal synchronization can be done at different levels. Figure 3.9 shows traffic signal synchronization at level I and level II. We can define the levels of synchronization within an area. One will be the inner circle and another will be the outer circle, where the inner circle reflects peer junctions of level I and outer circle reflects the peer junctions of level II.

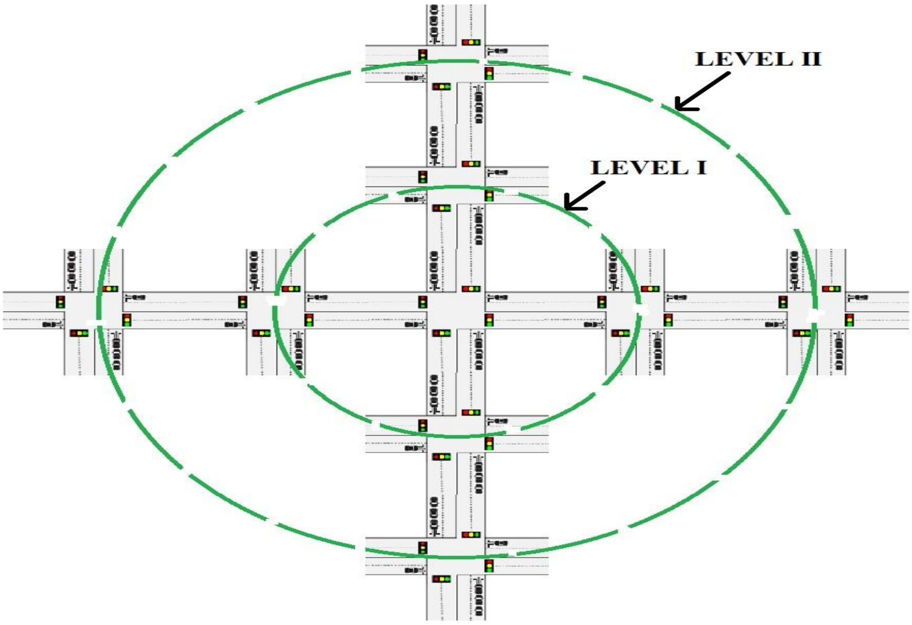


Figure 3.9. Levels of Synchronization

Level I consist of the nearest neighboring junctions, and level II consists of the junctions falling in the external area. The intelligence at level II also takes into consideration the density of the adjacent junctions. These levels of synchronization will help in reducing the congestion at neighboring intersections. This concept helps the vehicles to reach their destination in the shortest possible time by taking the fastest route. In this way, the system will become smart when it is connected to the server.

3.5 Simulation Results

We built SCADA based traffic simulation model for the visualization of a traffic signal synchronization operation where the whole operation is regulated with the help of PLC. For a duration of 9-hours, 300 vehicles are deployed randomly across 81 linked intersections to compare the conventional fixed time traffic control system with the proposed PLC and SCADA based traffic control system using this simulator. We recorded the traffic jam indicator and average waiting time of the entire journey for all 300 vehicles and 81 intersections. Figure 3.10 shows the SCADA based traffic simulation model for 81 linked intersections in the Wonderware Intouch SCADA software.

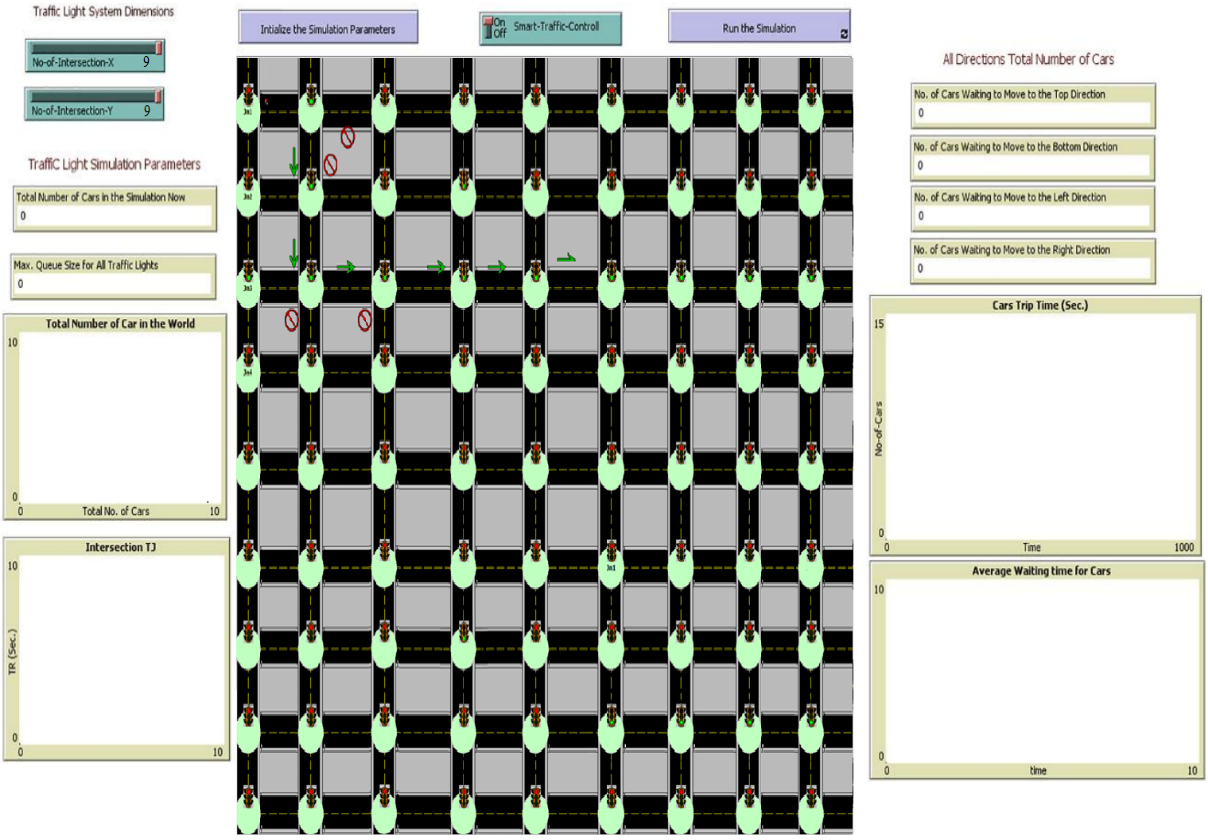


Figure 3.10. SCADA based traffic simulation model for 81 linked intersections

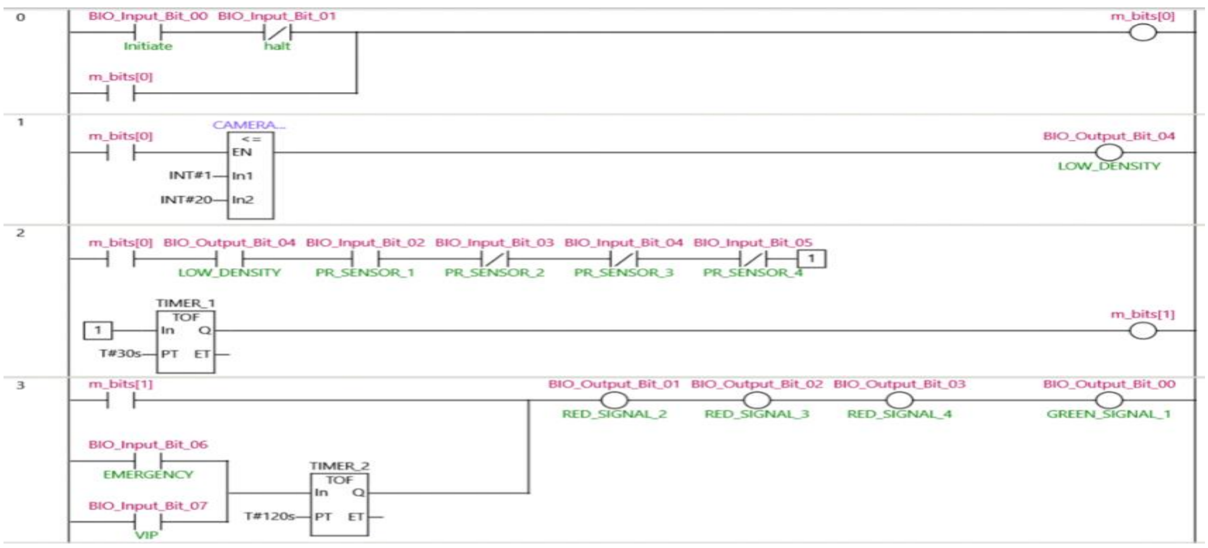
A record of traffic jam indicator has been maintained for the proposed system and fixed traffic control approach to see the impact of traffic movement at the junctions. Table 3.5 displays samples of lane flow control record using the proposed PLC and SCADA based approach which provides the existing status of a junction and the adjacent region to the traffic light controller. Table 3.6 displays a sample of lane flow control record using fixed traffic control approach. PLCs conduct the majority of the control components required to implement system logic [95]. It is important to understand how real-world stuff works and therefore to assist the user, PLC code is used with SCADA. Input/output, HMI (Human-machine interface), signal hardware controller, networks, communication, database, and software are all part of a SCADA system, which are all connected via a PLC program. PLC is capable of altering or modifying the sequence of operations in accordance with the settings of the purpose to prevent failure. The PLC ladder logic program of the SCADA based traffic simulation model has been illustrated in Fig. 3.11.

Table 3.5. Traffic jam indicator- Sample of lane flow control record using the proposed PLC and SCADA based approach

S. No.	Intersection ID	$T_{in}-1$	$T_{in}-2$	$T_{in}-3$	$T_{in}-4$	.	.	$T_{in}-n$	Average
1	111	471.78	461.68	483.91	435.42	.	.	.	471.7
2	112	516.84	503.54	530.09	476.97	.	.	.	516.7
3	121	401.81	391.53	410.08	368.73	.	.	.	401.8
4	122	516.5	503.7	532.08	476.87	.	.	.	516.8
5	131	414.43	391.5	412.08	368.96	.	.	.	402.7
6	132	405.76	391.53	412.08	368.97	.	.	.	406.9
7	141	347.27	338.34	356.2	320.48	.	.	.	347.27
8	142	409.33	396.86	419.8	375.92	.	.	.	.
.	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	.
77	932	302.52	330.08	296.972	305.24	.	.	.	302.52
78	941	351.60	348.56	315.604	322.34	.	.	.	351.6
79	942	548.97	610.08	548.972	564.27	.	.	.	548.97
80	971	296.97	361.34	346.43	490.25	.	.	.	296.9
81	992	313.5	564.24	446.55	578.37	.	.	.	313.61

Table 3.6. Traffic jam indicator- Sample of lane flow control record using fixed traffic control approach

S. No.	Intersection ID	$T_{in}-1$	$T_{in}-2$	$T_{in}-3$	$T_{in}-4$	.	.	$T_{in}-n$	Average
1	111	676.34	702.1	891.1	663.5	.	.	.	732.4
2	112	588.2	790.3	508.2	685.8	.	.	.	643.75
3	121	533.8	562.7	548.7	521.4	.	.	.	540.75
4	122	893.6	716.8	904.3	838.95	.	.	.	838.02
5	131	954.6	882.11	769.34	837.10	.	.	.	861.70
6	132	1443.2	1655.50	1931	1981.70	.	.	.	1651.64
7	141	1634.6	1938.76	1776.6	1547.45	.	.	.	1725.12
8	142	2367.5	2495.45	2431.90	2303.13	.	.	.	2410.45
.	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	.
77	972	10312.4	11,971.8	12,114.5	12,522.6	.	.	.	11,731.3
78	981	16,313.3	11,992.6	12,631.2	13,440.5	.	.	.	12,468.5
79	982	16,313.3	11,992.6	12,631.2	13,429.5	.	.	.	12,476.85
80	991	9434.58	109021.8	11,825.6	10859.4	.	.	.	10754.65
81	992	8449.52	8704.4	7722.2	9717	.	.	.	8149.88



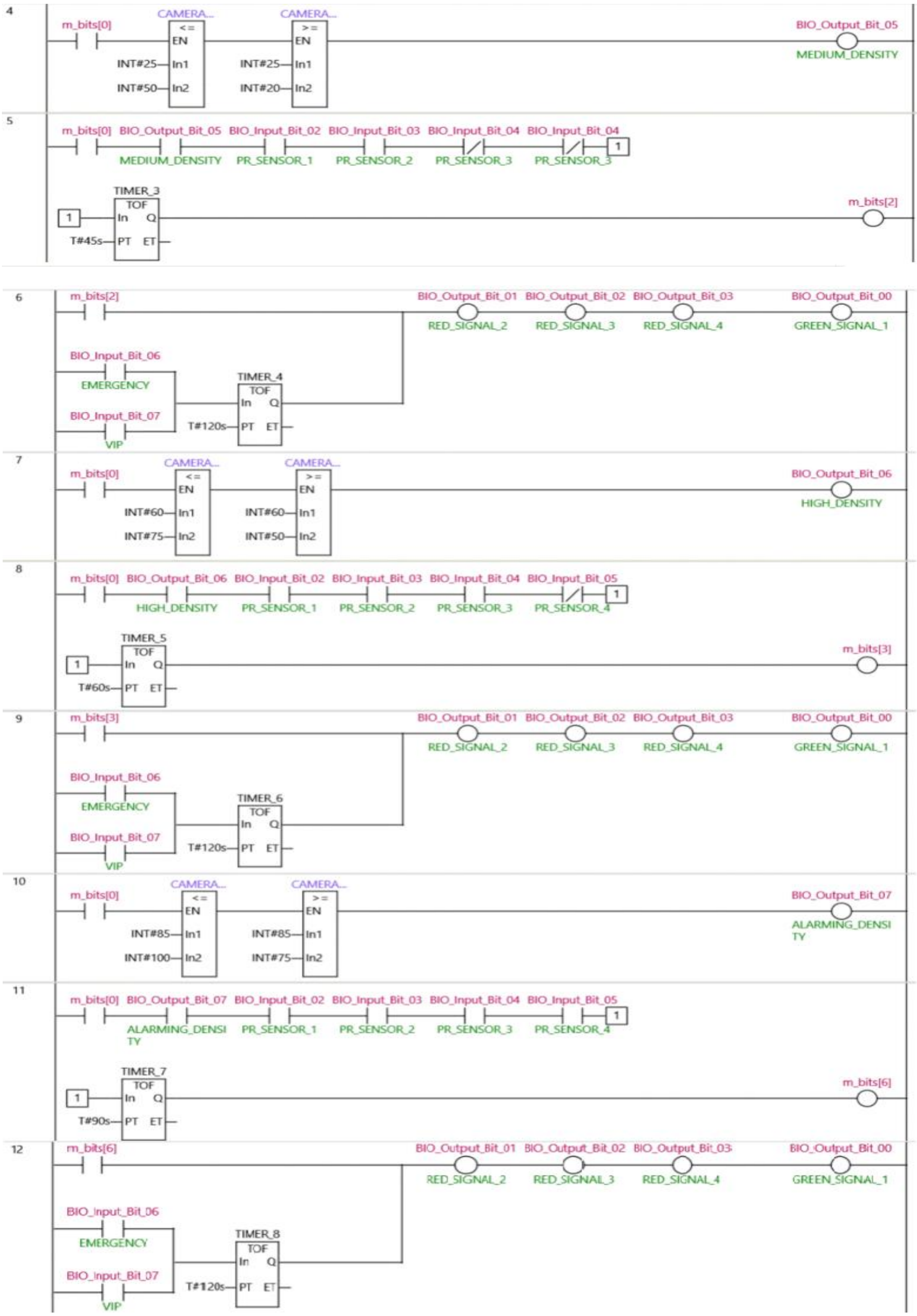


Figure 3.11. PLC ladder logic program of SCADA based traffic simulation model

3.6 Comparative Analysis and Discussion

Figure 3.12 illustrates the comparison of traffic jam indicator of proposed system with fixed traffic control approach. The results of proposed PLC and SCADA based system show a nearly constant line at the bottom of graph throughout the simulation period, whereas the results of fixed time traffic control system show high variable incremental values. This indicates that the proposed PLC and SCADA based system can handle traffic jams more effectively than fixed traffic control, which causes unexpected or incremental network behaviour.

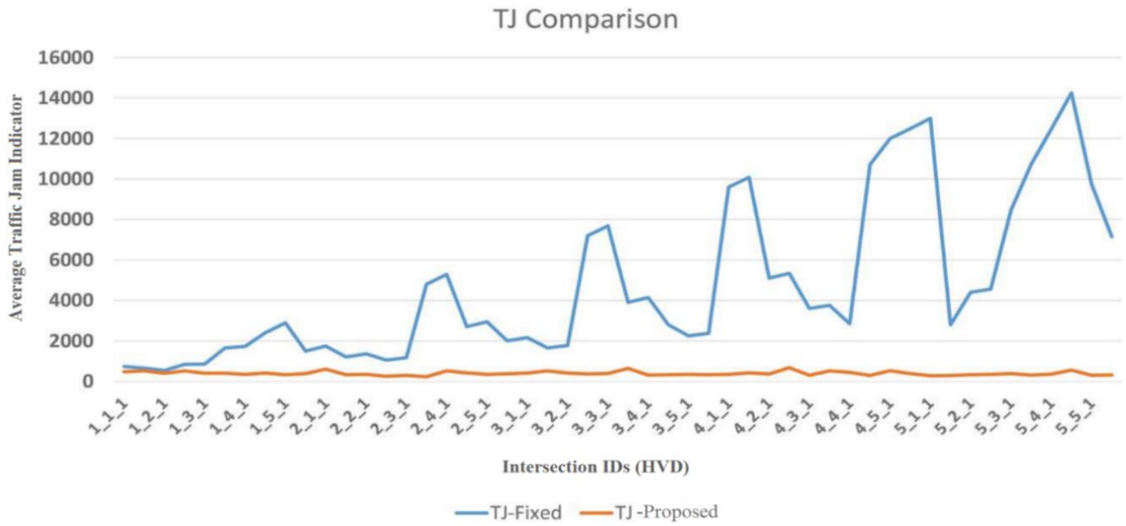


Figure 3.12. Comparison of traffic jam indicator of fixed traffic control approach with the proposed system

Table 3.7 shows some of the samples of total trip duration and average waiting time of vehicles. We have noticed a reduction in the waiting time of vehicles using the PLC and SCADA based system. The findings indicate that the computed average waiting time for the 300 cars using the conventional fixed time traffic control system gives an average of 40.48 sec and 26.97 sec for the proposed PLC and SCADA based system using the same traffic volume and the same average journey time i.e. 335.44sec. The suggested approach decreased the overall traffic network's average wait time at traffic lights by 29.98%.

Table 3.7. Samples of Total Trip duration and Average Waiting Time of vehicles

VehicleID	Total Trip duration (sec)	Average Waiting Time for fixed time traffic control system (sec)	Average Waiting Time for PLC and SCADA based system (sec)
1	236	25.46	22.8
2	204	27.4	24.86
3	216	34.68	30.74
4	335	39.88	29.95
5	412	35.1	30.55
6	133	38.57	29.13
7	513	44.31	28.64
.	.	.	.
.	.	.	.
296	332	39.66	25.24
297	289	39.46	26.53
298	541	38.57	27.65
299	323	46.57	28.26
300	332	44.24	30.66

Figure 3.13 shows the comparison of proposed PLC and SCADA based control system with fixed cycle traffic control systems according to total waiting time at the intersections. We have calculated the average traffic jam indicator for each path ID for both systems for comparison across the intersection and the network. We have taken a 9×9 network matrix which has 81 intersections, each of which have 4 paths. Figure 3.14 shows the comparison of traffic jam indicator (T_{in}) for lane flow and movement flow in network at different intersection lane IDs which consists of horizontal, vertical, directional identities i.e. IDx = HVD. Fig. 3.14 shows that the lane flow and movement control looked to be closely related. The proposed PLC and SCADA based system decreases the average waiting time of vehicles on traffic lights at junctions by 26.97 % for lane flow control and 35.18 % for the movement control for the whole traffic in road network.

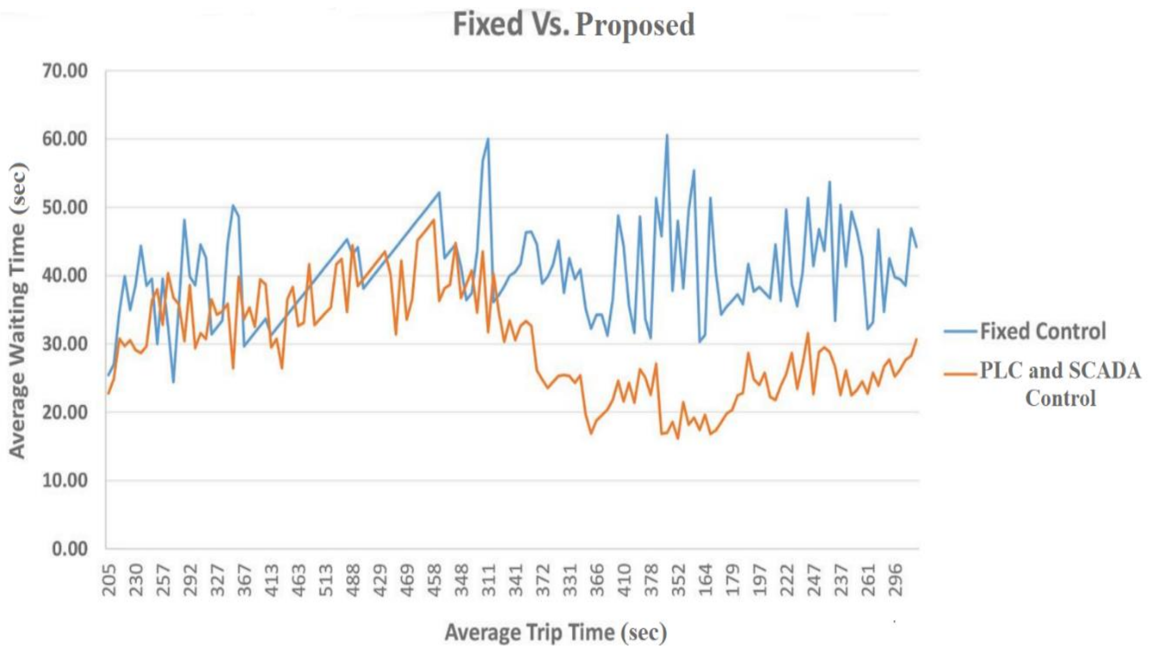


Figure 3.13. Comparison of total waiting time for proposed PLC and SCADA based control with fixed time control systems

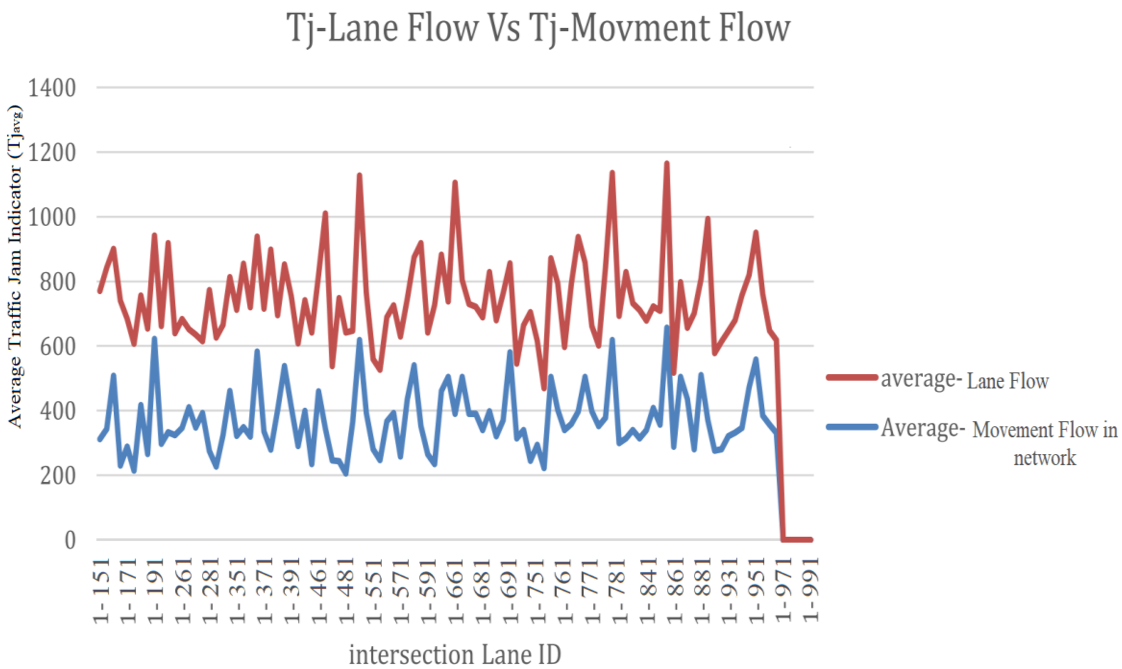


Figure 3.14. Comparison of Traffic Jam indicator for lane flow and movement flow at different intersections

Table 3.8 demonstrates the comparison of the developed PLC and SCADA based system with the existing literature on synchronization of traffic signals.

Table 3.8. Comparative analysis of the current work with other works

Ref. No.	Objective	Strategies Used	Comments	Disadvantages
[62]	Traffic light synchronization strategy for saturated road networks	Long green and long red method for highly saturated road networks	• Control the arrival and departure of queues • Increase the efficiency of traffic flows at signalized junctions	Not suitable to the undersaturated HGRN
[64]	Traffic signal synchronization with dynamic timer value	Image processing and Raspberry Pi in synchronization with cloud	• Obtains vehicle density using traffic cameras on every side of the junction using image processing on OpenCV • Increased efficiency with dynamic change in timer value	• Camera implementation cost is very high • System implemented on a small scale (in the laboratory, not in real-life scenarios) • Conflicts can arise when two emergency vehicles arrive on opposite sides of a junction at the same time
[65]	Self-organized traffic light control based on sensors	• Pressure sensors to detect vehicles approaching the intersection • Microcontroller and Zigbee module to transfer the information to signal controller	Increases traffic flow efficiency and reduce the waiting time at intersections	No synchronization of traffic signals
[67]	Wireless traffic light synchronization system	• Uses two control boards (sender and receiver) Control boards use NodeMCU V.2 (2.4GHz WiFi) for synchronization of control signals by ESP-NOW protocol	• Uses wireless communication Increased safety	For single-lane traffic control only
[68]	Rerouting and synchronization of traffic	Using the Long Range (LoRa) module	• Congestion control at intersection by rerouting vehicles	Synchronization for two traffic signals only

			• Vehicles reach their destination in the shortest possible time by taking the fastest route	
[69]	Synchronization scheme for traffic light controller	• Based on explicit finite state model (FSM) • FSM modeled using Verilog HDL and coding is done using Xilinx Spartan-6 XC6LX16-CS324 FPGA	Flexible architecture that uses a clock divider to give a delay in a certain state	Difficulty of modeling the FSM
[71]	Distributed traffic signal control method based on spontaneous synchronization	• Every junction is represented by a phase-oscillator model • These oscillators are synchronized to get the desired global coordination	• Local interaction leads to a stable state • Maintain the platoons flow	Mathematical complexity
[72], [73]	Distributed approach for synchronizing traffic signals	CTM-UT i.e., (Cell Transmission Model for Urban Traffic) via simulation	Surrogate method (SM), based on an online and stochastic control scheme, used for synchronizing the traffic signals	Computational complexity
[75]	Traffic signals synchronization for Bus Rapid Transit systems	Parallel evolutionary algorithm	• Different priorities can be assigned to buses and other vehicles using a multi-objective optimization analysis • Improves the average speed of public transport up to 15.3% and other vehicles up to 24.8%	In the context of Bus Rapid Transit systems
[76]	Model for synchronizing the traffic lights at road intersections	Hybrid metaheuristic approach that combines variable neighborhood search and Tabu search	Flexible and robust approach	Mathematical and computational complexity
[77]	Decentralized spatial decomposition of network for	Uses platoon model to calculate the weighted sum of delays induced by signalized crossings	Distributed communication architecture for networking of traffic lights	More robust to failure

	synchronization of traffic signals at the road junctions			
[79]	To synchronize the traffic signals at intersections	Using floating car data (FCD)	Increases the traffic safety and energy efficiency of transportation systems	• Only a beginning step toward addressing the synchronization problem; • need for more comprehensive optimization algorithms for general cases
[80]	Traffic signal synchronization in a small urban road network	Cellular automation	Minimize total delay and maximize the flow	Synchronization for two traffic signals only
Proposed Work	**Traffic Signal synchronization scheme for coordinated intersections**	**PLC and SCADA based system which collects real time traffic information using IPR sensors** **PLCs are linked by industrial EtherCAT networks**	• Decrease the overall traffic network's average wait time at traffic lights by 29.98%. • Decreases the average waiting time of vehicles on traffic lights at junctions by 26.97 % for lane flow control and 35.18 % for the movement control for the whole traffic in road network. • Operators can monitor and manage the entire operation from any of on-site HMI, or remotely using SCADA software. • Surveillance and remote monitoring & control functions using SCADA provides a cost-effective security solution. • Flexible and robust approach • New junctions can be incorporated easily	………………….

3.7 Conclusion

In this chapter, an intelligent and secure framework is proposed for networking and synchronization of traffic signals at road intersections that is efficient in determination of traffic light timings on the basis of current lane densities and the densities of peer junctions at various levels. Here, SCADA is used for the visualization of an automated process operation and then the whole operation is regulated using OMRON (NX1P2-9024DT1) PLC. OMRON's Sysmac studio programming software is used for developing the ladder logic of PLC. Wonderware Intouch SCADA software is used for the visualization of the operation. The new technique to synchronize traffic signals with the help of PLC and SCADA is helpful in effective management of traffic at road intersections. This chapter provides intelligent traffic signal scheduling method based on urban traffic to decrease waiting time of vehicles with the least amount of adjustments to the existing infrastructure. The suggested approach enhances the network-wide traffic flow and reduces the average vehicle waiting time for the simulation period by more than (29.98%). This method provides continuously updated traffic status values for the entire traffic network. With minor changes to the current system, new junctions can also be incorporated for synchronization. The designed SCADA system offers continuous access and visualization of all the data in a more efficient and timely manner. It also provides a centralized and thorough display of parameters. Based on PLCs linked by industrial EtherCAT networks, operators can monitor and manage the entire operation from any of on-site HMI, or remotely using SCADA software. Surveillance and remote monitoring & control functions using SCADA provides a cost-effective security solution.

Chapter 4

DESIGN & DEVELOPMENT OF TECHNIQUE FOR EMERGENCY VEHICLE AT ROAD INTERSECTIONS

4.1 Introduction

This chapter presents a simulated prototype for emergency vehicle management and traffic control at road intersections that uses Programmable Logic Controller (PLC) and SCADA for the real time monitoring and control of the traffic lights at various road junctions. Here, SCADA is used for the visualization of an automated process operation and then the whole operation is regulated with the help of PLC. The heart of this system is an industrial PLC. The PLC used in this process is OMRON (NX1P2-9024DT1) and OMRON's Sysmac studio programming software is used for developing the ladder logic of PLC. PLCs along with the sensors and cameras are used on the roads to collect the traffic density from different directions at a junction. This system allows the real time traffic signal control and traffic flow along with a feature which gives preference to high priority vehicles like VIP, police, ambulance and fire brigade etc. so that they can cross an intersection at their maximum speed. In the proposed scheme, sensors and cameras at different road junctions monitor the real time traffic information and transmit it to the PLC of that intersection. PLCs of every intersection calculate and distribute the traffic signal time to their individual junction traffic lights. This information is then sent to a central database authority which monitors the traffic density at each junction and helps vehicle users to take an alternate route to their destination during rush hours. By using the fastest possible path, this idea enables the automobiles to get at their destination as quickly as possible.

4.2 Related Work

ITSs are based on real-time data to avoid crowded regions and improve safety. There has been a significant rise in the number of automobiles on the road as cities throughout the world are develop and people's mobility is rising toward cities. This has led to an increase in the difficulties facing authorities in managing road traffic. This has led to more pollution, more accidents, and traffic congestion. Despite the development of advanced traffic management systems, congestion remain a leading issue in metropolitan cities. One of the primary causes of heavy traffic congestion in metropolitan areas is the use of traditional traffic signal controllers [96].

A crucial safety problem is also the facilitation and prioritization of emergency vehicle transit in metropolitan environments. Numerous traffic management strategies based on virtual traffic lights, self-organizing signals, cameras, GPS, RFID tags have been used in past to optimize traffic flows at junctions and prioritize the movement of emergency vehicles [97-100]. Traditional traffic signal controllers do not consider the presence of emergency vehicles into account while determining the light sequences. In traditional systems, the direction of movement of vehicles, the variation in automobile traffic over time, accidents, the passing of emergency vehicles, and pedestrian crossings are not considered. In order to avoid losing lives and livelihoods, emergency vehicles like ambulances, police jeeps, VIP vehicles and fire brigade must therefore wait at junctions [101].

When more vehicles approach an intersection, the response times and risk of accidents of emergency vehicles also increases because emergency vehicles approach junctions quickly at a very high speed. According to a report, more than 25% of emergency vehicle crashes have occurred at signalised crossings [102]. This is because cars approaching a green light at an intersection are unable to perceive an emergency vehicle due to line-of-sight issues caused by neighbouring structures, foliage, or hills [103]. These emergency vehicle crashes at crossings could be prevented by giving the emergency vehicle and other non-emergency vehicles green and red signals, accordingly. Poor traffic management infrastructure is a key contributor to accidents in the majority of the world's nations. The problem of rising rates of traffic accidents is a result of more automobiles creating congestion. With more than 110 fatalities reported in the USA every day [104], it has been found that there were over 43,000 fatalities in 2007 as a result of more than 10 million reported car accidents.

Real-time route planning helps to reduce traffic congestion in most urban locations. It is imperative to speed up emergency response times, especially for health and fire-related situations. Consequently, the development of a unified system for traffic and emergency vehicle management is essential. More efforts should be made in order to obtain maximal modeling, control, and monitoring of emergency vehicles. An efficient route planning algorithm is still need to be developed which keeps the emergency vehicles at a higher preference.

4.3 Problem Statement

One of the major issues facing contemporary civilizations is traffic congestion, which has received increasing attention. Because of the large number of cars on the road, fast rising population, and sluggish infrastructure investment, traffic congestion at road junctions is a significant issue in across the nation. This problem is more difficult to manage in the nations where vehicular traffic is increasing at a quicker rate. Existing methods are ineffective in addressing the issues of congestion control at intersections. One of the crucial effects of traffic congestion is the delay in arrival of emergency vehicles at accident scenes. These services must be able to reach the scene of an accident as quickly and effectively as possible to ensure the safety of public. Therefore, these emergency services must have a system that can make route planning more adaptable so that real-time data can be gathered more effectively to further reduce traffic congestion. The major objective of this chapter is to remove emergency cars as quickly as possible while ensuring fairness for vehicles on the remaining route segments. The proposed system avoids and regulate traffic congestion by reducing the time taken for real time traffic to cross a junction and reaching their destination in minimum possible time.

4.4 Architecture of Emergency Vehicle Management System

Figure 4.2 shows a high-level overview of the entire system. We suppose that each intersection has four roads (two lanes each) intersecting. So, there are eight lanes to keep an eye on at each intersection. Inductive Proximity Sensors (S1, S2, S3, S4 on each road segment) are used to gather real time for traffic density of a road segment.

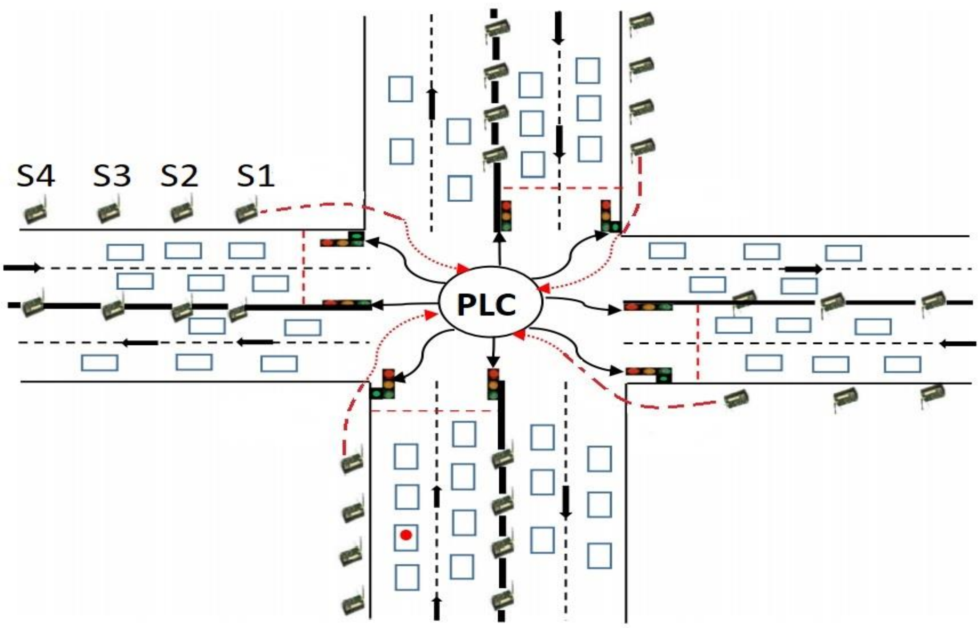


Figure 4.1. 4-way road intersection with the proposed system

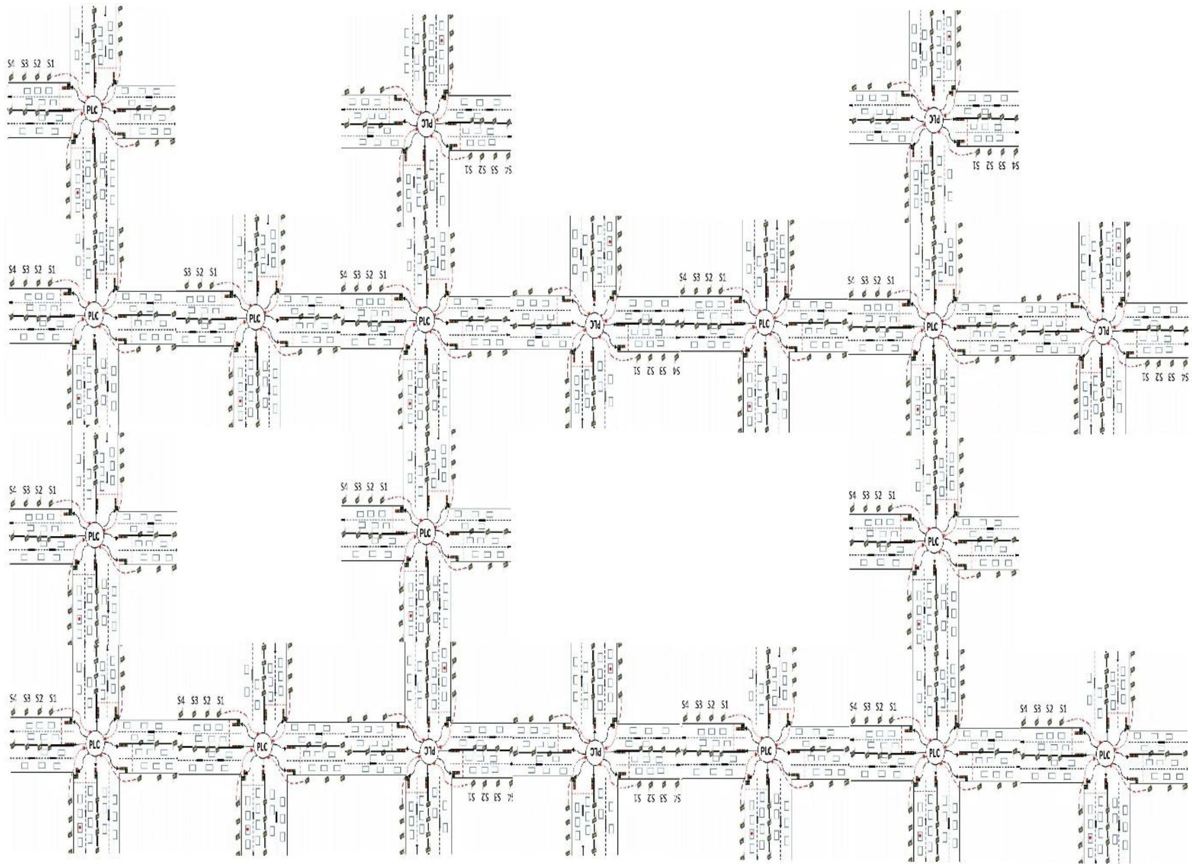


Figure 4.2. Overview of the road intersection network with the proposed system

The whole operation is regulated with the help of PLC. Every PLC works on Ethernet or serial communication like RS 242 or RS 485, but the PLC used in this process i.e. OMRON (NX1P2-9024DT1) works on EtherCAT which provides high speed, low latency/delay and incredible synchronization. IPR Sensors are installed along the 8 lanes of every junction at a distance of 10m each, which serve as the strength for PLC. Sensors are used for acquiring and transmitting traffic density to PLC. Every road junction has an OMRON (NX1P2-9024DT1) PLC installed in the middle of traffic signal intersection. Fig. 4.1 presents a 4-way road junction where IPR sensors are installed on each lane along with a PLC in the center of every intersection.

PLC, with the help of information from sensors, decides the order of green light phase for each road segments on the basis of vehicle density and give preference to the road with presence of emergency or VIP vehicle. PLC, at the center of every road intersection, gathers the real time traffic information of that junction with the help of the sensors on the road. After receiving the information from sensors, it determines the density of road as low, medium, high and alarming density and then determines the phase which has highest priority to get green signal. After that, it arranges road segments for green signal and red signal, accordingly. It also calculates the length of the green signal by taking into account the presence of VIP and emergency vehicles on a given road segment for important priority roads, and the vehicle density on other priority roads. Fig. 4.2 illustrates the overview of the road intersection network with the proposed system.

4.5 Operation Method

The operation of the entire system is shown using the flow charts listed below:

4.5.1 Functioning of PLC

Fig. 4.3 presents a flowchart which shows the working of PLC when it gathers the real time traffic information of a junction with the help of cameras on the road junction. After receiving the information from camera, it determines the density of road as low, medium, high and alarming density and then determines the phase which has highest priority to get green signal.

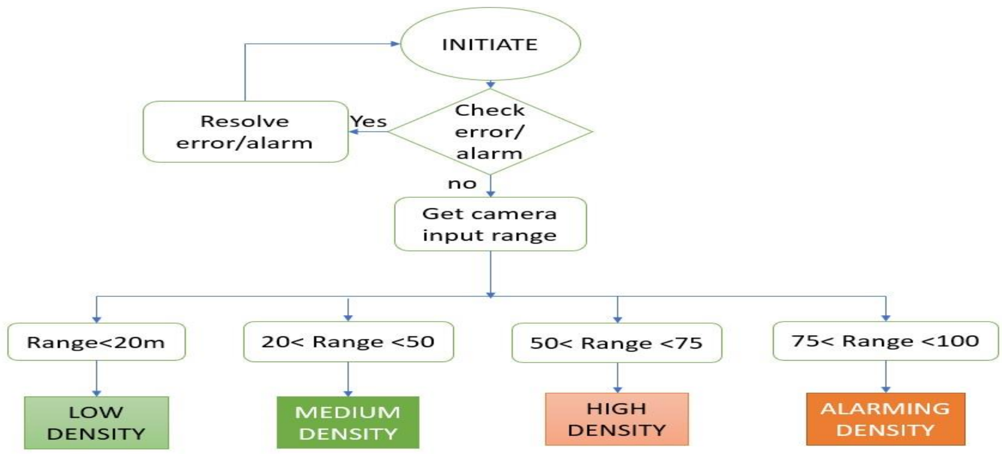


Figure 4.3. Flow chart for real time traffic information collection using camera

Fig. 4.4 presents a flowchart which shows the functioning of PLC at the centre of every road intersection, when it gathers the real time traffic information of that junction with the help of the sensors on the road. For collecting real time traffic information at each traffic light, inductive proximity sensors are used at starting of a lane or immediately after the traffic light to count the number of vehicles accurately. IPR Sensors are used for acquiring and transmitting traffic density to PLC.

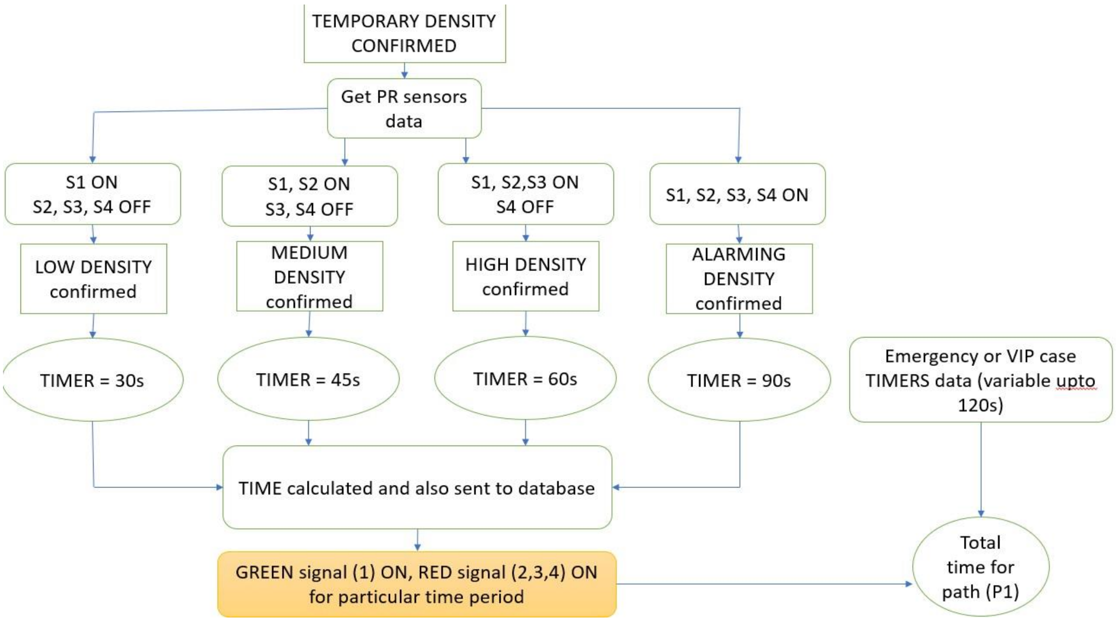


Figure 4.4. Flow chart for functioning of PLC for real time traffic information collection using sensors

The sensor range, 0–100 m/min, is used in the proposed approach to calculate traffic density. The duration of output green light timing is set to the range 0–90s. As indicated in Table 1, all of the inputs and outputs are split into four different ranges, ranging from low density to alarming density. Table 4.1 illustrates the calculation of green light according to traffic density and sensors range.

Table 4.1. Green light calculation according to traffic density

Traffic Density	Sensor Range (meters)	Maximum Green signal timing (sec)
Low Density	<=20m	30
Medium Density	20m<Range<=50m	45
High Density	50m<Range<=75m	60
Alarming Density	75m<Range<=100m	90

4.5.2 Priority Model for Vehicles

A simulation model for an intelligent and secure framework for emergency vehicle management at road intersections is suggested here in Table 4.2. Each vehicle, traffic signal, and intersection controller are treated as an independent agent and they are distributed across a map with 81 intersections. Junction Controller acts as a controlling unit which provides effective guidance and modifications process for traffic light units. Each PLC controls each traffic signal at a road intersection using an observer-oriented decision-making process with the help of SCADA. However, the traffic situation at an intersection is continuously being sensed by the junction control agent with the help of sensors and cameras. It then decides the behaviour of the traffic lights on the basis of collected information.

Table 4.2: Main attributes of Agent and method

Type of Agent	**Features/Characteristics/Attributes**	**Action**
Vehicle	• Vehicle ID • Priority/Preference • Direction/path/route/movement • Present lane • Stop time, waiting time and Exit time	• Setting the vehicle ID • Setting the priority • Transmit a signal to get priority
Traffic Signal	• Traffic Signal ID Junction ID • Direction of Traffic Signal • Total number of vehicles • Overall weight at a traffic light	• Set the traffic signal ID • Determine traffic density at a junction • Weight calculation at a traffic light
Junction controller	• Junction ID • Traffic Signal ID • Travel/trip/journey Direction of vehicle • Traffic jam Indicator (TJI) for lane flow • Selected traffic signal • Number of Green cycles • Number of Yellow cycles • Number of Red cycles • Present status • Duration of next status	• Calculate TJI • Assign order to traffic lights • Calculate the number of green cycles • Determine the red and yellow cycles. • Evaluate/identify/estimate the next change in status of traffic lights

We present a priority model for vehicles that gives preference to the vehicles of every lane according to the given priority categories illustrated in Table 4.3. This system calculates the length of the green signal by considering the presence of VIP and emergency vehicles on a given road segment for important priority roads, and the vehicle density on other priority roads. If the system recognizes a high-priority vehicle coming towards an intersection, then green signal is given to the lane on which the high-priority vehicle is present, precluding the periodic cycle from operating. For example, if Lane 1 receives a green light at first and the system recognizes a high-priority vehicle coming towards an intersection simultaneously, then green signal will be given to the lane on which the high-priority vehicle is present. After that, the system arranges road segments for green signal and red signal, accordingly. It also calculates the length of the green signal by taking into account the presence of VIP and emergency vehicles on a given road segment for important priority roads, and the vehicle density on other priority roads.

Table 4.3. Priority model for classification of vehicles

Type of vehicles	**Priority weight (P_v)**
Emergency vehicle	1.0
Public transport and school transport	0.5
Other vehicles	0.1

The controller agent is used to gather information and allocate schedules to HVDs, the traffic signal agent to keep track of the number of vehicles and their weight per HVD, and the vehicle agent to broadcast/proclaim the priority values of the HVDs. We rely on the ability of all emergency vehicles to identify themselves to the traffic light by sending a signal. PLC identifies an emergency vehicle with the help of cameras and sensors. Weight computation at each traffic signal is done using the given Eq. (4.1) where W is the weight of traffic light, m is the number of vehicles and P_v is the priority weight of vehicles. The intersection controller receives the calculated weight of traffic light i.e. $W(IDx)$ where IDx is the identification number of a traffic light consisting of horizontal, vertical, directional identities i.e. IDx = HVD, which represents the traffic light allocation as shown in figure 3.3 in chapter 3.

$$W(IDx) = \sum_{i=1}^{m} P_v(i) \tag{4.1}$$

4.5.3 Intersection Controller Operations

Using the data from PLCs, we differentiate each horizontal, vertical, directional (HVD) identities schedule on the basis of traffic light weight, traffic congestion indicator, order of traffic light, number of green cycles, time of present state and next state. Traffic jam/congestion indicator (TJI) is obtained from the sum of previous HVD weights that will drive traffic to the current HVD and the subsequent HVD weights that will be impacted by the current HVD vehicle flow in all directions as shown in Eq. (4.2). This indicator shows the flow of traffic at various intersections. Higher traffic jam/congestion indicator will result in a higher order for the traffic signal.

$$T_{in} = \sum_{H-i}^{H+i} W(IDx) + \sum_{V-i}^{V+i} W(IDx) \tag{4.2}$$

According to the density of a given lane, the minimum number of green signal cycles (N_{GSC}) required for the passing of total number of vehicles (V_n) through any junction is computed using Eq. (3.5), and then the minimum time required to change the status of the signal at any junction is determined by using Eq. (4.3). We take 3seconds as a safety buffer for each change in the status of the traffic light. The time after which the status of the signal changes is equal to T_{GSC}. Higher value of TJI indicates that V_n is higher which leads to a greater number of green signal cycles. Thus, the total time of green signal cycles (T_{GSC}) at any junction depends upon N_{GSC}.

$$\boldsymbol{T_{GSC}} = \sum_{\mathrm{i}=1}^{\mathrm{N_{GSC}}} \text{green signal time (i.e. 40s)} + \mathrm{N_{GSC}} \times 3 \tag{4.3}$$

4.6 Simulation Results with PLC Ladder Logic

All the cases for emergency vehicle management in different traffic densities at a road intersection is shown here with the help of runtime window in SCADA Wonderware Intouch software system (version 10.0, https://lab4sys.com/en/download-wonderware-intouch-scada/) and PLC ladder logic. Fig 4.5 shows the initialization and halting of the whole traffic management system. This represents the continuity of the system.

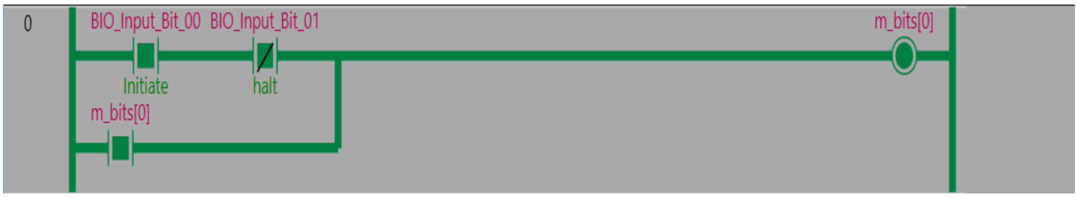


Figure 4.5. Initiate and halt

4.6.1 For Low Density Traffic

When we get the traffic camera distance (range < 20%), it temporarily means the low density of the traffic on that particular path (P1). But when proximity sensor (PR_SENSOR_1, placed at 20unit distance) is high and other proximity sensors (PR_SENSOR_2, placed at 50unit distance; PR_SENSOR_3, placed at 75unit distance; PR_SENSOR_4, placed at 100unit distance) are low, it confirms the low density of traffic. Fig 4.6 shows the runtime window an intersection in Wonderware Intouch SCADA software version 10.0 when traffic density is low.

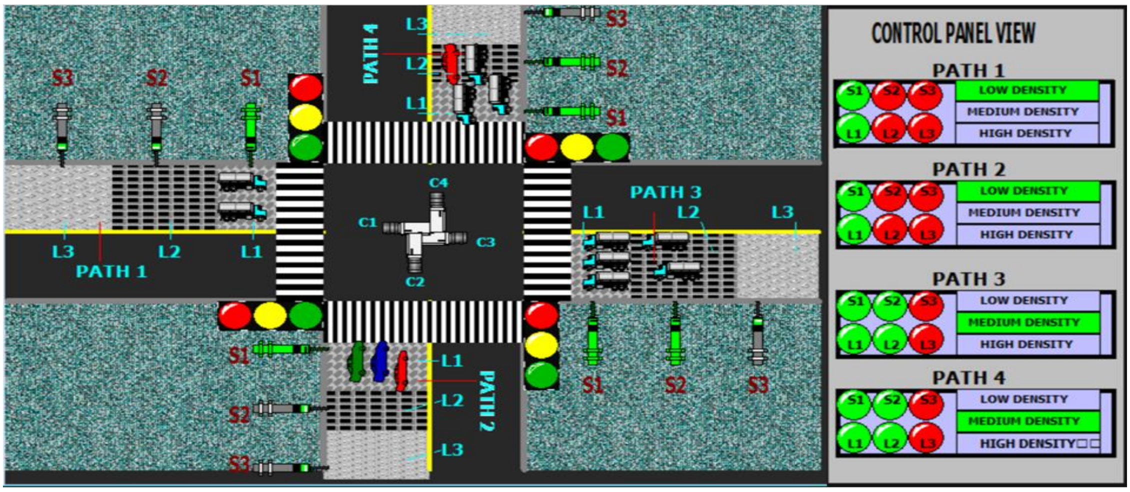


Figure 4.6. Runtime window an intersection in Wonderware Intouch SCADA software version 10.0 (Low density traffic)

If density is <20, then GREEN_SIGNAL_1 of path (P1) is ON for 30 sec and at the same time RED_SIGNAL_2 of path (P2), RED_SIGNAL_3 of path (P3), RED_SIGNAL_4 of path (P4) are ON. Similarly, in case of any EMERGENCY & VIP situation, then GREEN_SIGNAL_1 of path (P1) is ON for 120 sec and at the same time RED_SIGNAL_2 of path (P2), RED_SIGNAL_3 of path (P3), RED_SIGNAL_4 of path (P4) are ON. Fig 4.7 shows the PLC ladder logic program for priority management at an intersection with low density traffic.

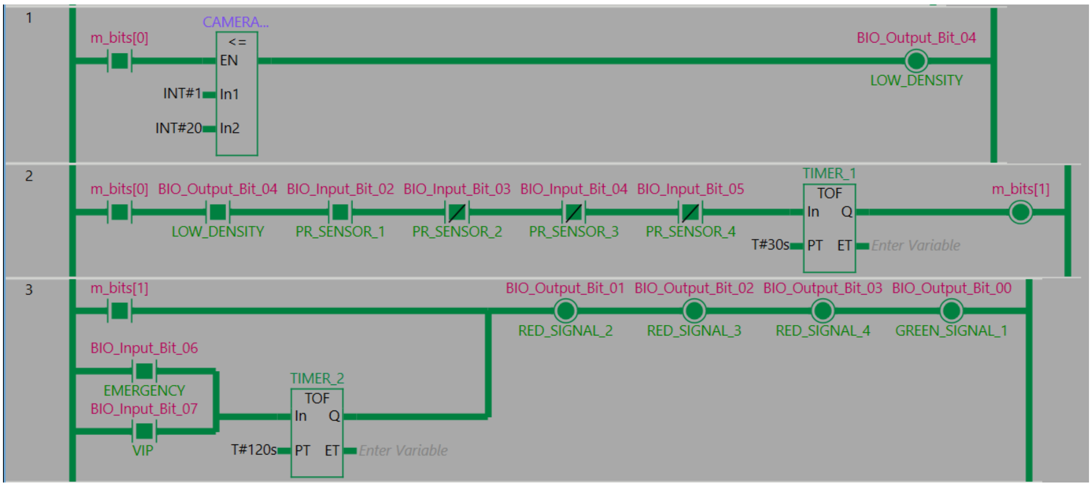


Figure 4.7. PLC ladder logic program for priority management (Low density traffic)

4.6.2 For Medium Density Traffic

When we get the traffic camera distance (20%<range < 50%), it temporarily means the medium density of the traffic on that particular path (P1). But when proximity sensor (PR_SENSOR_1, placed at 20-unit distance; PR_SENSOR_2, placed at 50-unit distance) are high and other proximity sensors (PR_SENSOR_3, placed at 75unit distance; PR_SENSOR_4, placed at 100unit distance) are low, it confirms the high density of traffic. Fig 4.8 shows the operational view of an intersection in SCADA when traffic density is medium.

If 20% < density < 50%, then GREEN_SIGNAL_1 of path (P1) is ON for 45 sec and at the same time RED_SIGNAL_2 of path (P2), RED_SIGNAL_3 of path (P3), RED_SIGNAL_4 of path (P4) are ON.

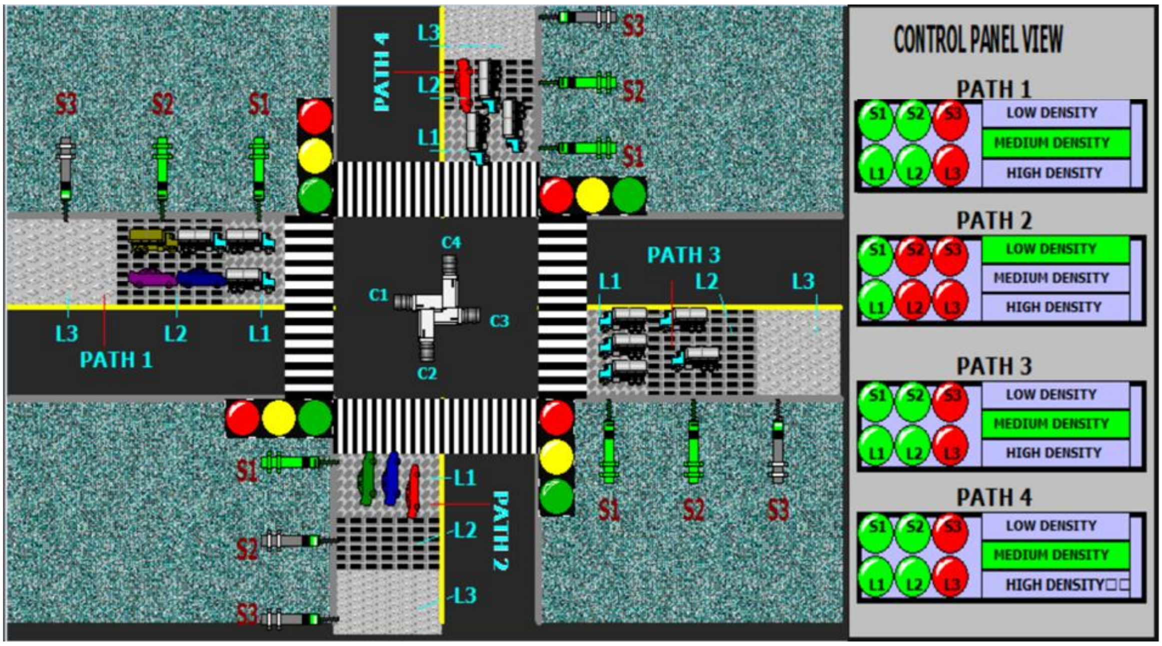


Figure 4.8. Operational view an intersection with medium density traffic in SCADA

Similarly, in case of any EMERGENCY & VIP situation, then GREEN_SIGNAL_1 of path (P1) is ON for 120 sec and at the same time RED_SIGNAL_2 of path (P2), RED_SIGNAL_3 of path (P3), RED_SIGNAL_4 of path (P4) are ON. Fig 4.9 shows the PLC ladder logic program of system with medium density traffic.

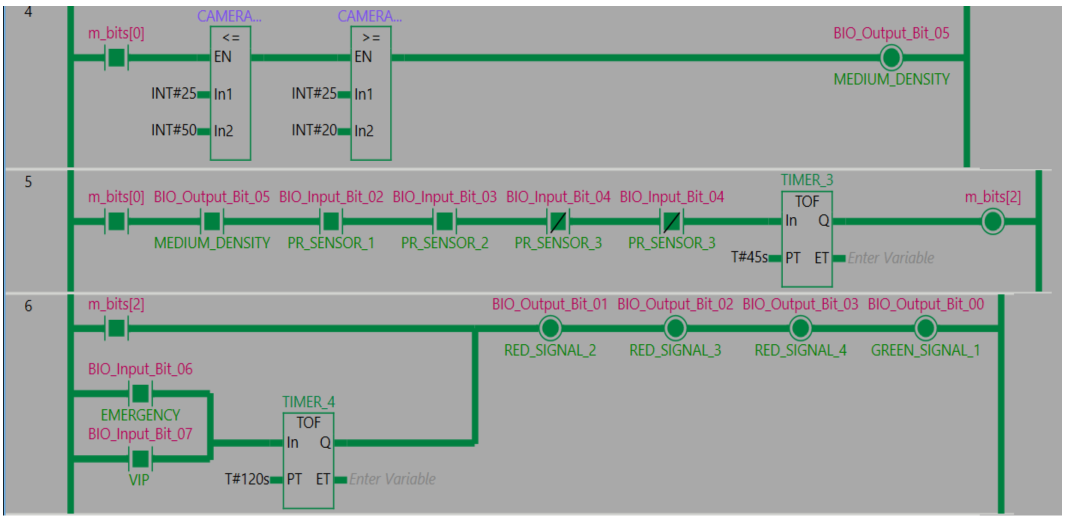


Figure 4.9. Ladder logic program of PLC for priority management with medium density traffic

4.6.3 For High Density Traffic

When we get the traffic camera distance (50%<range < 75%), it temporarily means the high density of the traffic on that particular path (P1). But when proximity sensor (PR_SENSOR_1, placed at 20-unit distance; PR_SENSOR_2, placed at 50-unit distance; PR_SENSOR_3, placed at 75unit distance) are high and other proximity sensor (PR_SENSOR_4, placed at 100unit distance) is low, it confirms the high density of traffic. Fig 4.10 shows the runtime window an intersection in Wonderware Intouch SCADA software version 10.0 when traffic density is high at the intersection.

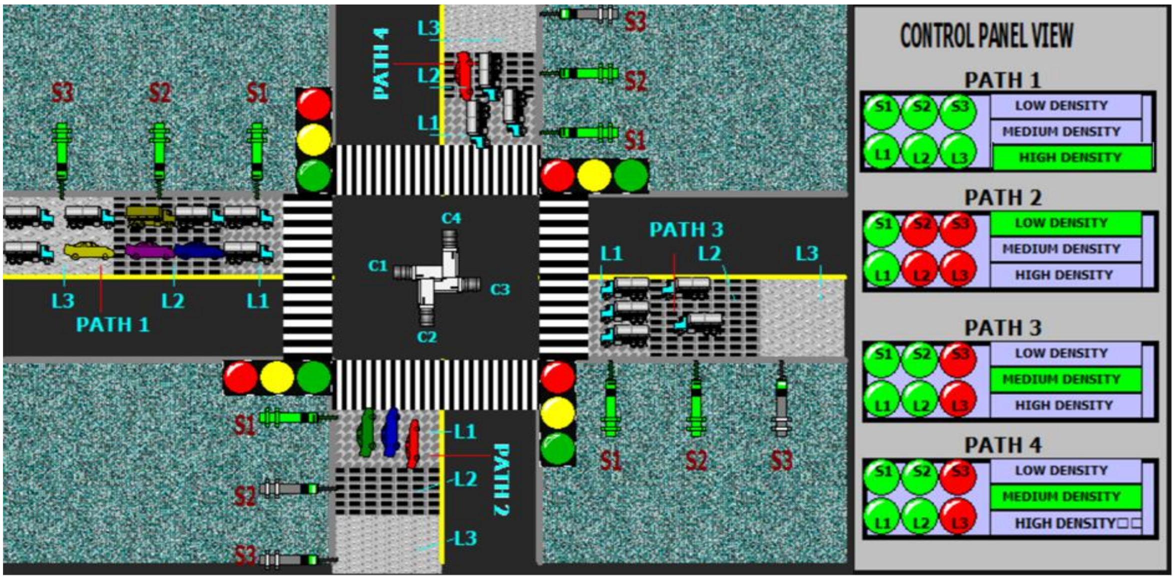


Figure 4.10. Operational view an intersection with high density traffic in SCADA

If 50% < density < 75%, then GREEN_SIGNAL_1 of path (P1) is ON for 60 sec and at the same time RED_SIGNAL_2 of path (P2), RED_SIGNAL_3 of path (P3), RED_SIGNAL_4 of path (P4) are ON. Similarly, in case of any EMERGENCY & VIP situation, then GREEN_SIGNAL_1 of path (P1) is ON for 120 sec and at the same time RED_SIGNAL_2 of path (P2), RED_SIGNAL_3 of path (P3), RED_SIGNAL_4 of path (P4) are ON. Fig 4.11 shows the PLC ladder logic program for emergency vehicle management when traffic density is high at intersections.

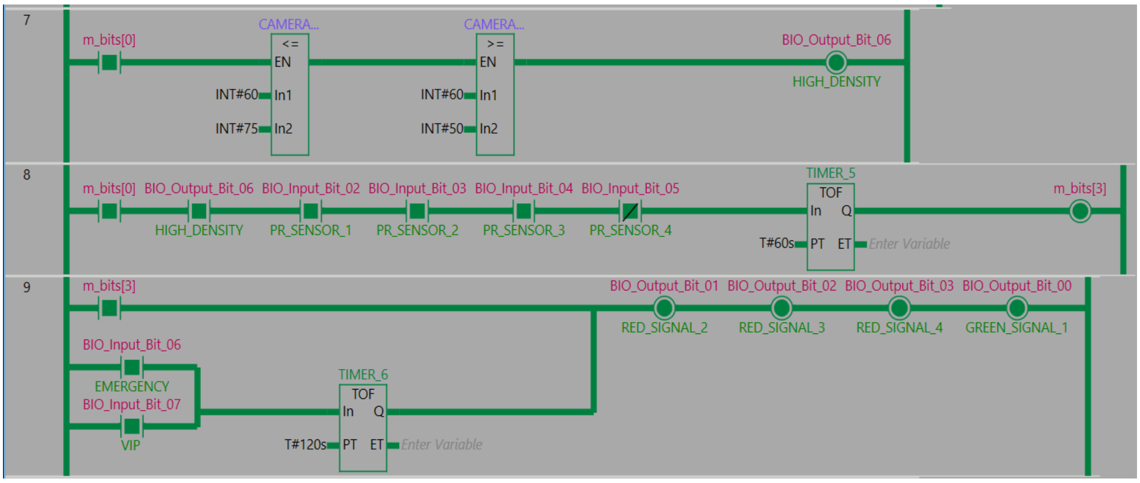


Figure 4.11. PLC ladder logic program for priority management at high density traffic

4.6.4 For Alarming Density Traffic

When we get the traffic camera distance (75%<range < 100%), it temporarily means the alarming density of the traffic on that particular path (P1). But when all proximity sensors (PR_SENSOR_1, placed at 20-unit distance; PR_SENSOR_2, placed at 50unit distance; PR_SENSOR_3, placed at 75unit distance; PR_SENSOR_4, placed at 100unit distance) are high, it confirms the alarming density of traffic.

If 75% < density < 100%, then GREEN_SIGNAL_1 of path (P1) is ON for 90 sec and at the same time RED_SIGNAL_2 of path (P2), RED_SIGNAL_3 of path (P3), RED_SIGNAL_4 of path (P4) are ON.

Similarly, in case of any EMERGENCY & VIP situation, then GREEN_SIGNAL_1 of path (P1) is ON for 120 sec and at the same time RED_SIGNAL_2 of path (P2), RED_SIGNAL_3 of path (P3), RED_SIGNAL_4 of path (P4) are ON. Fig 4.12 shows the PLC ladder logic program for emergency vehicle management system when there is alarming density traffic at intersections.

NOTE: In all the cases, the timings of the green signal can be changed manually via HMI, if user prefers to particular timings regarding the conditions of the traffic density.

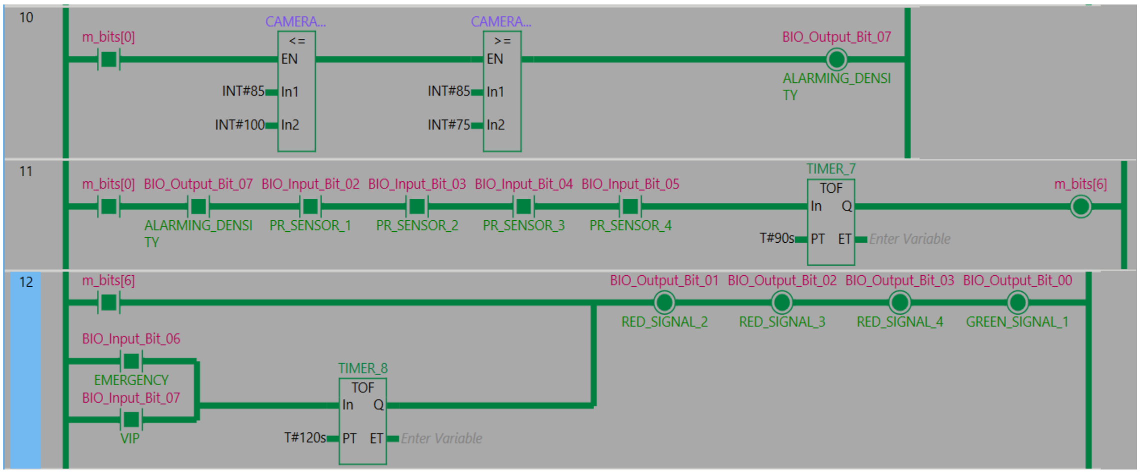


Figure 4.12. PLC ladder logic program for intersection management in case of alarming traffic density

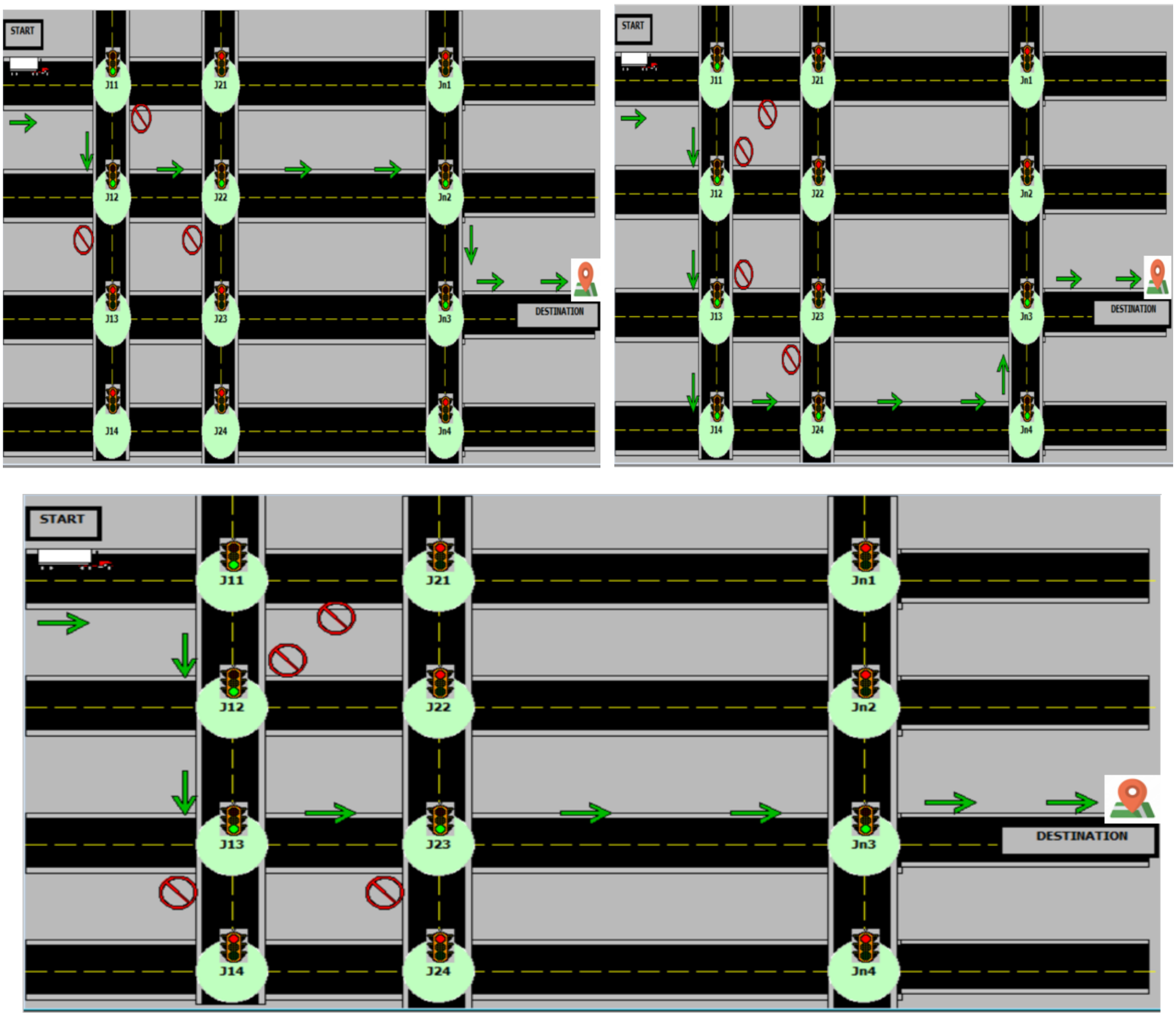


Figure 4.13. Cases of real-time route planning methodology that enable vehicles to avoid busy road stretches to reach their destination at the earliest

This priority management system is simply intended to facilitate a safety-critical operation to improve traffic efficiency at road intersections. The proposed system provides a green signal to emergency vehicles by using the phenomenon that several traffic lights of an area are synchronized together to reduce the vehicle waiting time at intersections. This real-time route planning methodology enable vehicles to avoid busy road stretches to reach their destination at the earliest. This suggested priority management approach is also tested and validated for successive crossings of coordinated multiple junctions instead of just one as shown in fig. 4.13. The same priority scheme might also be used to give priority to public transit vehicles at junctions during rush hour, which would in turn shorten urban workers' commute times.

4.7 Comparative Analysis and Discussion

Fig. 4.14 depicts the comparison of average travel time of vehicles with relation to the number of vehicles for proposed PLC and SCADA based system with traditional traffic signal control and virtual traffic light systems for emergency and non-emergency vehicles. We inserted emergency vehicle at different time intervals in the network which travels through more than 15 intersections before arriving at the destination. It is observed that the proposed scheme significantly cut the average journey time of emergency vehicles as compared to the physical traffic light scheme and VTL scheme. The suggested system further minimises non-emergency vehicle wait times in comparison to fixed time-slot and VTL schemes by allocating variable traffic light signal durations to all four approaches based on the volume of traffic on each approach. High-density approaches are given top priority in the suggested procedure to prevent traffic jams at crossings.

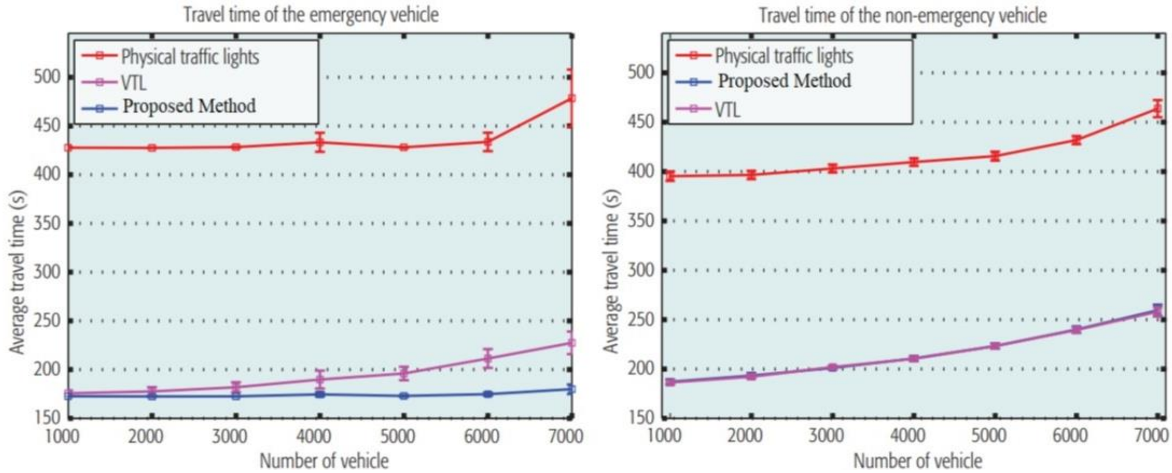


Figure 4.14. Comparison of the proposed system with different approaches

4.8 Conclusion

A robust and efficient PLC and SCADA-based traffic management strategy has been presented in this chapter that contributes in facilitating and accelerating the passage of emergency vehicles through urban traffic. The proposed priority management scheme uses PLC as an intersection controller which works on EtherCAT connectivity to interact with emergency vehicles and inductive proximity sensors to resolve possible conflicts at junctions and give higher precedence to particular routes or approaches. This technique is efficient for removing congestion and it greatly enhances real time traffic signal control and regular traffic flow at junctions along with a feature which gives preference to high priority vehicles. The suggested route optimization algorithm prevents emergency vehicles related accidents. In comparison to traditional and virtual traffic light systems, the simulation results showed that the suggested PLC-SCADA scheme enables an emergency vehicle to arrive at the accident scene with the least amount of delay in both moderate and heavy traffic conditions. speeding up emergency response operations. The proposed system enables emergency vehicles to reach the incident scene up to 5 minutes faster than traditional traffic light control systems. The reduction in emergency vehicle travel time will be considerably greater for denser regions. The proposed system barely affects the amount of time non-emergency vehicles.

Chapter 5

REAL TIME MONITORING AND CONTROL STRATEGIES FOR PUBLIC TRANSPORT

5.1 Introduction

Industrial Control Systems (ICS) and SCADA systems play a critical role in the management and regulation of critical infrastructure. SCADA systems brings us closer to the real-time application world. All process and equipment control capability is typically provided by a Distributed Control System (DCS) in industries such as power stations, railways, agricultural systems, chemical and water treatment plants. In this chapter, we propose to adopt SCADA and PLC technology in the improvement of the performance of real time signaling & train control systems in metro railways infrastructure. The main concern of this work is to minimize the failure in automated metro railways system operator and integrate the information coming from Operational Control Centre (OCC), traction SCADA system, traction power control, and power supply system. This work presents a simulated prototype of an automated metro train system operator that uses PLC and SCADA for the real time monitoring and control of the metro railway systems. Here, SCADA is used for the visualization of an automated process operation and then the whole operation is regulated with the help of OMRON (NX1P2-9024DT1) PLC and OMRON's Sysmac studio programming software is used for developing the ladder logic of PLC. The metro railways system has deployed infrastructure based on SCADA from the power supply system, and each station's traction power control is connected to the OCC remotely which commands all the stations and has the highest command priority. An alarm is triggered in the event of an emergency or system congestion. This proposed system overcomes the drawbacks of the current centralized automatic train control (CATC) system. This system provides prominent benefits like augmenting services which may enhance a network's full load capacity and network flexibility, which help in easy modification in the existing program at any time.

5.2 Related Work: Monitoring and Control of Metro Railways

Automation has been developed in the context of industrialization to provide various leverages such as process decentralization, virtualization, interoperability, real-time data acquisition, and an important role in mechanization, which provides the human operator with machinery to assist them with the manual requirements of work [105]. Figure 5.1 shows that automation reduces power consumption and increases industrial efficiency [106-108]. Energy performance can be improved directly and indirectly by implementing better monitoring, control and optimization strategies by using improved maintenance procedures that reduce the need for additional energy usage due to a process downtime or shutdown processes [109-112]. Automation assures the improved monitoring and control and also enhances the quality of work performed by control systems [113,114].

Railway systems play a vital role in today's constantly growing transportation sector. Metro railways deliver fast and convenient travels in the metropolitan cities to the daily commuters. The importance of signaling and train control systems in accomplishing these goals cannot be overstated because they offer an automated and connected control to improve train operations safety, efficiency and dependability [115-118].

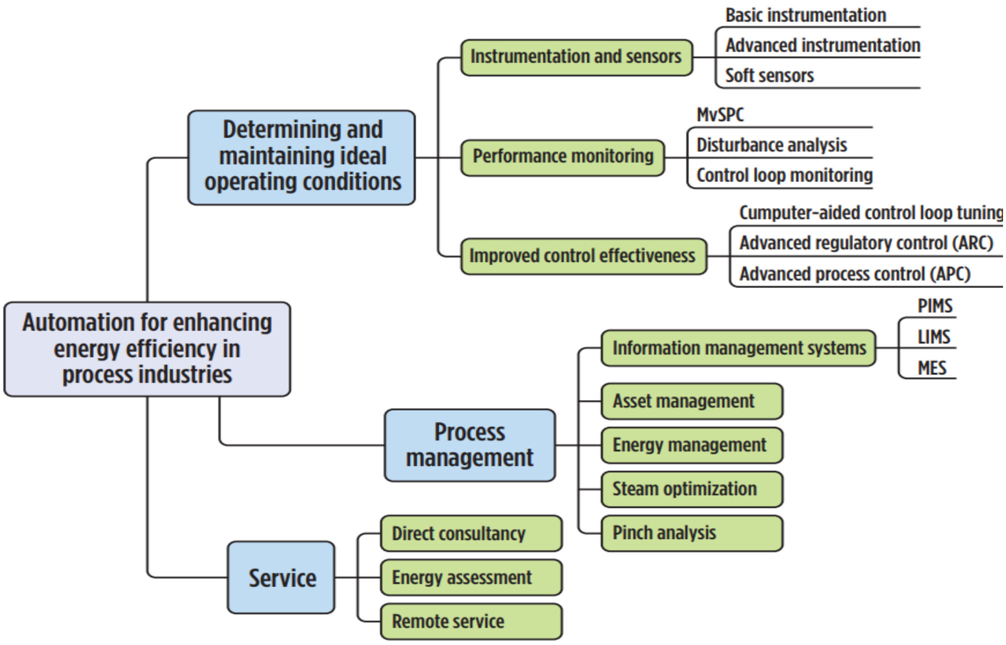


Figure 5.1. Automation for energy efficiency [108]

Earlier, track circuits and transmission-based systems were used for signaling & train control systems in metro railways. With advancements in telecommunications and information technology, the Communication based train control (CBTC) systems have now been used for railway signaling and train control systems [119,120]. Around the core issue of improving the signaling and train control systems, many researchers have focused on the CBTC techniques. But these systems have various drawbacks related to fault of traction power supply system (TPSS), train delays, security etc [121-123]. Due to unreliable wireless communication and frequency handover, CBTC systems have a significant impact on the functionality, efficiency and usefulness of the train control system. They have a large attack surface. They can be subjected to multiple hacking attacks like network intrusion, data tampering which eventually lead to security hazard.

Energy conservation in train operation is gaining major attention as issues over energy usage and operational costs in metro systems grow. Transit operations control plays an important role in the service delivery because it determines the impacts on passenger service quality [124]. However, the metro line frequently experiences traction power supply system problems, which result in more than 5-min train delays. Dispatching actions must be made right away during such a disruption to lessen the effects on quality of the passenger service. Most of the algorithms proposed in the literature have mostly concentrated on energy-efficient train scheduling and single-train optimum control [125-127]. Without energy storage devices, the former cannot guarantee the proper application of regenerative energy on the metro lines because it ignores the synchronization of moving and stopping trains. The latter involves planning rail operations to synchronize moving and stopping trains for greater regenerative energy consumption. It is required to take dispatching steps in order to maintain line capacity in the undersupplied area during the power supply shortage brought on by the malfunction of the TPSS in the metro line.

5.3 Problem Statement

In this chapter, our motivation is to overcome the drawbacks of the current CBTC and CATC i.e. centralized automatic train control system which comprises of train protection, signalling and operation systems. Our motivation is to effectively compensate the effects of fault of traction power supply system (TPSS), train delays and security so that the real time signalling, monitoring and train control can be done effectively in real time. Therefore, we propose PLC and SCADA based automation systems that can be used in metro railways to minimize the failure. This PLC and SCADA based real time monitoring and train control system for the metro railways helps in detecting exact location, avoiding train collisions and opening emergency exit even after the interruption of power system with the use of programmable logic controller. If the communications link between any of the trains is disrupted then the whole system/network will be affected but the impact is smaller.

5.4 Prototype of Metro Railways System Infrastructure

PLC and SCADA are utilized here for monitoring and control of metro railways system. PLCs conduct the majority of the control components required to implement system logic. It is important to understand how real-world stuff works and therefore to assist the user, PLC code is used with SCADA. PLC has an internal memory that stores instructions for executing certain operations while scanning the program. The purpose of a PLC is to modify process operations and monitor critical process parameters as needed. PLC receives data/signals from input devices such as sensors, push button switches, contact limit switches, and so on. The information is processed in the input module where logical operations are done on the inputs, and the required response is supplied to the operator via the output module linked device such as a motor, valve, or alarm (see Fig. 5.2). Input/output, HMI (Human-machine interface), signal hardware controller, networks, communication, database, and software are all part of a SCADA system, which are all connected via a PLC program. PLC is capable of altering or modifying the sequence of operations in accordance with the settings of the purpose to prevent failure. SCADA monitors, regulates, optimizes, and manages generating and transmission systems. Remote terminal units (RTU) are the core component of these systems, which gather data automatically and link directly to sensors, meters, recorders, or process equipment.

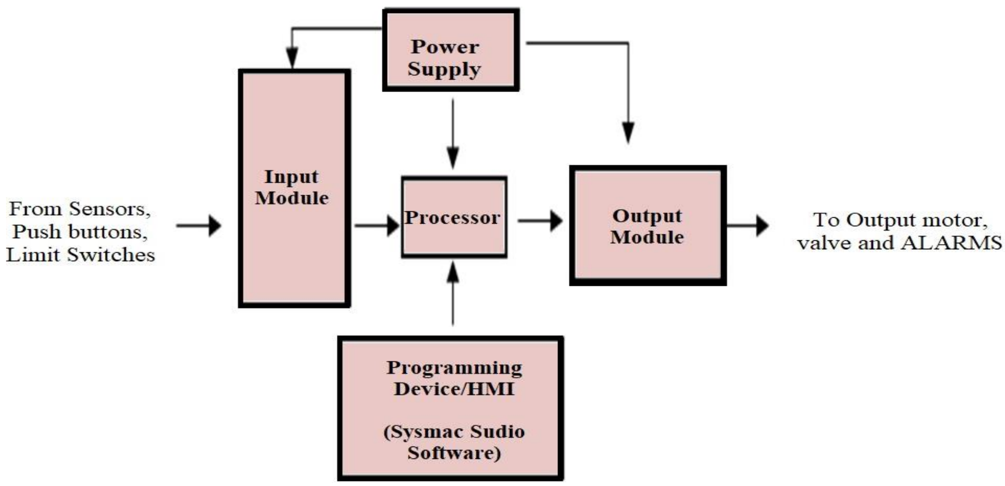


Figure 5.2. Working of PLC along with the components

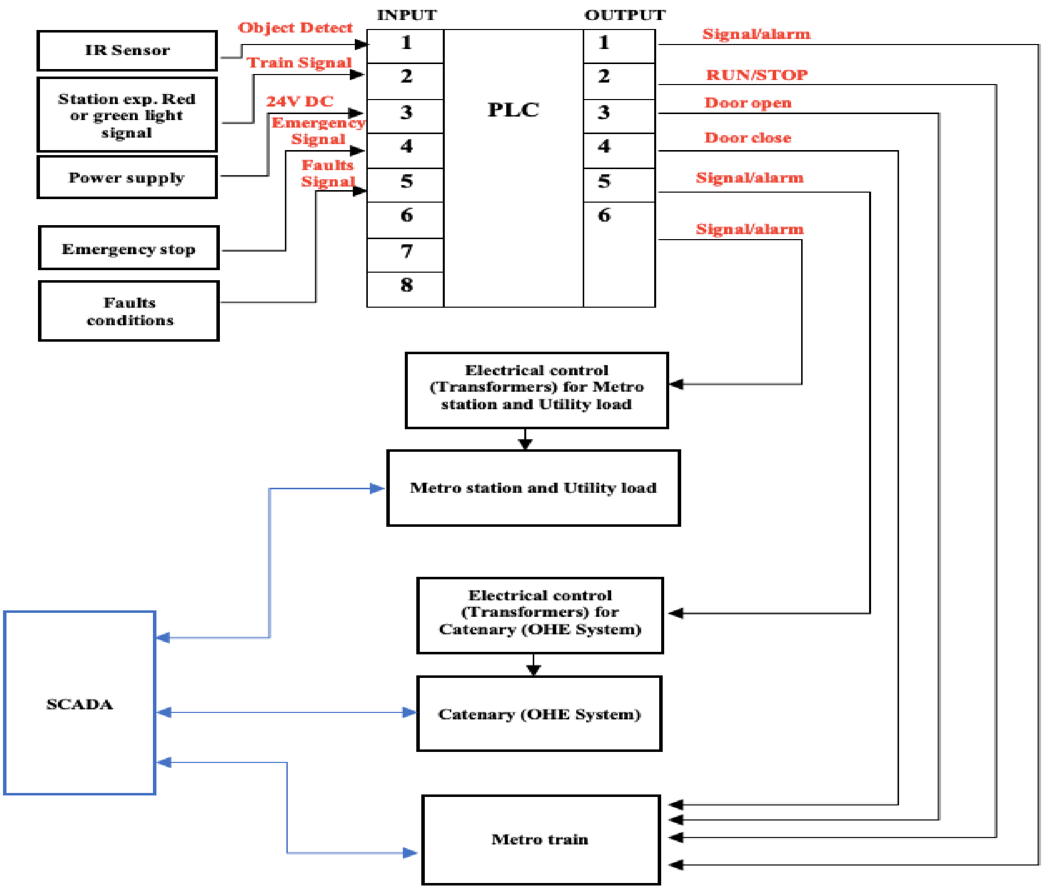


Figure 5.3. Working of metro railways system using PLC and SCADA

SCADA monitor and control the system via a centralized OCC and HMI that controls the traction system equipment and entire power supply through SCADA. Figure 5.3 shows the working of metro railways system using PLC and SCADA. To execute its tasks, the PLC requires a regulated power source of 24V DC. IR sensors, stations, and emergencies feed into the PLC, which generates six output signals such as signal/alarm, train running or halting, and door open or close. The PLC's output module will send commands from SCADA to the train. An essential feature is that in the case of an emergency, the alarm will send a status point with the value NORMAL or ALARM.

The prototype of the automated metro railways system operator has four main applications as shown in Fig. 5.4. OCC is the main application of this automated metro train system operator prototype. An operator sits in front of the HMI and controls the metro train system. Each station is linked to the OCC through a remote connection. It has command of all stations and handles all commands such as emergency and congestion with highest priority. CCTV function, metro stations and metro platform view, and electrical control are other sub-applications of the system (traction power control and power supply system).

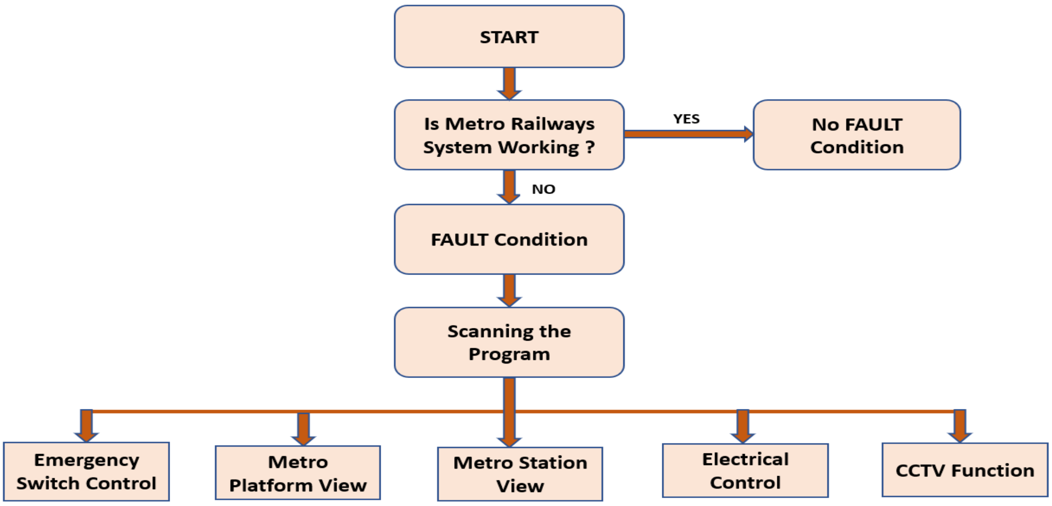


Figure 5.4. Functioning of automated metro railways system operator

Fig. 5.5 shows OCC runtime window in SCADA Wonderware Intouch software from where the operator may command and monitor. If the metro rail system is not working, then the operator can click to switch control or CCTV or metro station icon or electrical control icon. The IR and reflecting sensors on the RTU are used to scan the programs. If there is a problem with the process, the RTU sends a message to the master terminal unit (MTU), which then sends signals or alerts to the operator on the screen.

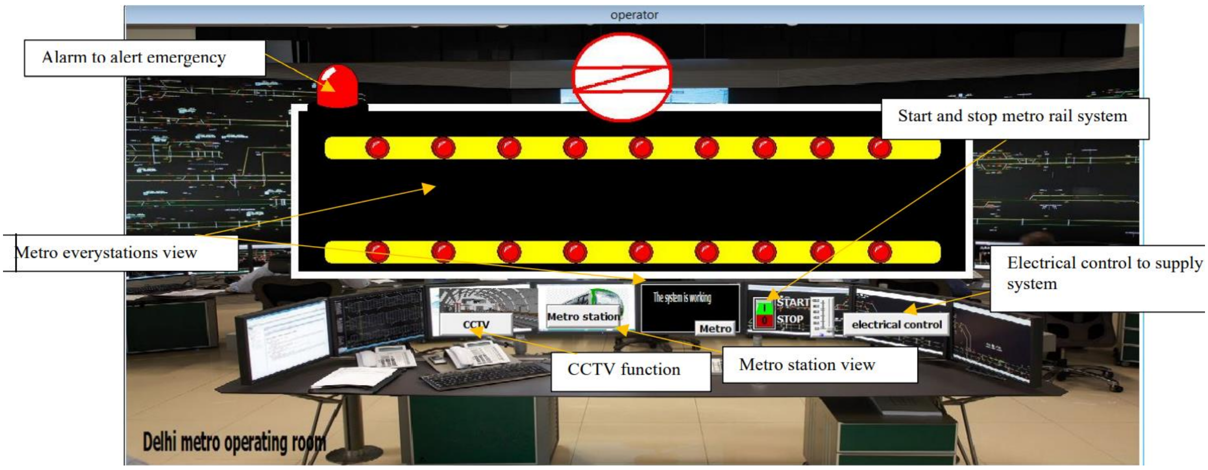


Figure 5.5. Operational control center runtime window in SCADA Wonderware Intouch software

5.5 Operations of the Metro Railways System

This section shows the operation of all the four applications of automated metro railways system.

5.5.1 Metro Platforms View Sub-Application

The driver of the trains controls the metro platforms, and the operator of any platform can manage the traffic of the metro station. Fig. 5.6 and Tab. 5.1 show the working of metro platforms view sub-application. Here, t is timing tag of process/tag of slider.

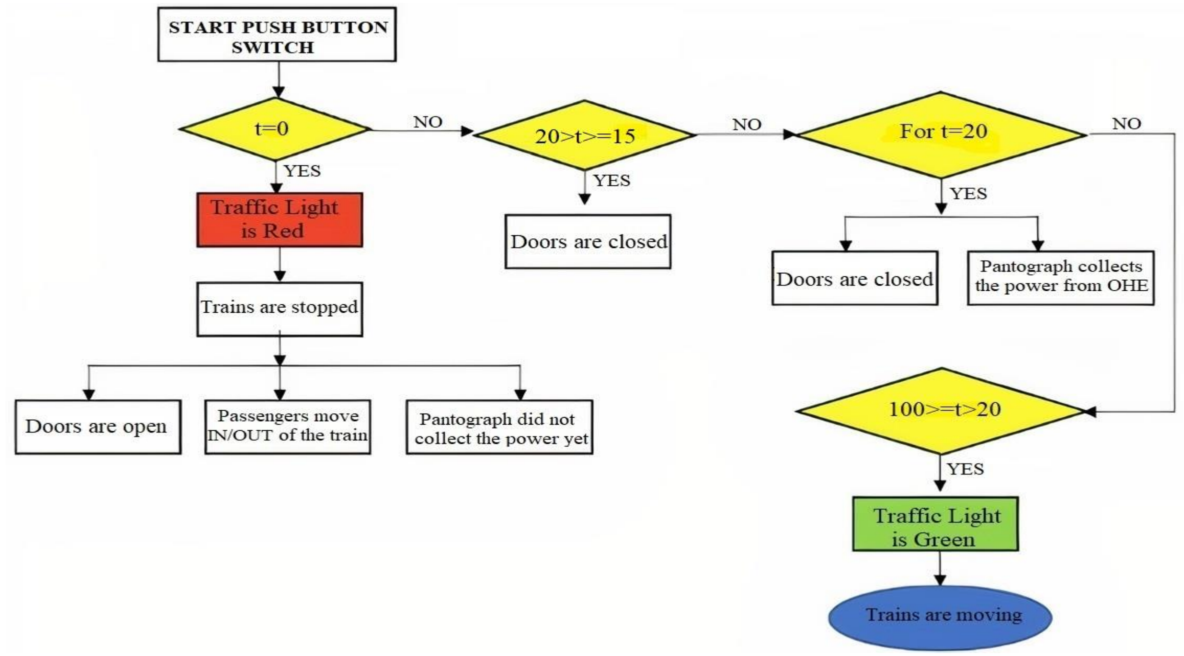


Figure 5.6. Working of metro platforms view sub-application

Table 5.1. Description of metro platform view sub-application

S. No.	State	Description
1.	t = 0	Traffic light is red. The trains are stopped and passengers move out/in of the train and pantograph has not collected the power yet.
2.	20 > t >= 15	Metro train doors are closed. Train is ready to move.
3.	For t = 20	Metro train doors are closed. Pantograph collects the power and electrical signal on overhead system is ON. Train starts running.
4.	100>= t > 20	Traffic light is green. The train starts moving forward.

5.5.2 Metro Stations (Traction SCADA System) View Sub-Application

Functioning of metro stations (traction SCADA) view sub-application is shown in Fig. 5.7. Metro train starts moving when the switch is turned ON. The LED in the control panel view indicates the proper location of the metro train. This system can track, control and recognize the location of the train even after a power outage or other breakdown. The emergency light will turn ON in case of any fault station and an alert message is displayed by the OCC in the relevant metro station on the HMI or operation display (see Fig. 5.16).

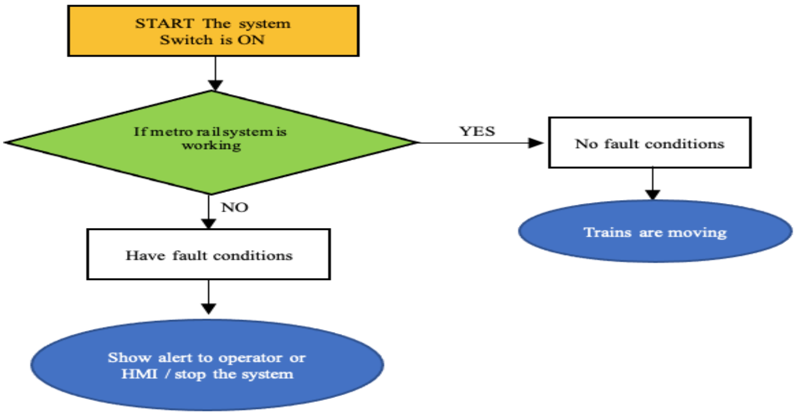


Figure 5.7. Working of metro stations (traction SCADA system) view sub-application

5.5.3 Traction Power Control and Power Supply System

Fig. 5.8 shows the functioning of electrical control view sub-application. Metro rail lines must be electrified with 25kV, single phase, 50 Hz for overhead equipment to deliver electrical energy to locomotives or trains for operating the motor. The substation, feeding post, and other equipment at the control post and switching station make up the power supply system. A catenary i.e. the overhead equipment (OHE) is used to deliver power to a metro train equipped with a pantograph in metro rail traction systems. Overhead equipment will incorporate sectioning posts, sub sectioning posts, and paralleling posts at various positions for maintenance purposes. Transformer1(T1) is a stepdown transformer for metro stations and utility load, transformer2(T2) is a stepdown transformer for the catenary, and transformer3(T3) is a step-up transformer for 132kV incoming line from generating station. This 132kV supply will be stepped down to single phase 25 kV for traction purposes and three phase 33 kV for lighting and general use. The system is turned on by pressing the button ON S0. The power control and power supply system where t is timing tag of process or the tag of slider is shown here (see Table 5.2).

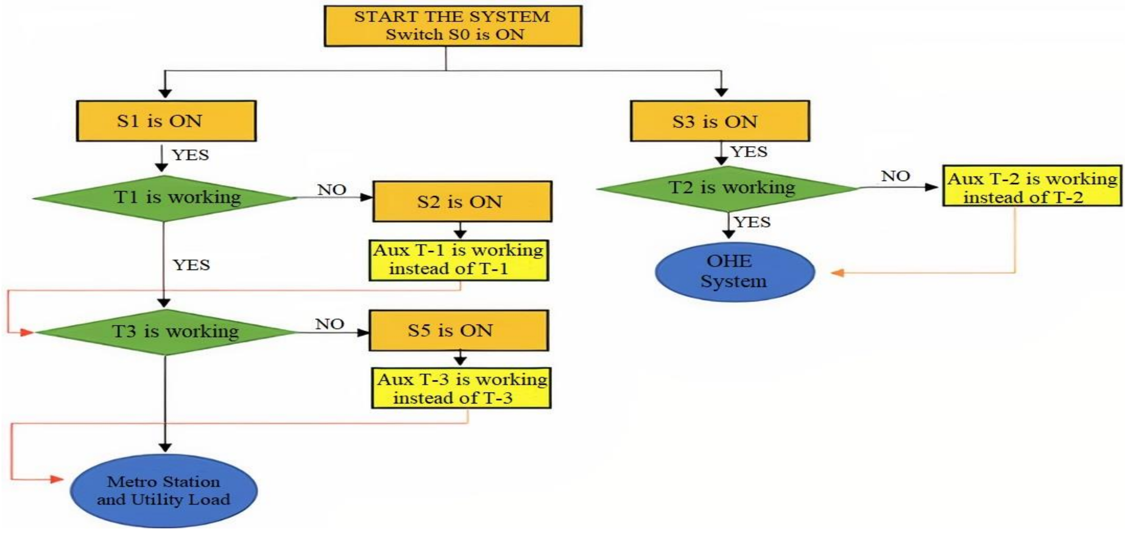


Figure 5.8. Working of traction power control system

Table 5.2. Description of Electrical control view

S. No.	State	Description
1.	S0 is ON	Power supply is ON.
2.	T1 and S1 are ON	Power supply(132kV/33kV) is fed to the stepdown transformer (T1), then fed to the step-up transformer (T3), and then fed to metro stations and utility load.
3.	For 50<= t1<100	Transformer (T1) is damaged.
4.	S2 is ON	When transformer1 (T1) is damaged, the Auxiliary transformer1 (Aux-T1) is operated, and the power supply is fed to the stepdown transformer on standby (132kV/33kV). If transformer3 (T3) is also not working, the power supply is running through the Auxiliary transformer3 (Aux-T3 step-up transformer 33kV/415kV) and then fed to metro stations and utility load.
5.	S3 is ON	Stepdown transformer2 (T2, 132kV/25kV) is ON and the power supply is fed to catenary overhead electrical lines (OHE) through which the metro train is connected.
6.	For 50<=t2<100	Transformer2 (T2) is damaged.
7.	S4 is ON	Auxiliary Transformer2 (Aux-T2) is ON and the power supply (132kV/25kV) is fed to the catenary (OHE).

5.5.4 Video Surveillance and Control (CCTV) System

A sophisticated intrusion detection system (IDS) will be placed at the platform, with comprehensive CCTV or video surveillance coverage of stations, parking, and public spaces. Internal security monitoring systems such as the SCADA, automatic train supervision system, passenger information system and public address system can be implemented to minimize reaction time from personnel. A smart interface is provided to the control room operator using this CCTV integration with SCADA approach. They can make quick and effective judgements for running the metro system and delivering the required services. The functioning of CCTV view sub-application is shown in Figure 5.9. SCADA systems use video data to get more information and a sharper view of the happenings at the remote locations.

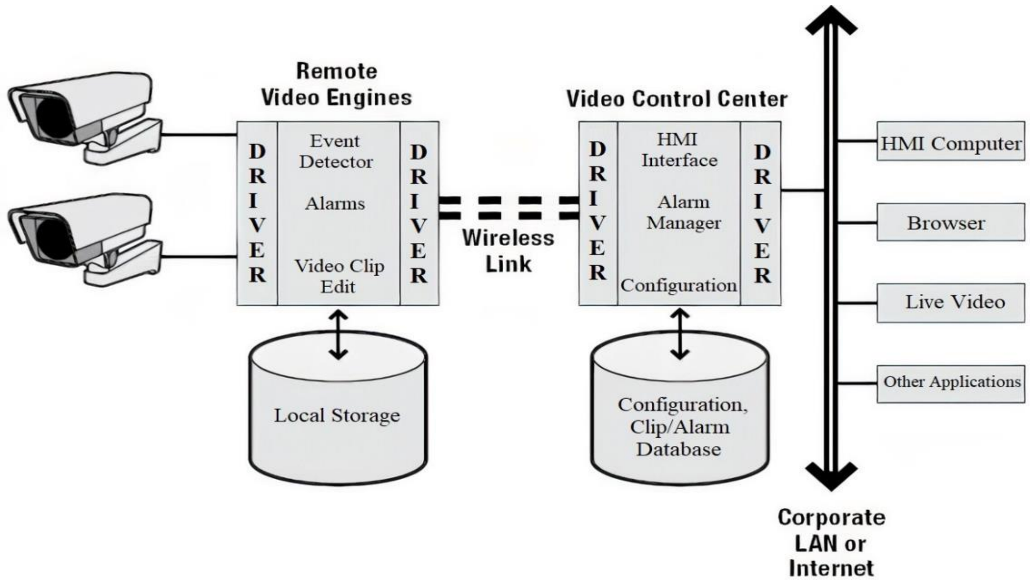


Figure 5.9. CCTV integration with SCADA

CCTV integration with SCADA systems consists of remote video engine and video control center. Video cameras of every remote site are connected to the remote Video Engine (RVE) that record live videos continually. PLC or RTU acts as the local DVR for continuously storing and processing the video data from the cameras at remote locations. Remote PLC/RTU gets the camera-initiated alarms with the help of an integrated Modbus TCP server. Dedicated radio networks are used by remote locations to communicate process data back to the control centre.

Network bandwidth might vary from 9600 baud serial radios to higher bandwidth TCP/IP radios. Video control centre (VCC) determines whether it has to send still images or video clips to the Wonderware HMI/SCADA system in the control room or not. The technology simultaneously transmits event clips and live video to the VCC at the control centre for the central office. The Wonderware SCADA system and this video surveillance system communicates directly with each other. The operator of the video surveillance system can view and handle video clips, as well as monitor alarms, using a Wonderware HMI. Through an EtherCAT link to the HMI computer, the remote locations can communicate to the main server.

Using this CCTV integration with Wonderware HMI SCADA, operators can have the information about the real-time data of the system operations and can view the videos and monitor the status of the system at any time. The remote video engine can be used in a variety of ways, including alarm video clip mode, live video recording, and continuous monitoring. All cameras' video is sent at a user-defined frequency by the system. All cameras are visible to the system operator on a single scrolling system overview screen. In case of an alarm event, the system records a brief motion video clip and sends it to the control room. When the operator clicks on a short clip of video connected with an alarm, it will play and illustrate what was happening right before, during, and after the event that set off the alarm. In the absence of warnings, a system tour is carried out every 25 minutes, giving the operators a new frame of video and an updated perspective of the distant site. The HMI/SCADA system provides operators with access to a sizable amount of real-time process data. Operators may get live, streaming video from any of the video cameras positioned in useful places with a single mouse click. The live video feeds can show as pop-ups immediately on operators' HMI screens, allowing them to monitor what's happening across the facility.

5.6 Simulation Results with PLC Ladder Logic Program

A SCADA Wonderware Intouch software window of every operation is shown here along with the ladder logic program of PLC.

5.6.1 Operational Control Center (OCC)

Fig. 5.10 shows the OCC runtime window in SCADA Wonderware Intouch software from where the operator may command and monitor. If the metro rail system is not working, then the operator can click to switch control or CCTV or metro station icon or electrical control icon. The IR and reflecting sensors on the RTU are used to scan the programs. If there is a problem with the process, the RTU sends a message to the master terminal unit, which then sends signals or alerts to the operator on the screen.

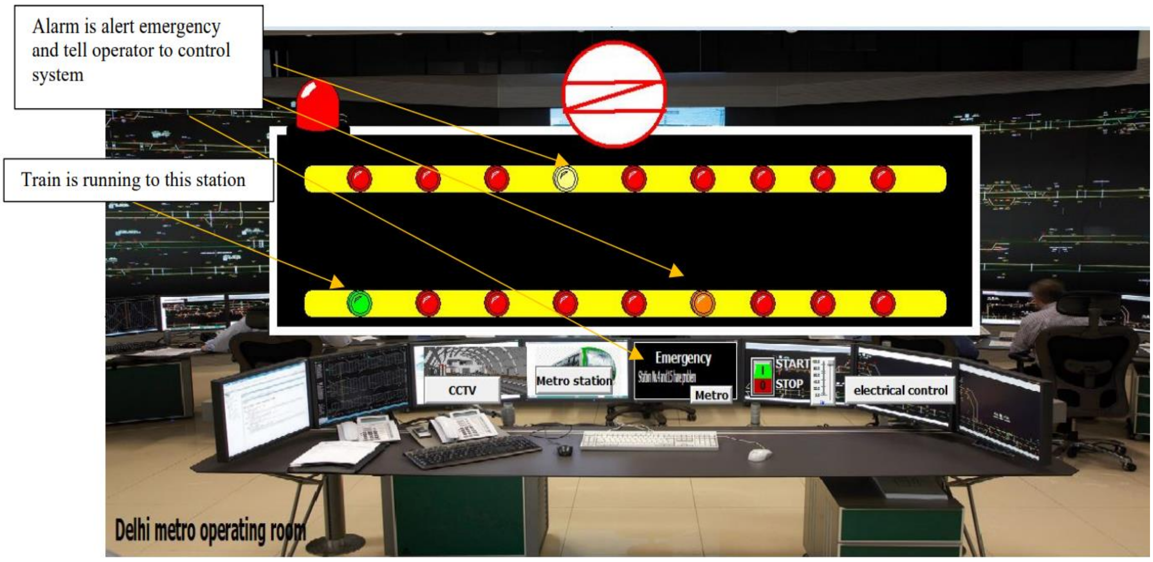


Figure 5.10. OCC view of main application with failure in the system

5.6.2 Metro Platforms View Sub-Application

According to the proposed system, the station master has only to give input once, which will go to the PLC, after which the PLC provides its output according to the timer circuit. In this way, the complete task can be done without too much human interference. All the cases of metro platforms view sub-application are shown here with the help of SCADA system and PLC ladder logic. Figure 5.11, Figure 5.12,

Figure 5.13 were generated using Wonderware Intouch SCADA software version 10.0, https://lab4sys.com/en/download-wonderware-intouch-scada/.

A. **For t = 0**

When t = 0 (t is timing tag of process/tag of slider), the traffic light is red. The trains are stopped. Metro train doors are open and passengers move out/in of the train. Pantograph has not collected the power yet.

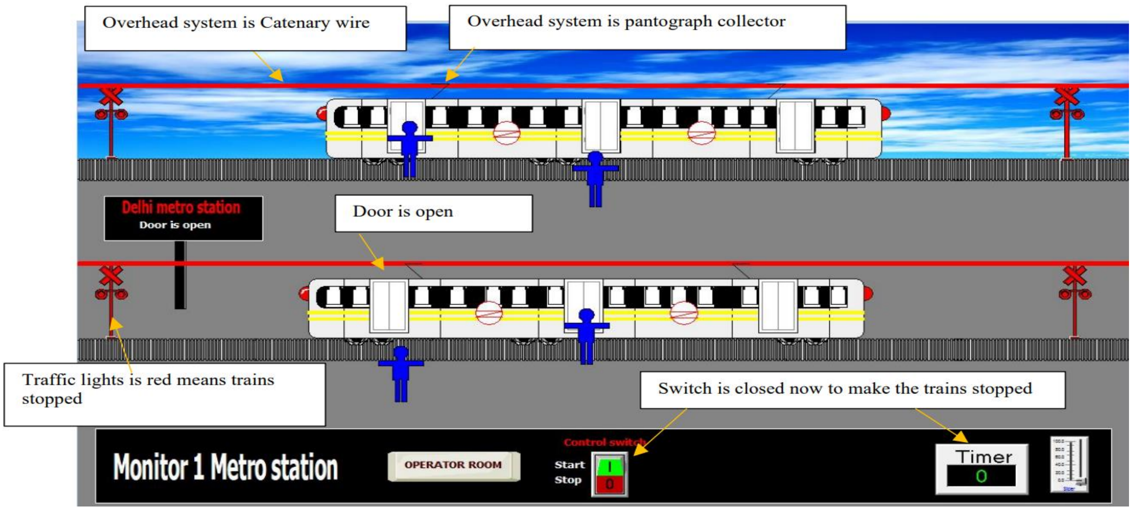


Figure 5.11. For t = 0, Trains are stopped and passengers move out/in of the train

B. **When 20 > t >= 15**

When 20 > t >= 15, metro train doors are closed and train is ready to move as shown in Fig. 5.12.

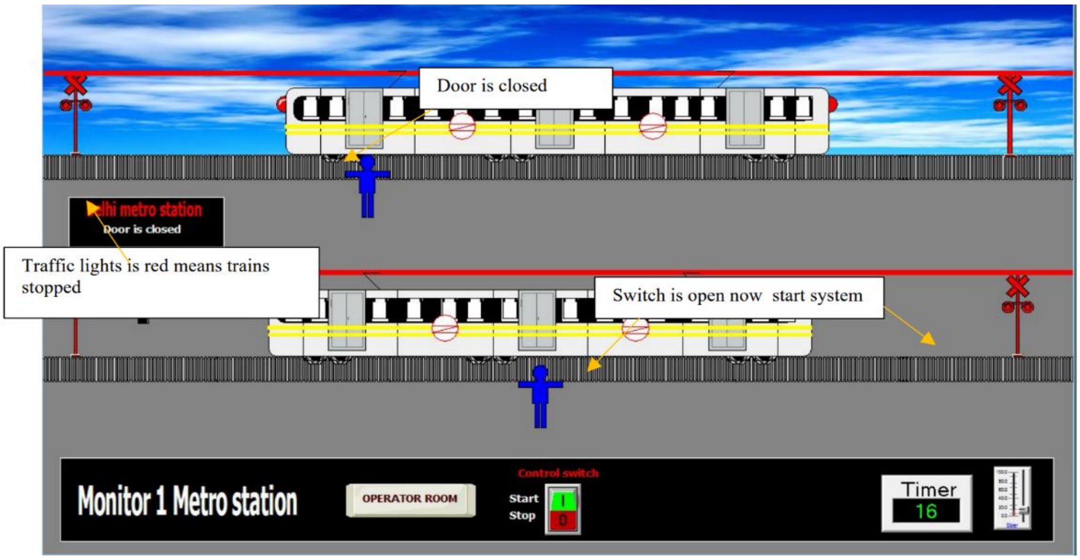


Figure 5.12. For 20 > t >= 15, Metro train doors are closed

C. **For 100>= t >= 20**

When 100>= t >= 20, metro train doors are closed. Pantograph collects the power and electrical signal on overhead system is ON. And train starts running. When the traffic light is green, train starts moving forward as shown in Fig. 5.13. Figure 5.14 shows the PLC ladder logic program of metro platforms view sub-application.

(a) (b)

Figure 5.13. **(a)** For t=20, Metro train doors are closed. Pantograph collects the power and electrical signal on overhead system is ON **(b)** For 100>= t >= 20, Traffic light is green and train starts moving forward

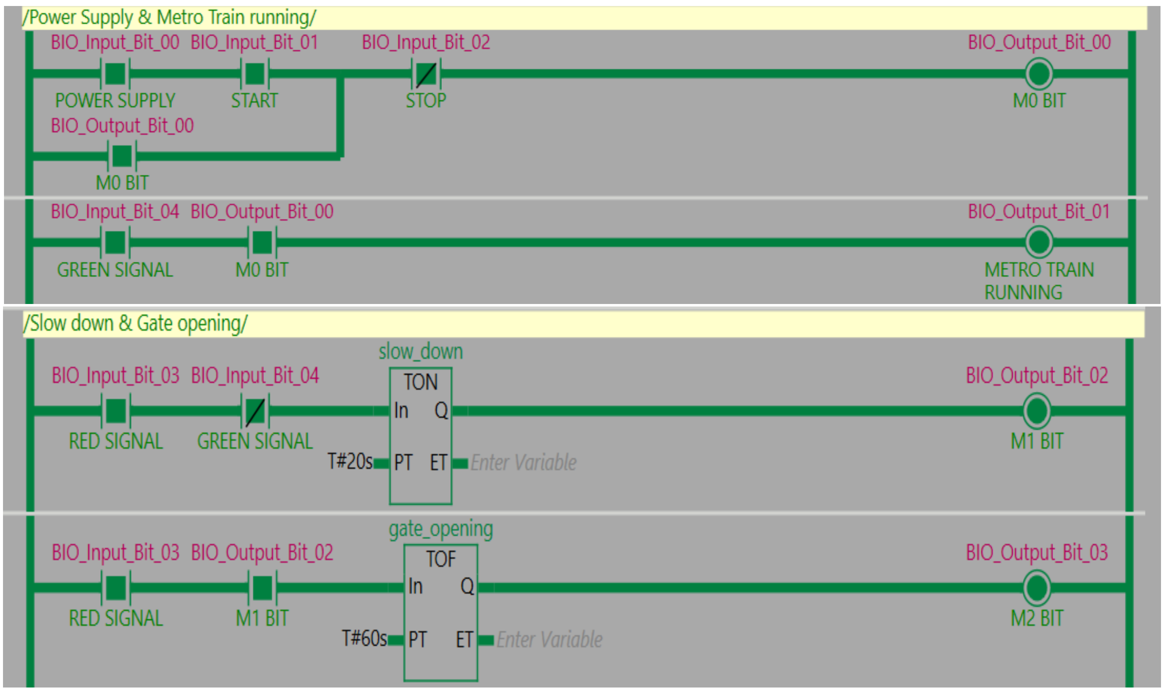


Figure 5.14. PLC ladder logic program of metro platforms view sub-application

There is a process object in SCADA software. We assign equipment identification, station number, block number, and bit number to link the application in a system with the field. Fig. 5.15 shows the metro stations (traction SCADA) of sub-application. Metro train starts moving when the switch is turned ON. The LED in the control panel view indicates the proper location of metro train. This system can track, control and recognize the location of the train even after a power outage or other breakdown. The emergency light will turn ON in case of any fault station and an alert message is displayed by the OCC in the relevant metro station on the HMI or operation display (see fig. 5.16).

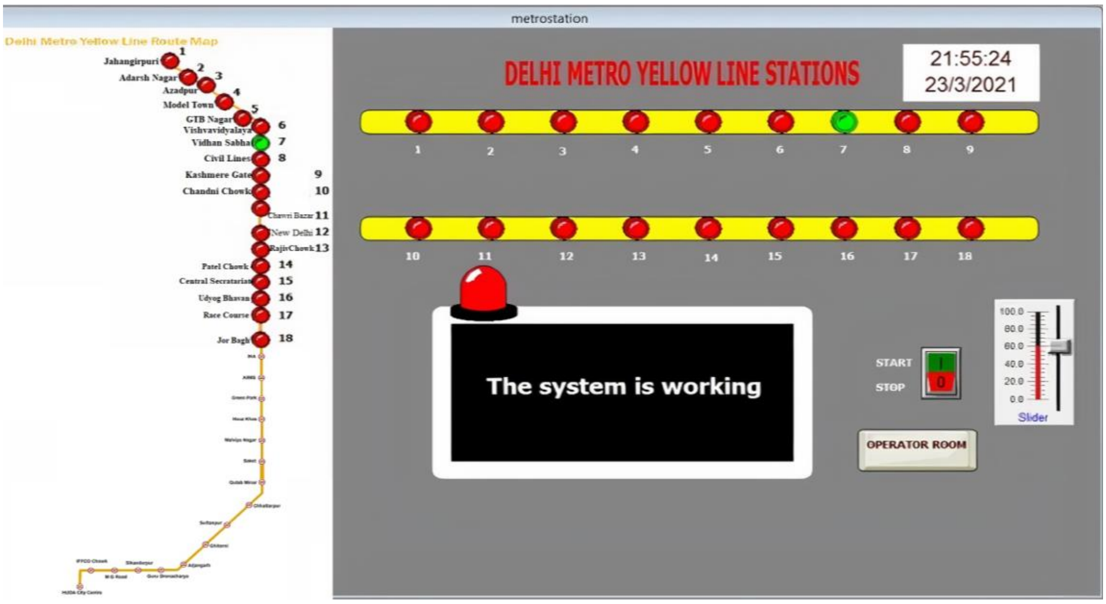


Figure 5.15. Metro stations (traction SCADA) of sub-application

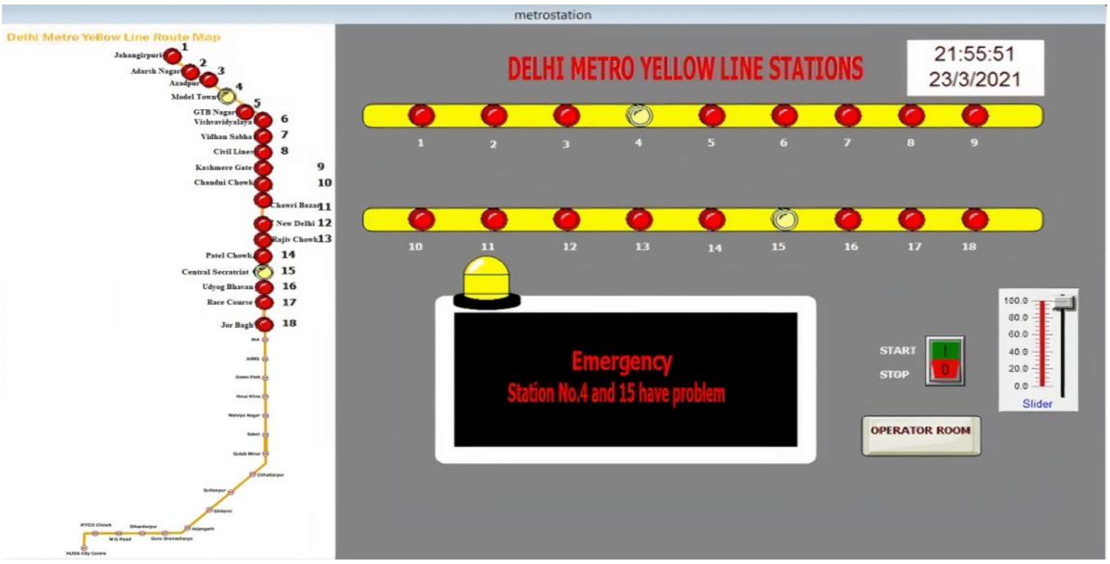


Figure 5.16. Metro stations (traction SCADA) of sub-application (failure)

5.6.3 Electrical Control (Traction Power Control and Power Supply System) View Sub-Application

Here, the functioning of Electrical control view sub-application is shown. Metro rail lines must be electrified with 25kV, single phase, 50 Hz for overhead equipment to deliver electrical energy to locomotives or trains for operating the motor. The substation, feeding post, and other equipment at the control post and switching station make up the power supply system. A catenary i.e. the overhead equipment (OHE) is used to deliver power to a metro train equipped with a pantograph in metro rail traction systems. Transformer1(T1) is a stepdown transformer for metro stations and utility load, transformer2(T2) is a stepdown transformer for the catenary, and transformer3(T3) is a step-up transformer for 132kV incoming line from generating station. This 132kV supply will be stepped down to single phase 25 kV for traction purposes and three phase 33 kV for lighting and general use. There is a PLC program implemented in SSP and SP posts. When the OHE 25 kV supply of the mainline fails, paralleling interrupter opens automatically within a predefined time. This program has been loaded in the RTU itself so that the operator can take action faster.

1. **No Fault Condition:**

For running the system, a power supply of (132kV/33kV) is fed to the stepdown transformer (T1), then fed to the step-up transformer (T3), and then fed to metro stations and utility load as shown in Fig. 5.17.

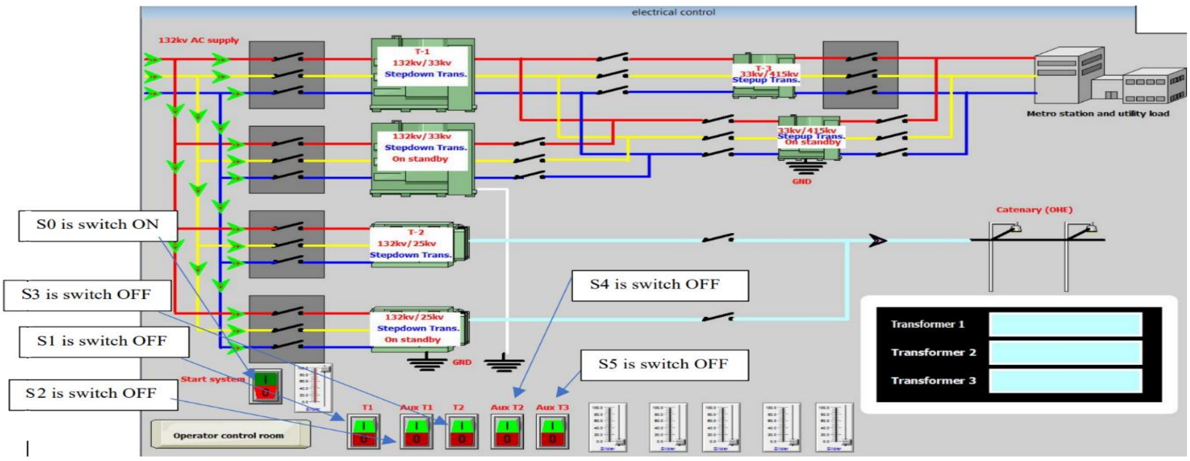


Figure 5.17. S0 is ON, Power supply is ON (No fault Condition)

Figure 5.18 shows the PLC ladder logic program of electrical control view sub-application with no fault condition.

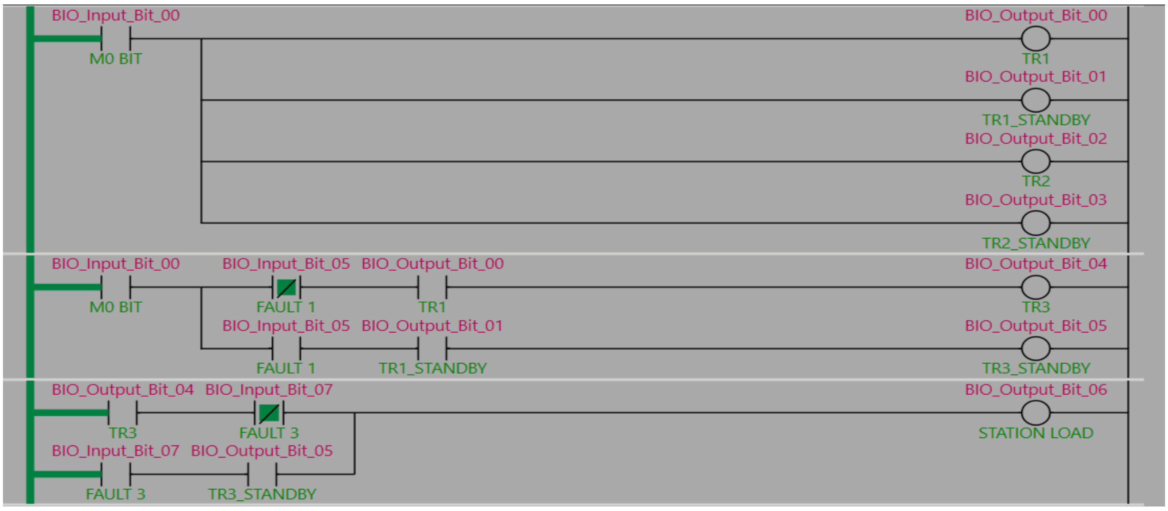


Figure 5.18. PLC ladder logic program of electrical control view sub-application (No fault condition)

2. For 50<=t1<100:

Switch ON S0 and S1 means the system are working. 132 kV in coming lines from generating station to transformer1 is stepdown transformer from 132kV to 33 kV. Transformer3 is step-up transformer from 33kV to 415 kV for metro station and utility load. Alarm tells the operator that transformer1 is damaged. When transformer1 (T1) is damaged, the auxiliary transformer1 (Aux-T1) is operated, and the power supply is fed to the stepdown transformer on standby (132kV/33kV). Switch ON S0 and S2 means the system are working. The auxiliary transformer1 provide the power in case of Transformer1 damage as shown in Fig. 5.20. Figure 5.19 shows the ladder logic program of PLC for transformer T1 damage.

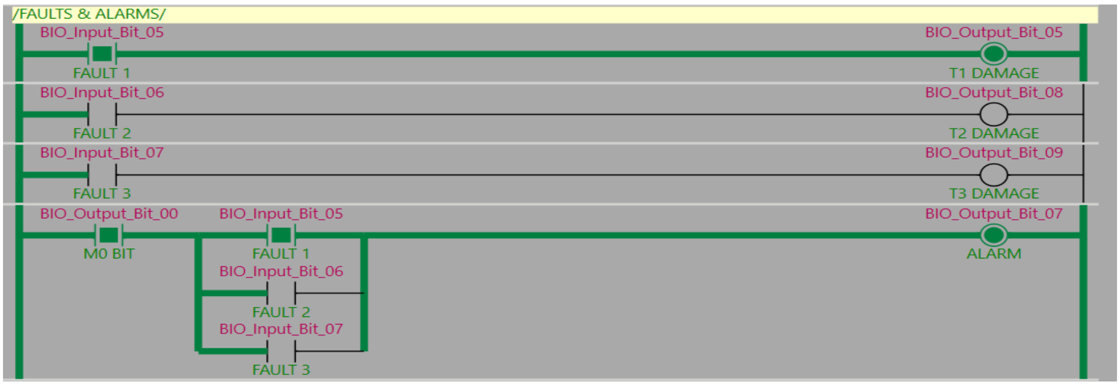


Figure 5.19. Ladder logic program of PLC (Transformer T1 damage)

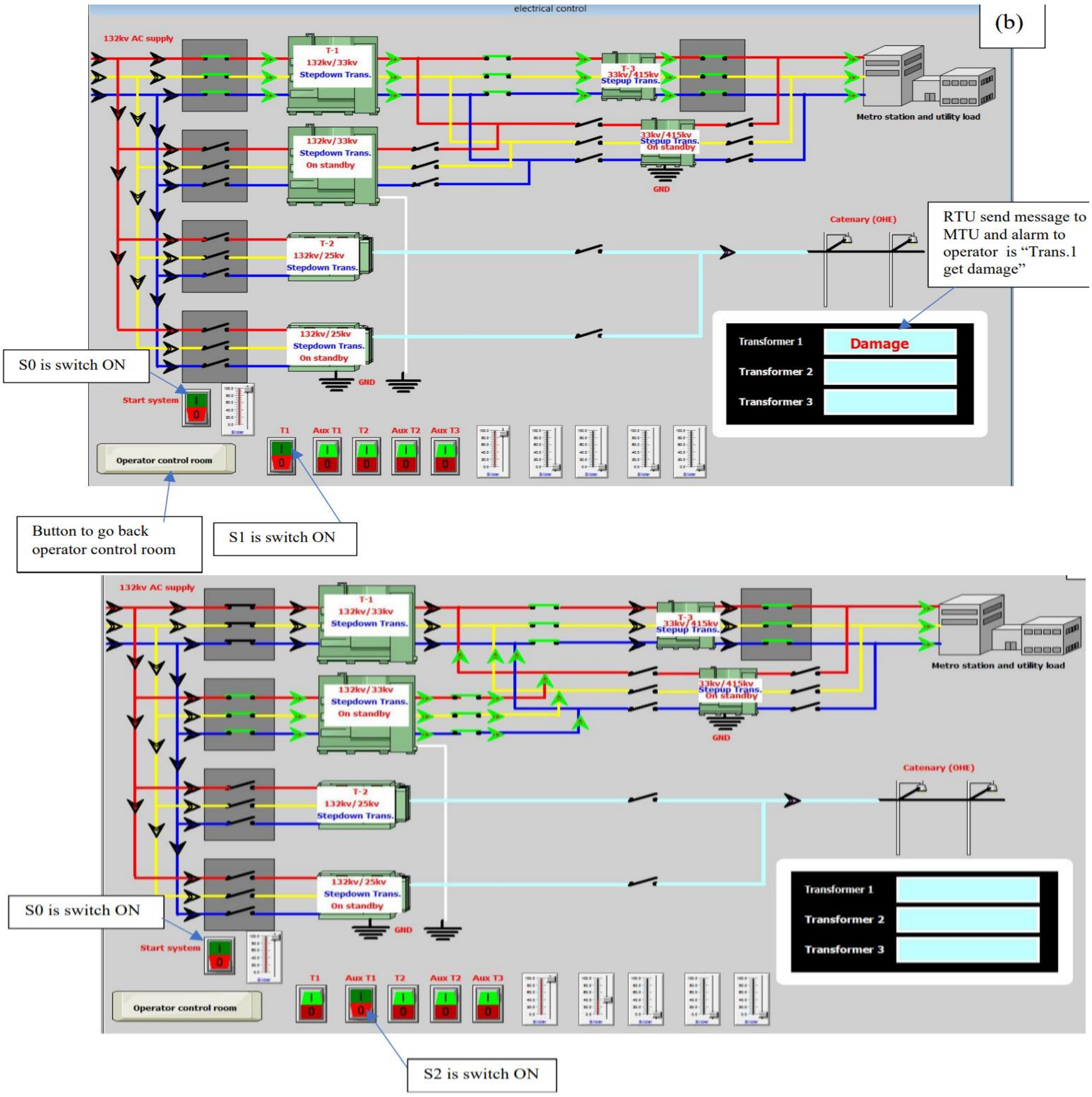


Figure 5.20. For 50 <= t1<100, When Transformer (T1) is damaged, then Aux-T1 is operated

3. For 50<=t2<100:

Switch ON S0, S2 and S3 means that the system is working. Stepdown transformer2 (T2, 132kV/25kV) is ON and the power supply is fed to catenary overhead electrical lines (OHE) through which the metro train is connected. After sometime if transformer2(T2) gets damaged, then Auxiliary transformer2 (Aux-T2) provides the power in case of transformer2(T2) as shown in Fig. 5.21. Switch ON S0, S2, and S4 means the system is working with Aux-T2. Figure 5.22 shows the ladder logic program of PLC for transformer T2 damage.

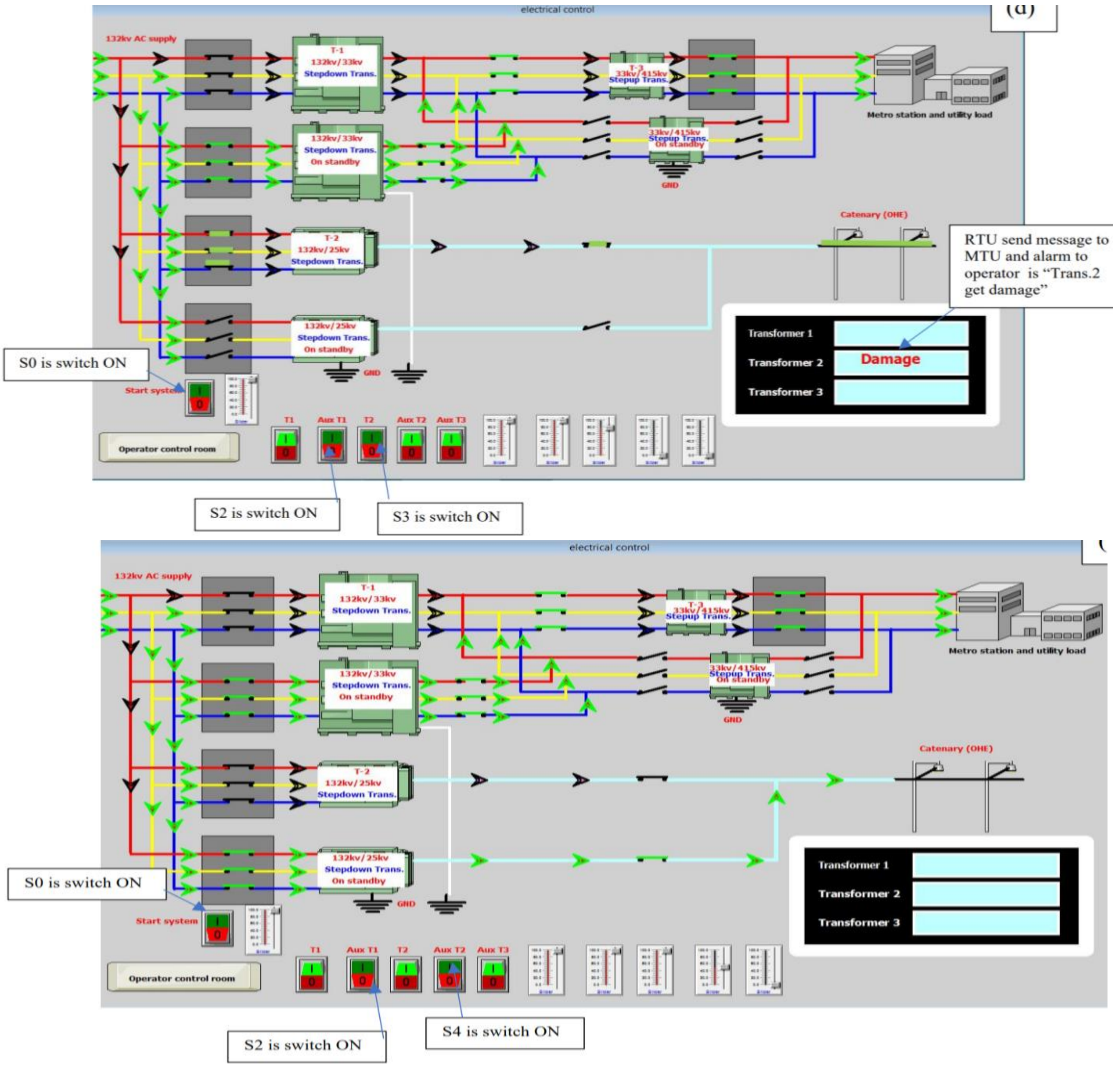


Figure 5.21. For 50<=t2<100, When Transformer (T2) is damaged, then Aux-T2 is operated

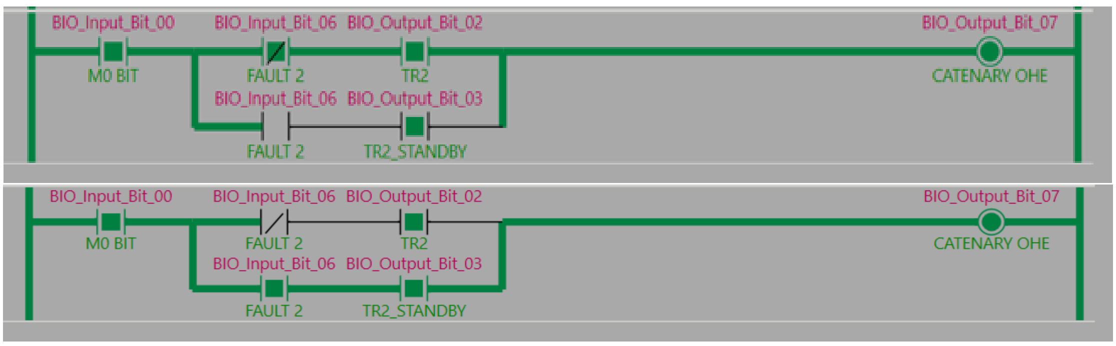


Figure 5.22. Ladder logic program of PLC (Transformer T2 damage)

4. When Stepdown transformer3(T3) gets damaged, then Auxiliary transformer3 (Aux-T3) provide the power in case of T3 as shown in Fig. 5.23. Switch ON S0,

S4, and S5 means the system is working with Aux-T3. Figure 5.24 shows the ladder logic program of PLC in case of faults (when Aux T1, Aux T2, Aux T3 is standby) and Fig. 25 shows the ladder logic program of PLC in case of T1, T2, T3 damage.

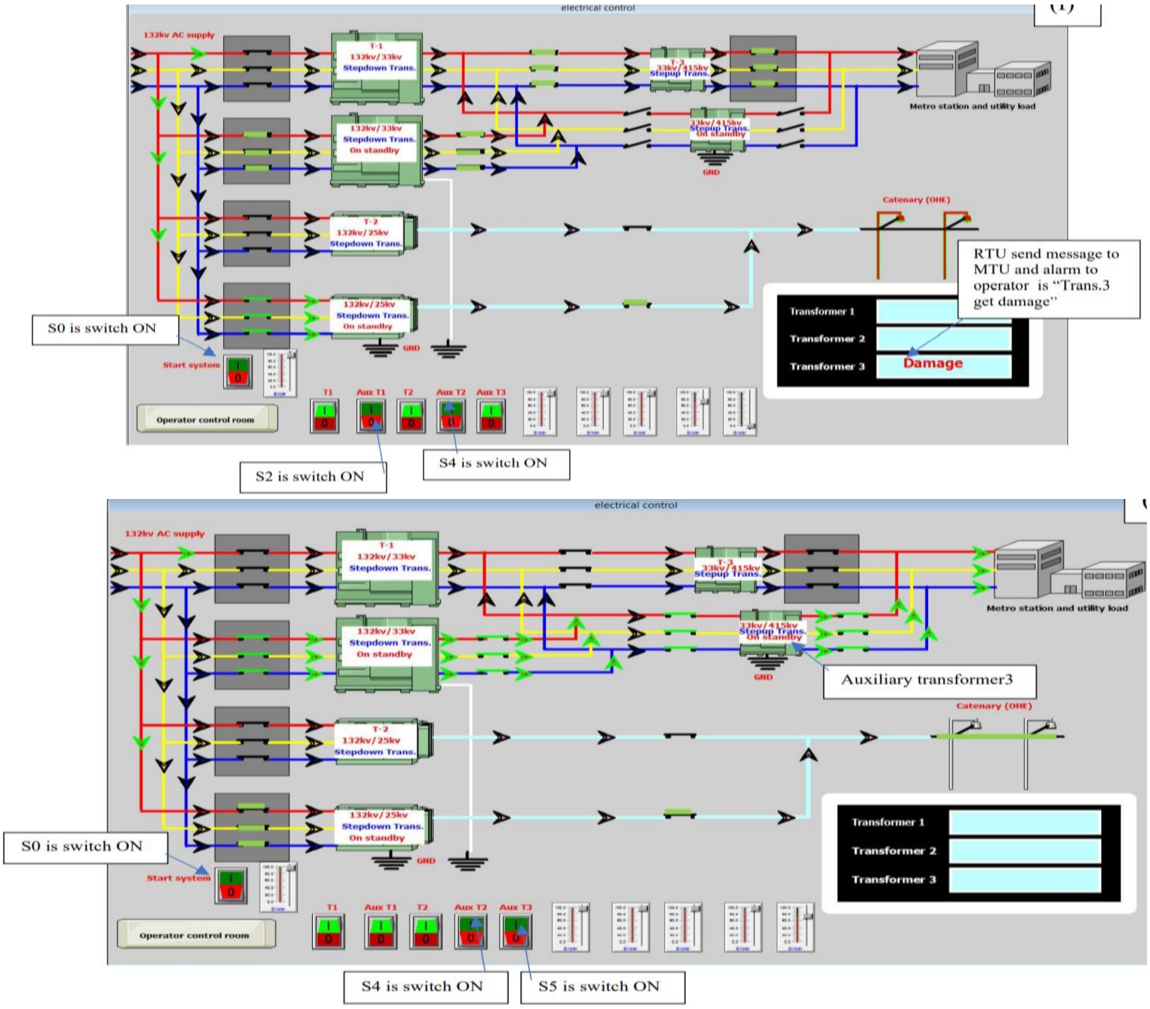


Figure 5.23. When T3 gets damaged, then Aux-T3 provides the power in case of T3.

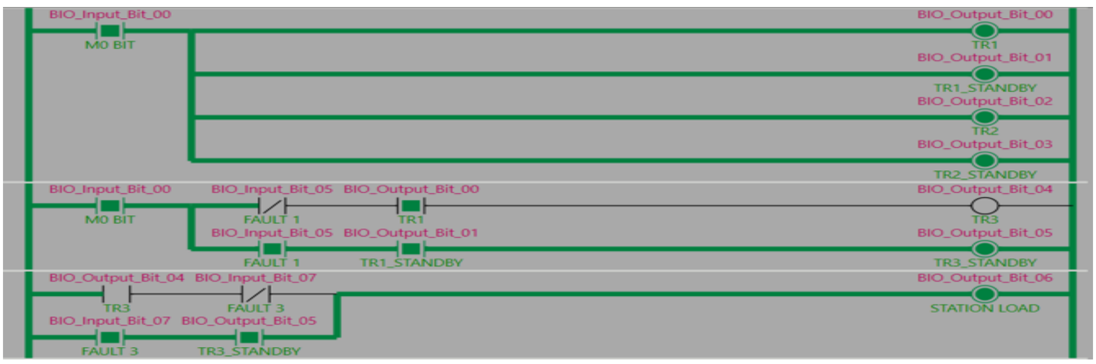


Figure 5.24. Ladder logic program of PLC in case of faults (when Aux T-1, Aux T-2, Aux T-3 is standby)

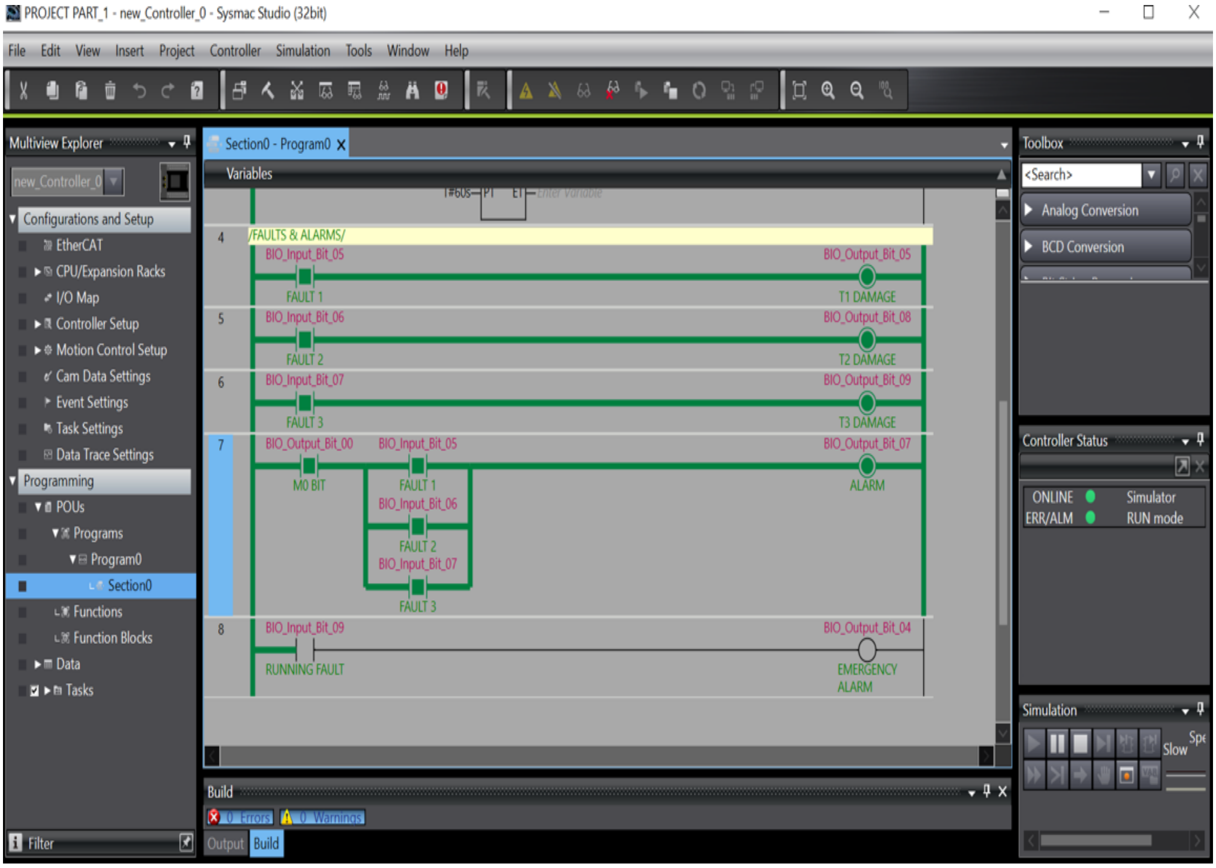


Figure 5.25. Ladder logic program of PLC in case of any faults (T1, T2, T3 damage)

5.6.4 CCTV

CCTV integration with SCADA systems continuously record the live videos of every remote site. The Wonderware SCADA system and this video surveillance system communicates directly with each other. The Wonderware HMI screen of CCTV sub application is shown is Fig. 5.26. Through an EtherCAT link to the HMI computer, the remote locations can communicate to the main server. Using this CCTV integration with Wonderware HMI SCADA, operators can have the information about the real-time data of the system operations and can view the videos and monitor the status of the system at any time. All cameras' video is sent at a user-defined frequency by the system. In the absence of warnings, a system tour is carried out every 25 minutes, giving the operators a new frame of video and an updated perspective of the distant site. Operators may get live, streaming video from any of the video cameras positioned in useful places with a single mouse click.

The live video feeds can show as pop-ups immediately on operators' HMI screens by travelling via the same broadband fiber optic-based EtherCAT network.

Figure 5.26. CCTV view sub-application window in Wonderware Intouch SCADA software version 10.0

Figure 5.27 shows the input and output mapping of PLC ladder logic for the proposed system in OMRON's Sysmac studio programming software.

	▼ CPU/Expansion Racks					
Built-in I/(	▼ Built-in I/O Settings					
	Input Bit 00	Input Bit 00	R	BOOL	BIO_Input_Bit_00	POWER SUPPLY	Global Variables
	Input Bit 01	Input Bit 01	R	BOOL	BIO_Input_Bit_01	START	Global Variables
	Input Bit 02	Input Bit 02	R	BOOL	BIO_Input_Bit_02	STOP	Global Variables
	Input Bit 03	Input Bit 03	R	BOOL	BIO_Input_Bit_03	RED SIGNAL	Global Variables
	Input Bit 04	Input Bit 04	R	BOOL	BIO_Input_Bit_04	GREEN SIGNAL	Global Variables
	Input Bit 05	Input Bit 05	R	BOOL	BIO_Input_Bit_05	FAULT 1	Global Variables
	Input Bit 06	Input Bit 06	R	BOOL	BIO_Input_Bit_06	FAULT 2	Global Variables
	Input Bit 07	Input Bit 07	R	BOOL	BIO_Input_Bit_07	FAULT 3	Global Variables
	Input Bit 08	Input Bit 08	R	BOOL	BIO_Input_Bit_08	PROXIMITY SENSOR	Global Variables
	Input Bit 09	Input Bit 09	R	BOOL	BIO_Input_Bit_09	RUNNING FAULT	Global Variables
	Input Bit 10	Input Bit 10	R	BOOL	BIO_Input_Bit_10		Global Variables
	Input Bit 11	Input Bit 11	R	BOOL	BIO_Input_Bit_11		Global Variables
	Input Bit 12	Input Bit 12	R	BOOL	BIO_Input_Bit_12		Global Variables
	Input Bit 13	Input Bit 13	R	BOOL	BIO_Input_Bit_13		Global Variables
	Output Bit 00	Output Bit 00	RW	BOOL	BIO_Output_Bit_00	M0 BIT	Global Variables
	Output Bit 01	Output Bit 01	RW	BOOL	BIO_Output_Bit_01	METRO TRAIN RUNNING	Global Variables
	Output Bit 02	Output Bit 02	RW	BOOL	BIO_Output_Bit_02	M1 BIT	Global Variables
	Output Bit 03	Output Bit 03	RW	BOOL	BIO_Output_Bit_03	M2 BIT	Global Variables
	Output Bit 04	Output Bit 04	RW	BOOL	BIO_Output_Bit_04	EMERGENCY ALARM	Global Variables
	Output Bit 05	Output Bit 05	RW	BOOL	BIO_Output_Bit_05	T1 DAMAGE	Global Variables
	Output Bit 06	Output Bit 06	RW	BOOL	BIO_Output_Bit_06	STATION & UTILITY	Global Variables
	Output Bit 07	Output Bit 07	RW	BOOL	BIO_Output_Bit_07	ALARM	Global Variables
	Output Bit 08	Output Bit 08	RW	BOOL	BIO_Output_Bit_08	T2 DAMAGE	Global Variables
	Output Bit 09	Output Bit 09	RW	BOOL	BIO_Output_Bit_09	T3 DAMAGE	Global Variables

	▼ CPU/Expansion Racks						
Built-in I/(	▼ Built-in I/O Settings						
	Input Bit 00	Input Bit 00	R	BOOL	BIO_Input_Bit_00	POWER SUPPLY	Global Variables
	Input Bit 01	Input Bit 01	R	BOOL	BIO_Input_Bit_01	START	Global Variables
	Input Bit 02	Input Bit 02	R	BOOL	BIO_Input_Bit_02	STOP	Global Variables
	Input Bit 03	Input Bit 03	R	BOOL	BIO_Input_Bit_03	RED SIGNAL	Global Variables
	Input Bit 04	Input Bit 04	R	BOOL	BIO_Input_Bit_04	GREEN SIGNAL	Global Variables
	Input Bit 05	Input Bit 05	R	BOOL	BIO_Input_Bit_05	FAULT 1	Global Variables
	Input Bit 06	Input Bit 06	R	BOOL	BIO_Input_Bit_06	FAULT 2	Global Variables
	Input Bit 07	Input Bit 07	R	BOOL	BIO_Input_Bit_07	FAULT 3	Global Variables
	Input Bit 08	Input Bit 08	R	BOOL	BIO_Input_Bit_08	PROXIMITY SENSOR	Global Variables
	Input Bit 09	Input Bit 09	R	BOOL	BIO_Input_Bit_09	RUNNING FAULT	Global Variables
	Input Bit 10	Input Bit 10	R	BOOL	BIO_Input_Bit_10		Global Variables
	Input Bit 11	Input Bit 11	R	BOOL	BIO_Input_Bit_11		Global Variables
	Input Bit 12	Input Bit 12	R	BOOL	BIO_Input_Bit_12		Global Variables
	Input Bit 13	Input Bit 13	R	BOOL	BIO_Input_Bit_13		Global Variables
	Output Bit 00	Output Bit 00	RW	BOOL	BIO_Output_Bit_0(	M0 BIT	Global Variables
	Output Bit 01	Output Bit 01	RW	BOOL	BIO_Output_Bit_01	METRO TRAIN RUNNING	Global Variables
	Output Bit 02	Output Bit 02	RW	BOOL	BIO_Output_Bit_02	M1 BIT	Global Variables
	Output Bit 03	Output Bit 03	RW	BOOL	BIO_Output_Bit_03	M2 BIT	Global Variables

I/O Map ×

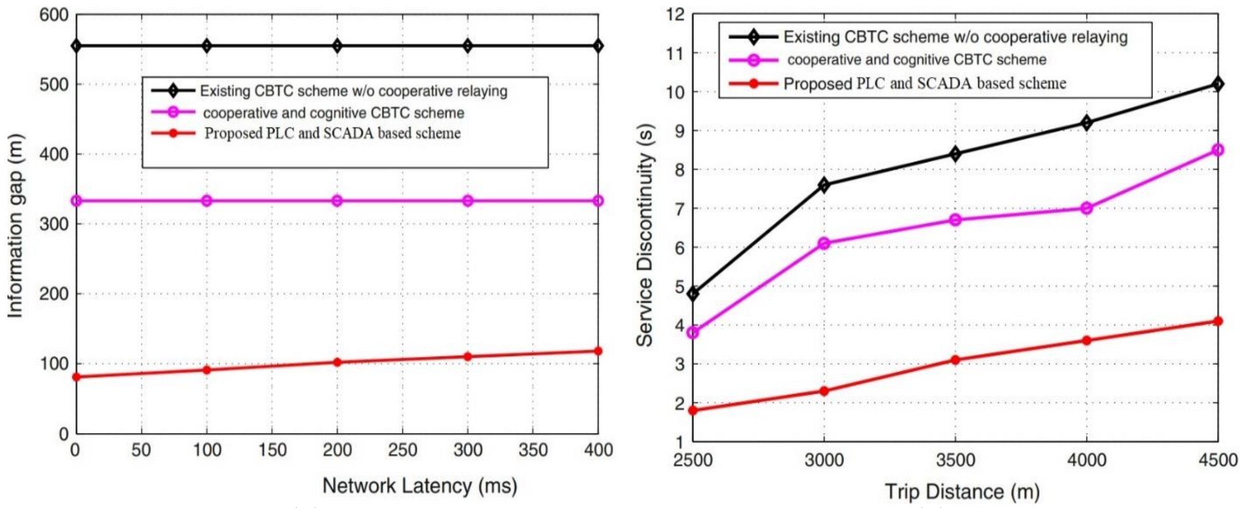
Position	Port	Description	R/W	Data Type	Variable	Variable Comment	Variable Type
Built-in I/(	▼ Built-in I/O Settings						
	Input Bit 00	Input Bit 00	R	BOOL	BIO_Input_Bit_00	M0 BIT	Global Variables
	Input Bit 01	Input Bit 01	R	BOOL	BIO_Input_Bit_01		Global Variables
	Input Bit 02	Input Bit 02	R	BOOL	BIO_Input_Bit_02		Global Variables
	Input Bit 03	Input Bit 03	R	BOOL	BIO_Input_Bit_03		Global Variables
	Input Bit 04	Input Bit 04	R	BOOL	BIO_Input_Bit_04		Global Variables
	Input Bit 05	Input Bit 05	R	BOOL	BIO_Input_Bit_05	FAULT 1	Global Variables
	Input Bit 06	Input Bit 06	R	BOOL	BIO_Input_Bit_06	FAULT 2	Global Variables
	Input Bit 07	Input Bit 07	R	BOOL	BIO_Input_Bit_07	FAULT 3	Global Variables
	Input Bit 08	Input Bit 08	R	BOOL	BIO_Input_Bit_08		Global Variables
	Input Bit 09	Input Bit 09	R	BOOL	BIO_Input_Bit_09		Global Variables
	Input Bit 10	Input Bit 10	R	BOOL	BIO_Input_Bit_10		Global Variables
	Input Bit 11	Input Bit 11	R	BOOL	BIO_Input_Bit_11		Global Variables
	Input Bit 12	Input Bit 12	R	BOOL	BIO_Input_Bit_12		Global Variables
	Input Bit 13	Input Bit 13	R	BOOL	BIO_Input_Bit_13		Global Variables
	Output Bit 00	Output Bit 00	RW	BOOL	BIO_Output_Bit_0(	TR1	Global Variables
	Output Bit 01	Output Bit 01	RW	BOOL	BIO_Output_Bit_01	TR1_STANDBY	Global Variables
	Output Bit 02	Output Bit 02	RW	BOOL	BIO_Output_Bit_02	TR2	Global Variables
	Output Bit 03	Output Bit 03	RW	BOOL	BIO_Output_Bit_03	TR2_STANDBY	Global Variables
	Output Bit 04	Output Bit 04	RW	BOOL	BIO_Output_Bit_04	TR3	Global Variables
	Output Bit 05	Output Bit 05	RW	BOOL	BIO_Output_Bit_05	TR3_STANDBY	Global Variables
	Output Bit 06	Output Bit 06	RW	BOOL	BIO_Output_Bit_06	STATION LOAD	Global Variables
	Output Bit 07	Output Bit 07	RW	BOOL	BIO_Output_Bit_07	CATENARY OHE	Global Variables
	Output Bit 08	Output Bit 08	RW	BOOL	BIO_Output_Bit_08		Global Variables
	Output Bit 09	Output Bit 09	RW	BOOL	BIO_Output_Bit_09		Global Variables

Figure 5.27. Input and output mapping of PLC ladder logic

5.7 Comparative Analysis and Discussion

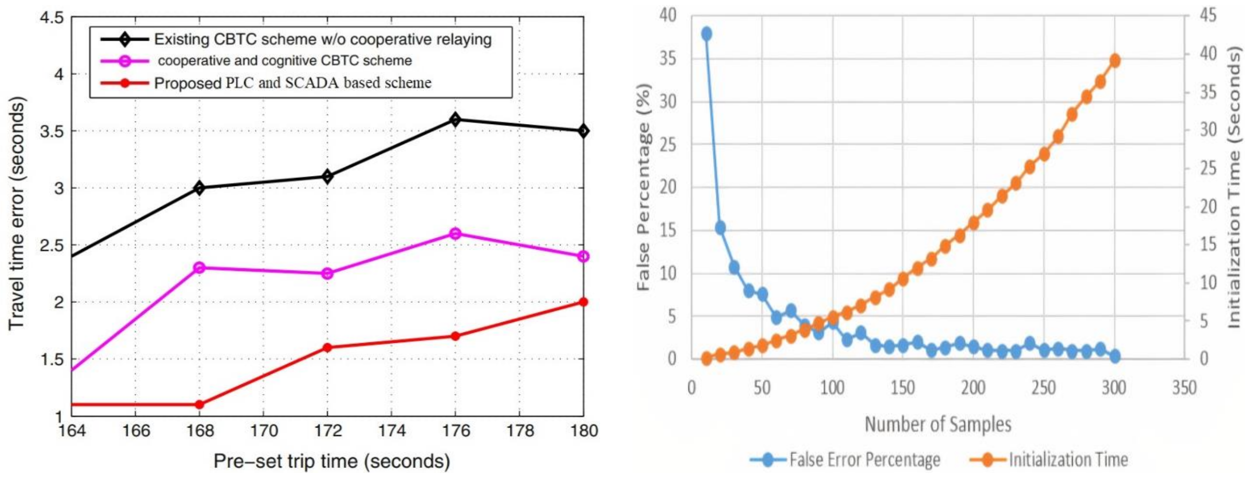
Industrial control systems and SCADA systems play a critical role in the management and regulation of critical infrastructure. SCADA systems are bringing us closer to the real-time application world. SCADA systems increase the efficiency of a control system operation while also providing improved protection for the equipment it uses. Furthermore, it increases employee productivity. SCADA frameworks use an established monitoring platform, advanced communication system, and sensors to provide required information and timely alerts/warnings to observing stations. The designed SCADA system offers continuous access and visualization of all the data in a more efficient and timely manner. It also provides a centralized and thorough display of parameters. The use of "Wonderware Intouch" software facilitates the gathering and visualization of data. The data collecting procedure in the proposed SCADA system is primarily centered on creating adequate communication links between SCADA server and numerous PLCs and sensors that measure and send the readings of a variety of valuable parameters. The performance comparison of the proposed PLC and SCADA based system is done with existing CBTC schemes, cognitive and cooperative CBTC schemes. CBTC systems used obsolete hard-wired relay logic system for controlling different processes, therefore, re-wiring needs to be done again and again for controlling or manipulating the system. Different counters and timers are used for relay which have their own delay. Therefore, the switching characteristics of relay takes a lot of time (or they are very time consuming) in CBTC scheme. But in PLCs, we have inbuilt counters and timers. Therefore, there is no propagation delay. Hard-wired relay logic system has several disadvantages like bulky control panel, frequent and complex wiring. But in the present invention, hard wiring is not needed for controlling or manipulating the system. Controlling or manipulating is done by changing the programming of PLC. So, there is no use of primitive relay control systems.

The information gap does not increase much when the communication latency in network is increased. The suggested technique also reduces the discrepancy between pre-set travel time and actual travel time. In compared to other approaches, this strategy provides improved average service discontinuity time length and enhances the performance of train control. The proposed system decreases the false error percentage in comparison to the traditional systems (Fig. 5.28 and Fig. 5.29). Therefore, this system is more stable and reliable for train control in comparison to the traditional systems. Table 5.3 shows the main characteristics and contribution of the developed platform.



(a) (b)

Figure 5.28. Comparison of **(a)** Information Gap **(b)** Average service discontinuity



(a) (b)

Figure 5.29. Comparison of **(a)** Error of Train Travel Time **(b)** Initialization time and false error percentage

Table 5.3. Key features and contribution of the developed platform

S. No.	Aspect	Contribution
1	System installation	System installation is easy and any new devices be incorporated easily to traditional power switches with few modifications.
2	Cost Saving	• Using a single central unit PLC that implements the load sharing algorithm and sends control commands to the basic switching parts. • Using Wonderware Intouch SCADA software for the visualization of the operation. • Eliminates the need to purchase extra network units or pay for a service subscription by using a secure remote access platform.
3	Interoperability	Safe and uninterrupted monitoring, control and signalling of the metro railways infrastructure.
4	Operation sustainability	Good operation sustainability by having a self-restoration capability after a power interruption.
5	Convenience	Provides remote access, and displays all parameters of the system in a single SCADA web interface.
6	Security	Hierarchical authentication scheme for management and visualization for controlling railways assets in SCADA system.
7	Extendibility	Extendible by configuring more devices, switches and screens in the SCADA software.
8	Equipment Maintenance	• Predictive maintenance practices could be scheduled on the basis of monthly performance evaluations. • The power quality indices at different nodes of railway system can be used to solve malfunctioning issues.

5.8 Conclusion

In this chapter, a real time monitoring and train control system has been used in to minimize the failure in automated metro railways system operator and integrate the information coming from operational control centre, traction SCADA system, traction power control, and power supply system. Here, SCADA is used for the visualization of an automated process operation and then the whole operation is regulated using OMRON (NX1P2-9024DT1) PLC. OMRON's Sysmac studio programming software is used for developing the ladder logic of PLC. Wonderware Intouch SCADA software is used for the visualization of the operation. This system helps in detecting exact location, avoiding train collisions and opening emergency exit even after the interruption of power system with the use of programmable logic controller. SCADA frameworks provide required information and timely alerts/warnings to observing stations. The designed SCADA system offers continuous access and visualization of all the data in a more efficient and timely manner. It also provides a centralized and thorough display of parameters. The designed SCADA systems increase the efficiency of a control system operation & overcomes the drawbacks of the current CATC and CBTC system. Based on PLCs linked by industrial EtherCAT networks, operators can monitor and manage the entire operation from any of on-site HMI, or remotely using SCADA software. Surveillance and remote monitoring & control functions using SCADA provides a cost-effective security solution.

Chapter 6

CONCLUSIONS & FUTURE DIRECTIONS

In this thesis, we formulated algorithms for road traffic management for reduction of road congestion at junctions and priority-based emergency services by synchronization of traffic signals at different junctions. This work provides an insightful discussion on several traffic light synchronization research papers to highlight the practicability of networking of traffic signals of an area. We formulated algorithms for improved real time monitoring and control of public transport infrastructure i.e. metro railways using PLC & SCADA based control systems. These developed frameworks have been compared with state-of-the-art techniques and have given significant results for different performance metrics for all the techniques being compared. We performed the real time monitoring and control of public transport infrastructure and synchronization of traffic signals using these algorithms and then compared the values of performance measures like network performance, traffic efficiency, network security, cost. Proposed methods have given improved results in terms of traffic flow and average waiting time of vehicles. Further, performance metrics viz., network performance, functional safety, specificity, accuracy, sensitivity, energy efficiency, latency etc. reveals that the proposed method is robust for monitoring and control of metro railways infrastructure.

6.1 Summary of the Work Done in the Thesis

For addressing the traffic congestion problem at road intersections, we devised a technique called networking and synchronization of traffic lights which continuously updates values of the traffic status for a junction and the entire traffic network. In order to increase the flow of traffic and decrease average vehicle waiting time at an intersection, we proposed a new technique to synchronize traffic signals with the help of PLC and SCADA for the effective management of traffic at road intersections. Using this technique, a vehicle traveling along one side of the road at a specific speed can continue to the opposite end of the road indefinitely by obtaining the maximum number of green lights at all the intersections. Moreover, the green light cycles for a series of junctions can be synchronized, enabling the greatest number of automobiles to pass through while avoiding waits and delays.

Thus, to address the problem of waiting time of emergency vehicles at road intersections, we proposed a system for emergency vehicle management which uses PLCs along with the sensors and cameras on the roads to collect the traffic density from different directions at a junction. PLC, with the help of information from sensors, decides the order of green light phase for each road segments on the basis of vehicle density and give preference to the road with presence of high priority vehicles like VIP, police, ambulance and fire brigade etc. so that they can cross an intersection at their maximum speed. PLCs of every intersection calculate and distribute the traffic signal time to their individual junction traffic lights. This information is then sent to a central database authority which monitors the traffic density at each junction and helps vehicle users to take an alternate route to their destination during peak hours. This algorithm can be integrated on traffic lights without implementing many changes in the infrastructure. The suggested solution incorporates a few indications and models to enhance network-wide traffic flow and decrease vehicle average waiting time for the simulation period by more than (29.98%). It is possible to extend this system for covering all the intersections of a city or state, thus moving toward a well-coordinated and lucid method of traffic control. This methodology is flexible and easily adaptable to new junctions without any problem.

Lastly, we developed a simulated prototype of an automated metro train system operator that uses PLC and SCADA for the real time monitoring and control of the metro railways infrastructure. The proposed system minimized the failure in automated metro railways system and integrate the information coming from Operational Control Centre (OCC), traction SCADA system, CCTV, traction power control, operator power supply system and CCTV system using SCADA and OMRON (NX1P2-9024DT1) PLC. This system helps in detecting exact location, avoiding train collisions and opening emergency exit even after the interruption of power system with the use of PLC. Furthermore, the designed SCADA system offers continuous access and visualization of all the data in a more efficient and timely manner. The designed SCADA systems increase the efficiency of a control system operation & overcomes the drawbacks of the current CATC and CBTC system.

6.2 Contributions

Traffic light control systems are used to control traffic at road junctions, pedestrian crossings and other areas. The work in the thesis helps in reduction of road congestion at junctions by synchronizing the traffic signals at different junctions. Following are the contributions of the thesis:

- We provided an insightful discussion on several traffic light synchronization research papers to highlight the practicability of networking of traffic signals of an area for the smooth flow of traffic at intersections and for reducing the congestion at neighboring intersections.
- We focused on calculating the timings of traffic lights on the basis of current lane densities and the densities of peer junctions at various levels.
- We developed an intelligent and secure framework for networking and synchronization of traffic signals at road intersections.
- We designed and developed a system for emergency vehicle management.

- We developed a method for Real time monitoring and control strategies for public transportation.

6.3 Future Directions

1. Creating a database for road intersections which covers all types of road intersections in different situations.
2. Handling the congestion at road intersections more effectively.
3. Enhancing the networking of traffic signals in real time scenario.

RESEARCH PUBLICATIONS

Papers Published/Accepted for Publication

Journal Papers

1. **Ishu Tomar,** Indu Sreedevi, Neeta Pandey, "State-of-Art Review of Traffic Light Synchronization for Intelligent Vehicles: Current Status, Challenges, and Emerging Trends," *Electronics* **2022**, *11*, 465. **SCIE**, (**IF: 2.9**), DOI: 10.3390/electronics11030465.

2. **Ishu Tomar,** Indu Sreedevi, Neeta Pandey, "PLC and SCADA based Real Time Monitoring and Train Control System for the Metro Railways Infrastructure," *Wireless Personal Communications*, **129**, pp. 521–548, 2022, **SCIE**, (**IF: 2.2**), DOI: 10.1007/s11277-022-10109-1.

3. **Ishu Tomar,** Indu Sreedevi, Neeta Pandey, "A PLC and SCADA based intelligent and secure framework for Networking and Synchronization of Traffic Signals at Road intersections," *Wireless Personal Communications,* **SCIE**, (**IF: 2.2**), (**Under Review**).

Conference Papers

1. **Ishu Tomar,** Indu Sreedevi, Neeta Pandey, "Traffic Signal Control Methods: Current Status, Challenges, and Emerging Trends," In Proceedings of Data Analytics and Management, Lecture Notes on Data Engineering and Communications Technologies, 2022, vol 90. **Springer,** Singapore. **(SCOPUS),** DOI: 10.1007/978-981-16-6289-8_14.

2. **Ishu Tomar,** Indu Sreedevi, Neeta Pandey, "PLC based System for Emergency Vehicle Management and Intelligent Traffic Control at Road Intersections," *International Conference on Innovations and Ideas Towards Patents (ICIIP 2021)*, **Official Journal of the Indian Patent Office**, Journal No. 42/21, (**Published**), Application No. 202111044707 A.

Patent

1. **Ishu Tomar,** Indu Sreedevi, Neeta Pandey, "Real Time Monitoring and Train Control System for Metro Railways Using PLC & SCADA," **Official Journal of the Indian Patent Office**, Journal No. 38/21, (**Published & Granted**), Patent No. 422345.

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