ROADWAY SAFETY INSTITUTE

Human-centered solutions to advanced roadway safety

Work Zone Mapping and Tag Deployment System

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Final Report

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16. Abstract (Limit: 250 words)

Roadway construction is an inevitable part of functional transportation infrastructure. However, work-zone incidents have increased over the years. This report is the third part of an interdisciplinary project to improve driver safety in work zones. The first component was a human factors study, performed by Craig et al. (2017), determining the most effective way to alert drivers to work zones without disrupting driver behavior. The second component, by Liao (2019), sought to determine whether Bluetooth low-energy tags could be deployed in work zones to provide real-time updates to drivers' mobile phones through an app. The third component, the Statewide Work Zone Information System (SWIS), establishes a real-time database of active work zones from the first advanced warning sign being placed to the time the crews pack up. SWIS uses beacons attached to traffic control devices, called assets, that send messages to a central cloud repository. From there, messages are processed, categorized into Projects, Traffic Control Plans, and Work Zones. SWIS continuously updates based on asset messages it receives. Users can access SWIS through a web interface, to view active, past or future projects, plan a project, or update existing projects. SWIS provides an online, real-time portal for storing, monitoring, and inspecting work zone traffic-control operations.

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Work Zone Mapping and Tag Deployment System

FINAL REPORT

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EXECUTIVE SUMMARY

Work-zone incidents and fatalities have become an unfortunate part of the transportation landscape as it has matured over the years. As little new construction is being added, and instead drivers and workers are forced to share space, the potential for conflicts in work zones is high. Drivers who disregard warnings and speed through work zones or who are driving distracted are most at fault for incidents. This project is part of a three-pronged approach to increase driver awareness of work zones and influence driver behavior accordingly.

The first component was a human factors study, performed by Craig et al. (2017), determining the most effective way to alert drivers to work zones without disrupting their driving tasks. The second component, by Liao (2019), sought to determine whether Bluetooth low-energy tags could be deployed in work zones to provide real-time updates to drivers' mobile phones through an app. This project, the third component, established a real-time database of active work zones from the moment the first advanced warning sign was placed to the time the crews packed up. When completed, this Statewide Work Zone Information System (SWIS) will be a fully updated database of active work zones at any time; it will also archive past projects and allow users to pre-plan projects for future dates.

SWIS utilizes traffic control devices (TCDs) already being placed by workers in a work zone; the TCDs are outfitted with a SWIS asset beacon tracking their location and movement throughout the work zone as they are laid out. SWIS uses processing algorithms to determine where a work zone is located and to update its information in real time. In addition, SWIS uses a novel algorithm to determine whether a work zone is fully set up and flags it for inspection if it is ready. The inspection algorithm checks whether the work zone is set up in compliance with *Manual on Uniform Traffic Control Devices* (MUTCD) layout guidelines or with pre-approved planned project layouts; if it is, no manual inspection is required. If it is not, the project is flagged for manual inspection.

Users, both those involved with the project and the general public, can access SWIS through an Internet interface. Users can move around the map to find work zones, search for work zones that are currently active in SWIS, and also look for past or future planned projects using a chronological view. Users with more advanced permissions can create or update projects through the SWIS web interface as well.

SWIS can also play a vital role in future connected and automated vehicle (CAV) applications by providing accurate, up-to-date work zone traffic-control conditions like new road alignments, lane closures, etc.

More field testing with SWIS needs to be done before the system is ready for use around the state. When active, the research team hopes SWIS will be a valuable support technology for drivers that helps reduce incidents in work zones and for right-of-way (ROW) owners to monitor work-zone activity and compliance without physically having to visit the site. The team also hopes SWIS will become a cloud-based source of traffic and traveler information.

CHAPTER 1:   INTRODUCTION

As the roadway transportation system of the U.S. and Minnesota has matured, roadway construction under traffic conditions has become the rule, rather than the exception. There is little construction taking place on new alignment. Instead, transportation agencies must maintain, repair, and reconstruct existing roadway facilities while allowing traffic to continue using the roadway. Sharing of right-of-way between construction and traffic creates the potential for many conflicts and can have a negative impact on safety. Nationally, in 2012, 609 fatalities out of 33,561 were located in work zones, while in Minnesota, 4 out of 395 (1) occurred in work zones.

The two major causal factors for single-vehicle crashes in Minnesota in 2012 were illegal/unsafe speed at 21.6% and driver inattention/distraction at 14.1%. Work zones are locations especially sensitive to these two factors because the vast majority of drivers are required to adjust their speed (slow down) and adjust their course due to changes in road geometry. The standard practices for traffic control in work zones are identified in the *Manual on Uniform Traffic Control Devices* (MUTCD). However, despite the experience and expertise that agencies have developed over the years with work zone traffic control, work zone crashes have continued to increase. One reason may be that the information directing drivers to adjust their behavior is currently transmitted through static or variable signs on the roadside. Such signs are visible within a range of approximately 450 feet (1). On the other hand, drivers engaged in texting have their eyes averted from the road for an average of five continuous seconds, which at 55 mph is equal to crossing a football field (360 feet) blindfolded (2). Given that at any daylight moment across America, approximately 660,000 drivers are using cell phones or manipulating electronic devices while driving (10) — a number that has held steady since 2010 — the danger of failure or delay to notice the work zone warning signs when relying only on attentive vision is clearly high. It will continue to rise as opportunities for distraction inside a vehicle multiply (texting, emailing, using touch-based navigation systems, etc.)

This project is one of three components of a work zone safety research proposal to investigate the effectiveness of using in-vehicle messages to improve drivers' understanding of the work zone and reduce risky behavior. The first effort, led by human factors experts, assessed driver distraction in work zones using crash-data analyses and by collecting objective driver-behavior data. Based on this understanding, dynamic in-vehicle messages are being refined to improve drivers' understanding of the work zone. The second effort investigated an inexpensive new technology based on Bluetooth low-energy (BLE) tags that could be deployed in or ahead of work zones. These could trigger spoken and contextual messages in existing smartphones located in vehicles passing by the tag.

The third effort, this project, investigates how information about the layout of the work zone can be efficiently gathered in one place in the cloud to then be disseminated to drivers through in-vehicle alerts or an online interface. An important criterion for this information gathering system is that it should not cause crews any additional work. This project sought to develop a passive information gathering system for work zones across the state, or a Statewide Work Zone Information System (SWIS). SWIS uses

beacons, or SWIS assets, that are part of the traffic-control devices in the work zone-- currently implemented as an add-on device-- and that continuously transmit information about their location to SWIS. Efficient deployment of the triggering devices will blend seamlessly with current work zone traffic-control setup procedure and should not increase the work zone crew's workload, and therefore the project cost. When asset messages are received, SWIS uses a series of algorithms to extract more information about the work zone based on asset information, places the work zone into a geo-database, and makes that information available to both the public and the on-site crew. SWIS will also serve as a remote work zone status-monitoring system, providing the Regional Transportation Management Center (RTMC) and maintenance operators with real-time work zone information.

CHAPTER 2: CONCEPT OF OPERATIONS

SWIS receives data from project sites all over the state. Figure 2.1 depicts how SWIS functions as a broker between projects throughout the state and users of the system.
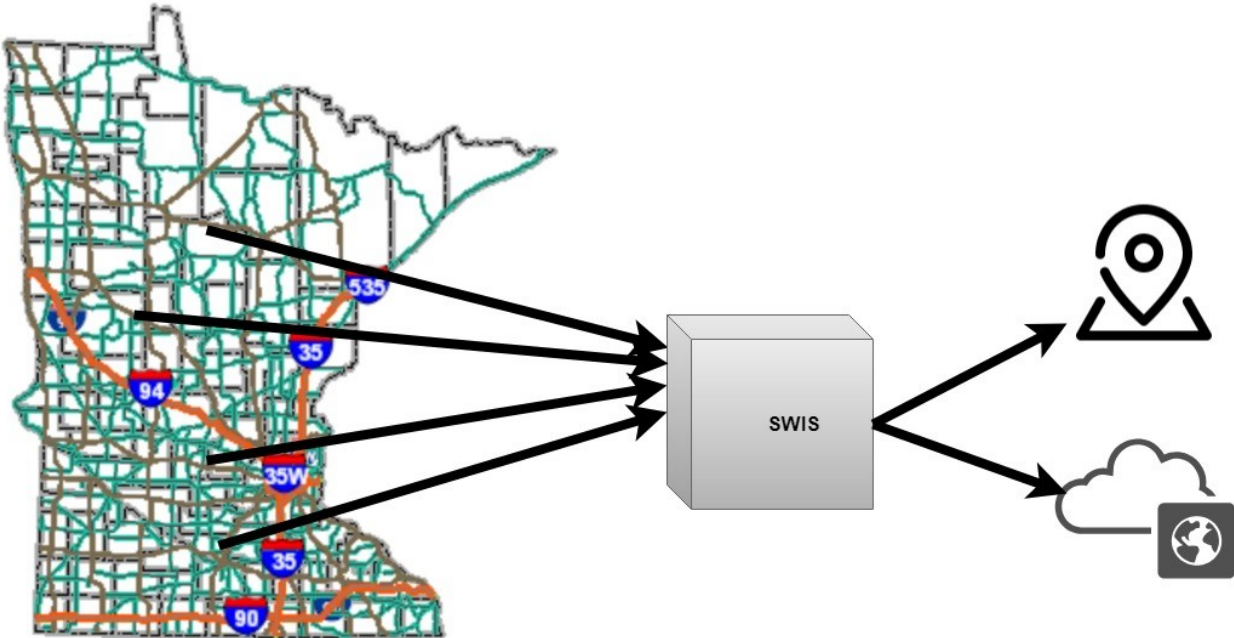
Figure 2.1 SWIS System Overview

Once data from work zones is gathered and formatted by SWIS, users are able to interact with it in the system through its web-based official client. Users can also access SWIS work zone data through the information providers and entities that the system is configured to push information to.

2.1 WORK ZONE PLANNING AND OPERATIONS

Road work zone operations, like other areas of traffic operations, are heavily regulated in order to present a unified set of guidance information to drivers and ensure the safety of everyone when the normal function of a road is disrupted. These regulations, as well as decades of experience and testing, have led to established best practices and organizational norms that guide transportation planners, operations personnel, and work crews as an essential part of road work activities.

The primary authority that dictates the requirements for temporary traffic control is the *Manual on Uniform Traffic Control Devices* (MUTCD), specifically Part 6 "Temporary Traffic Control" (TTC). This document (14), issued by the Federal Highway Administration (FHWA) of the United States Department of Transportation (USDOT), establishes a national standard for the design and placement of traffic control devices based on decades of research on human factors and traffic safety. Individual state Departments of Transportation (DOTs) are permitted to use their own MUTCD based on the federal one,

or provide a supplement to the national MUTCD, though they must substantially conform to the national MUTCD.

The Minnesota Department of Transportation (MnDOT) is one of the state DOTs that has chosen to adopt its own MUTCD, the MN MUTCD (15), with some modifications made to conform with Minnesota State law or better reflect the conditions and policies of the state. As in the federal MUTCD, Part 6 of this document refers to "Temporary Traffic Control." In addition to being contained in the MN MUTCD, this section is made available as a separate printed document termed the *Minnesota Temporary Traffic Control Field Manual* for use by planners, work crews, and work zone inspectors in the course of their work. This document guides every road construction project, big or small, that takes place in the state of Minnesota, though exactly how depends on the work being performed and the duration of the project, as well as the type of road, speed limit, and traffic level.

2.1.1 Elements of a Work Zone

Figure 2.2 outlines the standard components of a temporary traffic control zone. Despite the wide variety of road work that might take place, these major components do not change. Every work zone has four areas: the *Advanced Warning Area*, where drivers are notified of upcoming road work by a series of signs; the *Transition Area*, where traffic control gradually transitions from the original to the temporary traffic control in place for the work; the *Activity Area*, where the actual work takes place; and the *Termination Area*, where the original traffic control is restored.

Figure 6C-1. Component Parts of a Temporary Traffic Control Zone

Legend
- → Direction of travel
- ▪ Channelizing device
- ▨ Work space
- ⚓ Sign

Downstream Taper

Buffer Space (longitudinal)

Termination Area lets traffic resume normal operations

Traffic Space allows traffic to pass through the activity area

Work Space is set aside for workers, equipment, and material storage

Activity Area is where work takes place

Buffer Space (lateral) provides protection for traffic and workers

Buffer Space (longitudinal) provides protection for traffic and workers

Transition Area moves traffic out of its normal path

Shoulder Taper

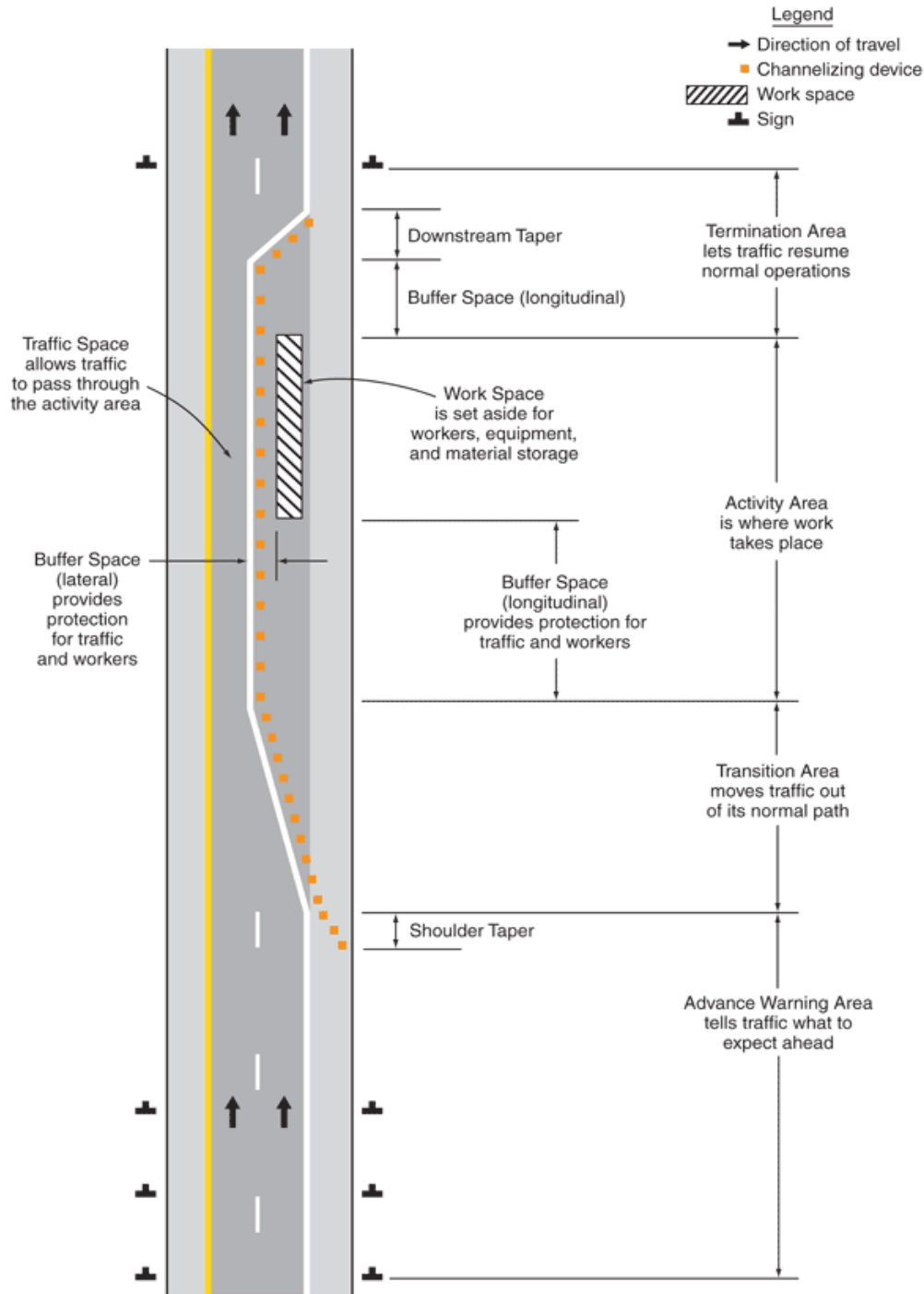**Advance Warning Area** tells traffic what to expect ahead

Figure 2.2 MUTCD Figure 6c-1 Showing Components of a Temporary Traffic Control Zone.

In the Advance Warning Area, drivers will always first encounter a "Road Work Ahead" sign (MUTCD W20-1), followed by more specific signs that depend on the change in traffic control such as "Shoulder

Closed" (W21-X5a) or "One Lane Road Ahead" (W20-4), among many others. The specific signs that must be used are outlined in the MUTCD based on the nature of the work. The spacing of these signs is dictated based on the posted speed limit prior to starting work in order to provide drivers sufficient time to prepare for the change.

In the Transition Area, channelizing devices such as cones, weighted channelizers, drums, or barricades, among others, are used to gradually force drivers out of the work area over a distance, called a taper, followed by a longitudinal buffer. The length of the taper and buffer also depends on the speed limit. The specific channelizing device depends primarily on the duration of the work.

In the Activity Area, where work takes place, a lateral clear zone is created between the channelizing devices that restrict movement of traffic, and the work area. Channelizing devices continue along the whole of the Activity Area. The size of the clear zone and spacing of channelizing devices varies depending on the road's posted speed limit prior to starting work.

In the Termination Area, a downstream taper which is typically much shorter than the upstream taper closes the activity area for the resumption of normal traffic control. An "End Road Work" sign is typically placed after the downstream taper to indicate that drivers have exited the work area.

In smaller work zones, these areas are often clear and well-defined. In larger work zones that span many miles, by contrast, vehicles may drive through an extended activity area with several transitions. The differences between these types of work zones are outlined further in the next sections.

2.1.2 Short-Term Work Zones

There are several types of short-term work zones, with the MN MUTCD defining guidelines for work occurring for: 15 minutes or less, 1 hour or less, 12 hours or less, and up to 3 days or less. For short term work, traffic control is generally established on the spot by the crew based on one of the layouts in the TTC Field Manual. Work that can be completed in a short or intermediate time frame like this occurs quite frequently, and often fairly spontaneously when weather turns out to be favorable. Because of this, it is generally not economical to spend too much time planning traffic control. Instead, the effectiveness of the TTC deployed relies on the experience of the work crew managers on site and their understanding of the guidelines in the field manual. The personnel who decide on the traffic control used in these situations typically have an intimate understanding of the art of safe and effective TTC gained from years of experience working in the field. Regular inspections are also carried out to ensure that crews are adequately following the necessary guidelines.

While the experience of workers generally ensures that road work can be carried out safely and with minimal disruption to traffic, there are nonetheless numerous realities that limit the availability and accuracy of information describing this work for anyone who is not physically present at the site. Notice of short-term work is often not announced to the public with much or any advanced warning, and documentation of the work activity is often limited. These situations can often surprise drivers who

encounter unexpected road work, as well as potentially exacerbating poor traffic conditions during peak periods.

In addition to this, the demands of the work particularly in the case of moving workspaces, can lead workers to make certain decisions for convenience that can potentially confuse drivers. A common practice, which is not allowed by regulations but is often effectively ignored, is the deployment of multiple sets of advanced warning signs over the course of a day as the work area moves down the road. For example, in the morning a crew might place the necessary advanced warning signs within the correct distance of the work area, but as the work moves down the road they might simply place a second set of signs 2 miles downstream without removing the upstream signs (as they are supposed to), subjecting drivers to two sets of advanced warnings. This repeated, unnecessary exposure may encourage drivers to frequently disregard these warning signs.

2.1.3 Long-Term Work Zones

Work lasting longer than 3 days generally involves additional planning to minimize the traffic impact. In these cases, the planning can begin up to three years in advance (16). In these cases, the road authority will usually develop the traffic control plan itself, based on their knowledge of the work that needs to take place, the common traffic conditions in the area, and other construction projects that may need to occur in the region. The traffic control plans in these situations are generally very detailed, as seen in Figure 2.3, outlining exactly which signs and barricades should be placed where. The plans are then included along with the work requirements so that a bidding process may take place to select one or more contractors to do the work and implement the traffic control plan. These projects generally also involve the assignment of a full-time project engineer located on-site in a temporary office, overseeing the work and responding to the inevitable issues and schedule changes that may occur during the course of the project.

Even with this additional planning and oversight, issues remain regarding the dissemination of information to the public during these projects. Though the road authority generally provides information about the project to the public well in advance of the start of work, it is almost always very limited in the level of detail provided about when the project will actually begin, how it will progress, and when it will finally end. Major closures will usually be announced with at least a few days' notice, but this is not generally the case for the smaller disruptions that occur frequently during the project. The sequence of work may also change depending on many factors such as weather, the availability of materials, and technical complications encountered during work.
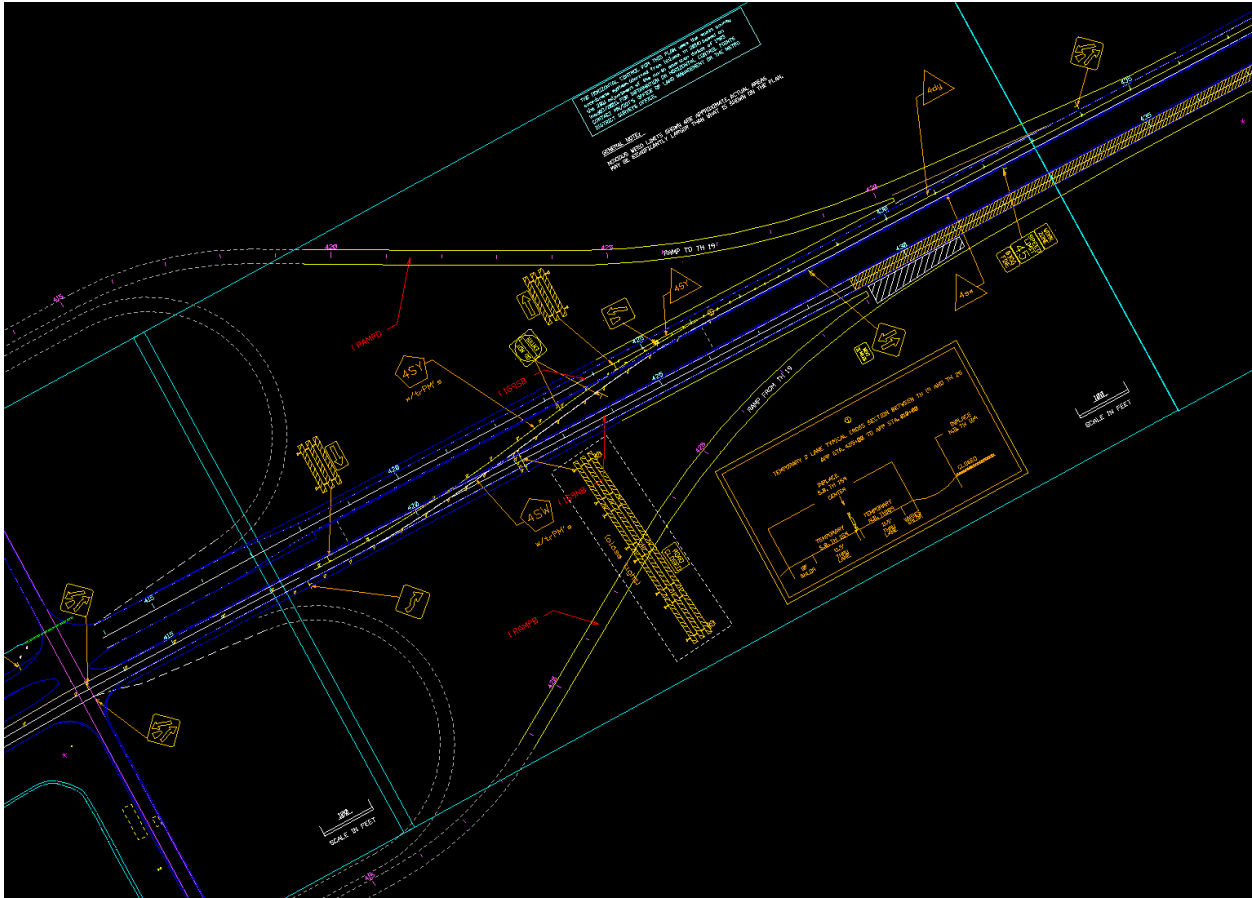
Figure 2.3 Sample from a traffic control plan developed by MnDOT for construction occurring on US-169

2.1.4 Availability of Work Zone Information

As stated previously, near real time information about the actual state of a work zone is usually hard to come by. The reasons for this are understandable, as the complexity of projects and variables such as weather conditions and contractor schedules make it hard to predict when work will take place. Recognizing these realities, there is still a general need for this information. Disruptions to traffic from road constructions take a toll on the already heavily loaded traffic network, often leading to severe congestion or crashes that cost society significant amounts in both money and lost productivity. The rapidly approaching future of Connected and Automated Vehicles (CAVs) also will necessitate an improved system for tracking the real-time state of work zones to allow their navigation technology to function properly. Finally, the stress of ageing infrastructure means that road maintenance will only occur more frequently as time goes on, placing an additional burden on inspectors who must ensure that the work being carried out is being done safely and according to regulations (Figure 2.4). Having an improved system for disseminating this information, therefore, would not only be beneficial to many parties, but is essentially a requirement to ensure that road work does not severely disrupt the very same infrastructure it is intended to improve.

Mn/DOT Maintenance Work Zone Inspection Short Form

DISTRICT:	SUBAREA:	SP / PERMIT / TH:	
DATE:	TIME:	WEATHER:	
REVIEWED BY:			

ROADWAY:

☐ 2 LANE 2 WAY	4 LANE: ☐ FREEWAY	☐ DIVIDED	☐ UNDIVIDED	☐ OTHER

OPERATION:

	☐ DAY ☐ NIGHT	WORK (☐ IN ☐ NOT IN) PROGRESS		
☐ MOBILE/MOVING	☐ STATIONARY :	☐ ≤ 1 HR ☐ ≤ 12 HRS ☐ ≤ 3 DAYS ☐ > 3 DAYS		
LAYOUT(S)		☐ ADDITIONAL:		

☐ LANE CLOSURE	☐ SHOULDER CLOSURE	☐ PILOT CAR ☐ BYPASS ☐ 2L2W ☐ DETOUR
☐ FLAGGING OPER	☐ PORTABLE SIGNALS	☐ OTHER:

☐ PAVING	☐ MILLING	☐ GRADING	☐ SWEEPING/FLUSHING
☐ SHOULDERING	☐ PATCHING	☐ STRIPING	☐ CRACK SEALING
☐ GUARDRAIL	☐ CULVERTS	☐ JOINT REPAIR	☐ BRIDGE INSPECTION
☐ DECK REPAIR	☐ UTILITY	☐ OTHER:	

SPEED LIMIT:	☐ POSTED: MPH	☐ ADVISORY: MPH	☐ WZ: MPH

1. SEE FIELD MANUAL Pages 6K-xxi TO 6K-xxiii FOR DROP OFF DELINEATION STANDARDS
2. SEE FIELD MANUAL Pages 6K-93 TO 6K-106 FOR QUALITY STANDARDS

DRIVE THROUGH:	N/A	YES	NO	COMMENTS	FOLLOW UP REQD	FOLLOW UP COMPL.
MANEUVERABLE TRAFFIC SHIFTS	☐	☐	☐		☐	
ADEQUATE ADVANCE WARNING	☐	☐	☐		☐	☐
APPROPRIATE SIGN SEQUENCE/SPACING	☐	☐	☐		☐	☐
APPROPRIATE CHANNELIZER SPACING	☐	☐	☐		☐	☐
APPROPRIATE ARROW BOARD MODE	☐	☐	☐		☐	☐
ADEQUATE WORK AREA PROTECTION	☐	☐	☐		☐	☐
APPROPRIATE WORKER PPE	☐	☐	☐		☐	☐
ADEQUATE EQUIP/MATERIAL STORAGE	☐	☐	☐		☐	☐
APPROPRIATE DROP OFF DELINEATION[1]	☐	☐	☐		☐	☐
APPROPRIATE FIELD MANUAL LAYOUT	☐	☐	☐		☐	☐
SIGN CONDITION (A=ACCEPTABLE, M=MARGINAL, U=UNACCEPTABLE)[2]	☐	☐A ☐M	☐ U		☐	☐
CHANNELIZER CONDITION (A=ACCEPTABLE, M=MARGINAL, U=UNACCEPTABLE)[2]	☐	☐A ☐M	☐ U		☐	☐
☐ NO ACTION REQUIRED				☐ FOLLOW UP REQUIRED BY:		
☐ ACTION OBSERVED ONSITE				☐ FOLLOW UP COMPLETE:		

FLAGGING:	N/A	YES	NO	COMMENTS	FOLLOW UP REQD	FOLLOW UP COMPL.
ADEQUATE ADVANCE SIGNING	☐	☐	☐		☐	☐
ADEQUATE PROCEDURE	☐	☐	☐		☐	☐
ADEQUATE POSITION/VISIBILITY	☐	☐	☐		☐	☐
APPROPRIATE HI-VIS CLOTHING	☐	☐	☐		☐	☐
APPROPRIATE COMMUNICATION	☐	☐	☐		☐	☐
ADEQUATE ATTENTION/FOCUS	☐	☐	☐		☐	☐
ESCAPE ROUTE	☐	☐	☐		☐	☐
CERTIFICATION	☐	☐	☐		☐	☐
☐ NO ACTION REQUIRED				☐ FOLLOW UP REQUIRED BY:		
☐ ACTION OBSERVED ONSITE				☐ FOLLOW UP COMPLETE:		

Figure 2.4 Inspection form used by maintenance inspectors to ensure adequate traffic control and safety of work.

2.2 USER NEEDS

Broadly speaking, users can come from the public sector, like state DOTs, municipalities, or different parts of the private sector, like construction contractors, traffic control device rental places, or from traveler information brokers and providers. Focusing more on the roadway stakeholders' side, these users can be split into the following groups: planners and designers, inspectors, and work crews. Drivers, especially in the context of connected vehicles, maybe direct consumers of work zone information as well. Each of these groups has unique concerns that affect their view of what a useful information system looks like.

Planners need to be able to add traffic control plans for future work to work zones. Inspectors need to have an active, updated list of sites to visit to ensure compliance with the traffic control plans. Managers need to be able to create and manage traffic control plans effectively. Work crews need to be able to

work safely, so receiving alerts such time-sensitive work zone intrusions would be a benefit. Drivers need real-time information on where work zones begin and end, to alter their driving behavior safely or even change routes ahead of the work zone.

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2.3 STATEWIDE WORK ZONE INFORMATION SYSTEM CONCEPT

</div>

Given the problems and needs discussed previously in this chapter, the concept for a real-time work zone information system has multiple criteria to fulfil.

Here, the inadequacies and inefficiencies regarding the current modus operandi of work zone traffic operations are described in more detail, along with the needs that should be addressed to solve them, and how a system would be developed to handle these needs.

2.3.1 Structure

Currently, work zone related information is not structured in a way that allows easy comprehension of what is happening on the road. For example, MnDOT maintains a list of active and upcoming long-term work zones. The records on this list lump together information in an ambiguous and unstructured way, demonstrated by the fact that some records have information showing what the road will look like during work while others do not. The work zone traffic operations are depicted with text or a user created image of a map showing where the work zone will be placed. The format of information in these records differs depending on what district is involved. Even if these records have work zone traffic operations, they are not machine readable.

Considering those issues, there needs to be a schema for structuring information about work zone traffic operations. The schema developed for SWIS follows the naming convention "Projects", "Traffic Control Plans" (TCP), "Work Zones" (WZ), and "Traffic Control Devices" (TCD). Each of these concepts encapsulates an amount of data about the work zone. For example, in "Projects" the following information is included:

"Projects" can include one or many TCP. The data stored in this structure are limited to information describing general traffic operations. An example would be recent construction on I-94 East, which had two TCPs. The active TCP in the morning had three lanes of traffic inbound for downtown and two away, while the active TCP in the evening had three lanes of traffic outbound and two inbound. SWIS Projects can have one or more TCP (i.e., AM and PM peak), TCP can have one or more WZ (i.e., a crew fixing a pothole while another crew repairs an on-ramp), and WZ can have one or more TCD (i.e., barrels, advanced warning signs, etc.).

To maintain consistency, this structure is also defined by the following constraints of relationships:

- Projects do not overlap in space and time.
- The Project's upstream boundary is at least 250 feet away from the first traffic control device.
- Although a project can have many traffic control plans, only one Traffic Control Plan can be active at a time.

- The boundaries of each Traffic Control Plan are the boundaries of the Project.
- The boundaries of Work Zones do not overlap.
- Work Zones depend on when a Traffic Control Plan is active.
- Each Work Zone has a single temporary traffic control layout.
- The Work Zones upstream boundary is at least 250 feet before the first traffic control device.
- The Work Zones downstream boundary is at the termination traffic control device.
- Distance between Work Zones in a Project must be no less than what the MUTCD temporary traffic control distance specifies.

2.3.2 Organization

The manner in which current work zone related information is stored leaves much to be desired. As previously stated, MnDOT maintains a loosely formatted list of active and soon-to-be active long-term work zones. This list does not include small, short-term maintenance work zones. If these types of work zones were included in this list, it would be much more difficult for users to find the work zone they are looking for. Thus, finding a work zone in the list depends directly on the number of items in it. This list of work zones is also manually updated, creating a significant gap between when conditions on the roadway change due to work happening, and when information about those changes become viewable. To address all of these problems, records of work zones must reside in an organized medium.

To achieve the appropriate level of organization, users should be able to utilize a Relational Database Management System (RDBMS) to store the records. A RDBMS is beneficial because it avoids data duplication and inconsistent records, allows for the easy addition or removal of data, and is flexible in its handling of changing data format. The use of an RDBMS also allows for data to be quickly and efficiently accessed in a uniform manner. SWIS's RDBMS is referred to as a Dynamic Memory Database (DMD), as it is dynamic and much faster than searching the entire database.

2.3.3 Retrieval

MnDOT states that "during the design phase of long term projects, planners must get project layout approval from cities; this process involves 19 federal and state agencies, considers 49 federal and 25 state environmental laws and looks at 26 environmental subjects." (16) This translates to there being a significant amount of information to look through, and much of this information is stored in a way that prevents it from being methodically retrieved.

State DOT workers and Private Transportation Information Companies (such as Google, Inrix, Here, etc.) should be able to access information describing what is happening or should happen in a work zone. Therefore, the DMD utilized by SWIS enables its users to look up records of SWIS Projects quickly, deterministically, and efficiently. Using the DMD allows its users to retrieve records of SWIS projects based on criteria such as location, date, or if the SWIS project is currently active. As well, the use of the DMD ensures that the amount of time it takes to find a record is not dependent on how many records exist in the system.

2.3.4 Real-Time information

As previously mentioned, there is a significant lack of real-time work zone information. This means that there is no way to know the precise placement of traffic control devices without physically being at the work zone in question. While Minnesota's 511 website can be a source for present and future work zone location information, the system lacks real time information. In addition to only having records of planned long-term work zones, 511 is limited in that the information it has about these work zones only shows where the projects *should* be as opposed to where they *actually* are. The actual location of a work zone can differ significantly from what 511 reports. Furthermore, this information would not be useful to Connected and/or Autonomous Vehicles (CAV), as they need much more detailed and current information when navigating a work zone. There is a need for accessible real-time information showing the placement of traffic control devices in order for state DOT officials, Connected and Automated Vehicles, and human drivers to have useful information about the layout of a work zone. To fulfil this need, SWIS is built to handle the tracking of traffic control devices that are critical to describing the layout of a work zone. This enables SWIS to aid in a variety of other work zone layout related tasks.

2.3.5 Monitoring

While there can be many work zones throughout the state, there is a limited number of individuals who are qualified to oversee criteria such as performance management, asset and work zone management, as well as contract monitoring. MnDOT employs project managers who are spread throughout 9 districts in the state, and oversight of current projects is only one of their many responsibilities. The level of monitoring quality at work zones depends on the individual project manager in charge and his/her other pressing responsibilities. The current way that work zones are overseen is inefficient and can give way to costly delays. Today, much of the criteria fulfilled by this supervision can be achieved remotely or even programmatically. For this functionality to be realized, there needs to be an entity that aids the project managers in the monitoring of their work zones. SWIS is built to be capable of monitoring functionalities that aid project managers in the fulfilment of the previously mentioned criteria.

2.3.6 Inspection

As is the case with work zone monitoring, the current means of carrying out a work zone inspection is inefficient. This is also because inspections are currently done manually. There is a limited number of inspectors who are responsible for multiple work zones.

Having responsibility over multiple work zones means that inspectors spend a majority of their time traveling and insufficient time inspecting work zones. With a limited number of inspectors available it is inevitable that certain work zones will be missed. At most risk for not being inspected are the short-term work zones, which can last up to three days. If a short-term work zone is only active for six hours, it is unlikely that it will be inspected before any violations it has can be detected; this may compromise the safety of work crews and drivers. For these problems to be solved, there needs to be an intermediary that assists inspectors in carrying out their job. By automating the prioritization and needs of inspection

sites—and in some cases, verifying there is no need for inspection—SWIS will help inspectors be better able to serve all ongoing projects.

Inspections are carried out using the sheet in Figure 2.4. Criteria such as "Maneuverable Traffic Shifts", "Adequate Advance Warning" and "Appropriate Sign/Sequence Spacing" can be determined programmatically. Therefore, SWIS is built to inspect work zones and determine if they fulfil these criteria. This way, SWIS can cut down on the sites that need inspection, enabling inspectors to focus their attention on work zones that need intervention.

2.3.7 Automatic Short-Term Work Zone Creation

Currently, short-term work zones are not preplanned to the extent that their long-term counterparts are. They do not require as much extensive planning, as they utilize MUTCD layouts. Short-term work zones are also usually much less documented than their long-term counterparts, as they are not nearly as expensive and do not impact travel as extensively. That being said, most work zones are short-term maintenance operations, and there is much that can be learned from them. Historical data detailing when, where, and how a short-term work zone is set up could aid in the generation of statistics such as traffic flow analysis. For this analysis to be possible, there needs to be a means of efficiently and cost-effectively collecting information about a work zone in an organized way. SWIS is designed to be capable of creating and storing this historical information about work zones in a way that does not create significant overhead. For short-term work zones, the system is able to create a record of a work zone layout based on the locations of traffic control devices. This not only allows for allows for the work zones layout to be documented, but also for it to be compared against MUTCD standards for inspection.

2.3.8 Long-Term Work Zone Data Importation Information

While long-term work zones are extensively planned, they suffer-- like short-term work zones -- from a lack of statistics regarding the efficacy of traffic control. To generate meaningful statistics for these work zones there needs to be a means of collecting real-time work zone layout information and comparing it to what planners have determined to be the appropriate layout. In addition to the previously mentioned collection of real-time work zone information, SWIS addresses this need by being built to handle the importation of CAD files describing the layout of work zones. These files serve to put the work zones layout in context for SWIS, and serve as a benchmark for the work zone to be inspected against.

It is critical that the public be notified about road work sufficiently in advance, be that before reaching a work zone on the roadway or even before getting in a vehicle. Access to real-time work zone information would allow drivers to select different routes or modes of transportation in response to all kinds of work -- not just the long-term projects that cause the most disruption. This can have wide-reaching benefits for the transportation network as a whole.

SWIS uses location trackers attached to assets (in this case, traffic control devices like signs and cones) to monitor the activity of work zones. Even before a crew begins working, SWIS has been continuously listening to incoming messages from these trackers. SWIS asset trackers send a message to the system continuously. When a message is received, it undergoes a Pre-Processing Routine to determine if SWIS should add it to the system. Messages are disregarded when the TCD is in a known storage area, or was at the same spot in a previous message. However, when TCD are placed in a work zone or moved significantly within or to a new work zone, the message is flagged for SWIS to review. These SWIS messages consist of device location in latitude and longitude, the type of traffic control device to which the tracker is attached, and information about the hardware in the tracker itself. SWIS uses this data to express the tracker's location as route and mile point, and then adds the message to a queue of other SWIS messages for further processing.

Two other main routines are scheduled for activation within the SWIS system. The first routine is a Processing Routine which is scheduled to run every five minutes to process the messages from the trackers in the order that they are received. This processing involves associating the traffic control device (represented by the message sent from the asset tracker) to a specific SWIS "Project". The other scheduled SWIS routine in this scenario is the "Sanity Check" Routine; within which falls the Inspection Routine. Triggered once for every three activations of the Processing Routine (or about every 15 minutes), the Sanity Check Routine first checks to see if a "Project" should be inspected, and if so, passes it to the Inspection Routine, which inspects the "Project" using MUTCD temporary traffic control layouts or, if imported, a custom temporary traffic control layout. As the Sanity Check Routine is ultimately part of inspection, the scenario references it in the scope of the Inspection Routine.

2.4.1 Use Scenario for Short-Term Road Construction Project

MnDOT District 3 in St. Cloud, responding to a pothole complaint, deploys a maintenance crew to fill potholes on County Road 138. As the work zone is on a two-lane, two-way road, it requires a flagger to provide traffic control so that vehicles can safely merge into the adjacent lane when one lane is closed. The crew in charge of the operation is trained on following MUTCD Work Zone layout procedures and have SWIS asset trackers at their disposal. After it is decided to use a flagger-assisted lane closure, the crew is dispatched with one truck. Following MUTCD regulations regarding temporary traffic control device deployment, they deploy the work zone in the direction of traffic.

The first traffic control device the crew drops is a "Road Work Ahead" sign tagged with a SWIS asset. The asset connected to this sign sends its location to SWIS at 07:31 AM. The next sign - a "One Lane Road Ahead" sign with an asset - is dropped by the crew 762 feet downstream from the previous sign and sends its location to SWIS at 07:32 AM. The crew then drops a tagged "Be Prepared to Stop" sign 743 feet further downstream and a tagged "Flagger Ahead" sign another 750 feet downstream. The assets connected to these signs send their location at 07:34 AM and 07:35 AM, respectively. The asset connected to the "Be Prepared to Stop" sign sends its location to SWIS at 07:33 AM and the asset

connected to the "Flagger Ahead" sign sends its location at 07:34 AM. Barring communication issues, it can safely be assumed that by 07:35 AM, SWIS has received the aforementioned messages. At this point, SWIS has not concluded that any of these devices are on the same work zone. At 07:35 AM, unrelated to any events in the field, the scheduled Processing Routine within the system is invoked. It uses the traffic control devices dropped by the crew to create a record of an active project. As no traffic control plan exists for the project, SWIS uses MUTCD rules and route metadata from MnDOT to determine the boundaries of the project. After the signs have gone through asset processing, the pothole-filling project (albeit not fully set up) is now viewable to its managers in SWIS. Figure 2.5 shows the work zone with beacons deployed, and timestamps of messages received.

After the "Flagger Ahead" sign comes the work area itself. It begins with an upstream transition, consisting of a merging taper responsible for channeling traffic into the adjacent lane, circumventing the workspace. The crew set up the flagging station and merging taper 1028 feet from the Flagger Ahead sign. They use cones and drop them in the manner described by MUTCD protocol. Only the first and last barrels are equipped with SWIS assets which send their location to SWIS at 07:36 AM and 07:39 AM. At 7:40 AM the scheduled asset Data Processing Routine is triggered again. It adds the recently dropped traffic control equipment to the project and extends the project's boundaries.

The project is using a flagging layout on a two-lane road; therefore, the crew needs to deploy another Advance Warning Area for the adjacent lane. This Advance Warning Area is referred to as the Termination Advance Warning Area. At 07:45 AM the asset data processing function is triggered again, before the Be Prepared to Stop and Flagger ahead signs can send their location. Only the Road Work Ahead and One Lane Road Ahead signs are added to the record. This time, the Processing Routine activates the Inspection Routine. As the pothole-filling project's Termination Advance Warning Area is missing signage, SWIS determines the project is not fully set up, and does not inspect it. After the "Be Prepared to Stop" sign and the "Flagger Ahead" sign are dropped, the setup of the work zone is complete. Devices are dropped in the locations shown in Figure 2.5, completing deployment at 07:46 AM.

At 07:50 AM, the data associated with all tagged traffic control devices in the work zone of this project is processed. At 08:00 AM, the Inspection Routine is activated again. Now that the work zone for the project is completely set up, an inspection is warranted. In the case of the pothole-filling project, the work zone has been set up correctly and all asset trackers are functioning normally. Therefore, no alerts are generated.

Work on the pothole-filling project concludes at 11:03 AM. The next time it is called, SWIS's Inspection Routine can determine that project takedown is occurring due to the significant changes in location. SWIS updates its records to show that the project has concluded. Upon reaching the equipment warehouse, SWIS recognizes the location trackers attached to the signs are inside the geo-fence of a warehouse and orders them to enter power-save mode.
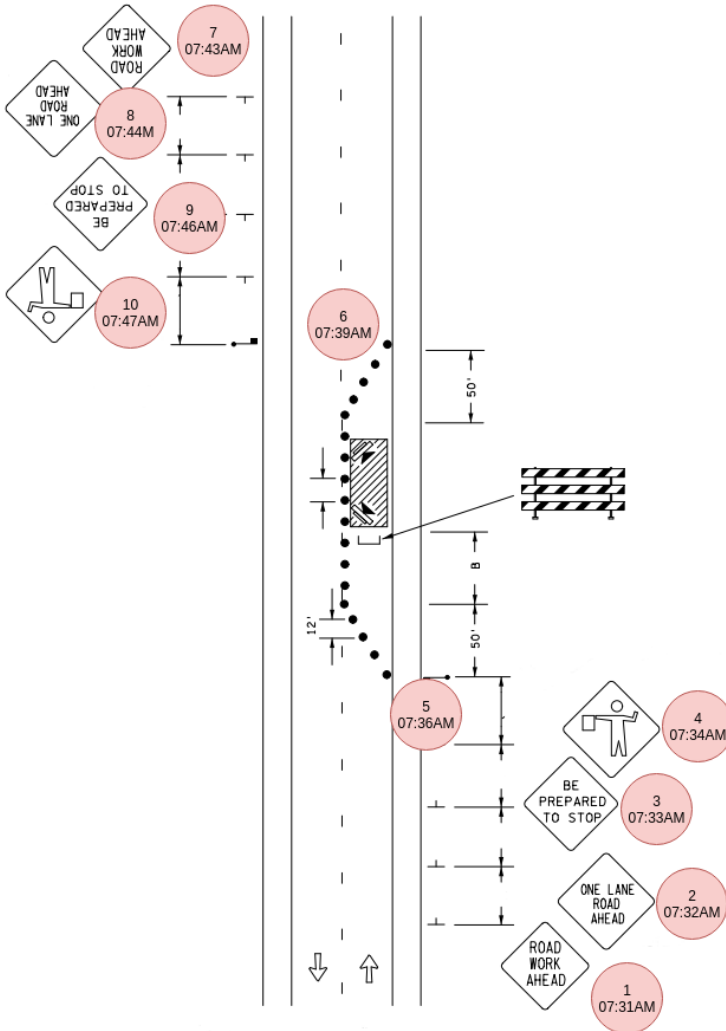
Figure 2.5 Order Traffic Control Devices are dropped and when their information is sent to SWIS for this scenario

2.4.2 Scenario Deviations

This section describes deviations, or "forks", in the previous scenario. Each fork states where it begins in the scenario, how it is handled by the system, and where it ends and the scenario resumes. If the fork does not specify time, then the scenario is not drastically impacted chronologically.

2.4.2.1 Converging Deployment of Traffic Control Devices

This fork begins at the beginning of the scenario. Instead of one truck to deploy TCD, the crew uses two. One truck begins at the Advance Warning Area while the other begins at the Termination Area of the Pothole Project's Work Zone. By 07:35 AM, the crews have deployed signs one through four, and seven through ten. When these TCD are processed by the system, it groups them into two different SWIS

Projects. When the system processes TCD again at 07:40 AM, SWIS adds assets five and six to these projects. At 07:45 AM, SWIS Sanity Routine is triggered. It evaluates both projects and generates warnings for them. The routine then further assesses the projects and determines they should be one project. Therefore, the two SWIS projects are then merged. When this merged project is evaluated by the Inspection Routine at 08:00 AM, no further violations are generated and the warnings are suppressed and the scenario continues normally.

2.4.2.2 SWIS Uses the Wrong Speed Limit for the Route.

This fork begins at 07:35 AM when the first TCD are processed by SWIS. During setup, SWIS incorrectly determined the speed of the road to be 45 miles per hour instead of 55 miles per hour. This means that SWIS now expects the spacing between advance warning signs to be 600 feet instead of 750 feet. At 8:00 AM, when the SWIS Project is inspected for the first time, the system raises an alert to the crew's supervisor that their project is in violation of MUTCD spacing requirements. As they know the speed limit is 55 miles per hour, the supervisor can either suppress the alert, or change the speed limit SWIS has inferred for the project. Regardless of their choice, the alert is resolved and the scenario continues normally.

2.4.2.3 Violation: Advance Warning Sign Spacing

This fork begins when the crew deploy the "Be Prepared to Stop" sign. Instead of 743 feet, the crew erroneously deploy the sign 942 feet downstream from the previously placed sign. This distance is greater than the accepted margin of error for sign spacing. When it runs at 08:00 AM, SWIS's Inspection Routine recognizes the placement as a violation of acceptable work zone layout and raises an alert to the crew's supervisor. Once they receive the alert, the supervisor can either suppress the violation or order their crew to move the sign to its correct location. They choose the latter option, and when the Inspection Routine is invoked again at 08:15 AM no violations are detected. The scenario continues normally.

2.4.2.4 Violation: Improper Temporary Traffic Control Layout.

This fork begins with the deployment of the sign after the "Road Work Ahead" sign. Instead of the "One Lane Road Ahead" and "Be Prepared to Stop" advanced warning signs, the crew deploy a "Flagger Ahead Sign". They then set up the workspace and make the same error with setting up the downstream advance warning area. When SWIS runs its Inspection Routine at 08:00 AM, it determines that both advance warning area setups are in violation of MUTCD work zone layout rules and generates an alert to the crew's supervisor.

The supervisor sends the truck back to the yard to obtain the required TCD. When it returns at 8:47 AM, the crew correct the layout by moving the "Road Work Ahead" sign for both advance warning areas upstream by approximately 1500 feet, making space for the two signs in between. When they complete the deployment by 08:55 AM, SWIS's scheduled Processing Routine updates the start and end points of

the SWIS Project and its Work Zone to reflect the placement of the "Road Work Ahead" signs. At 09:00 AM the project is inspected by SWIS's scheduled Inspection Routine, which yields no violations. The scenario continues normally.

2.4.2.5 Non MUTCD Compliant TCD Deployment

This fork assumes that the pothole filling project is comprised of two pothole filling operations along County Road 138. After completing TCD deployment at 07:39 AM, the crew preemptively deploy another set of Advance Warning Area Signs 2000 feet before the "Road Work Ahead" sign of the Termination Advance Warning Area. This is a common practice in the industry, but it does not comply with MUTCD. While the extra signage may confuse motorists and compromise the safety of the crew, it means they will not need to walk all the way upstream to collect the first four Advance Warning Area signs. They complete this setup by 07:52 AM and begin filling the potholes in the first work area.

When SWIS's scheduled Inspection Routine is invoked at 08:00 AM, it detects three Advance Warning Areas in the project's work zone. As there are no subsequent TCDs after the last Advance Warning Area, SWIS determines that it is not actively part of the current work zone. Therefore, SWIS removes the devices from the work zone and associates them as rogue TCDs of the project.

The crew finish filling the potholes of the first work zone at 11:03 AM and proceed to deploy the second. They pick up the TCDs from the Work Area and Termination Advance Warning Area and deploy them after the preemptively deployed Advance Warning Area, leaving the first Advance Warning Area. This deployment is completed by 11:14 AM. The preemptively deployed Advance Warning Area is still associated with the project as a set of rogue TCDs. When SWIS's Inspection Routine is invoked at 11:15 AM, the distance between the first Advance Warning Area's last TCD and the Work Area's first TCD violates the MUTCD. This prompts SWIS to further assess the project and determine that the previously rogue TCDS are exactly where an Advance Warning Area should be. Therefore, SWIS re-classifies the TCDS in the preemptive Advance Warning Area as being part of the project and updates its bounds. The system then associates the TCDS from first Advance Warning Area as rogue TCDs of the project.

Work on the pothole-filling project concludes at 3:06 PM. The next time it is called, SWIS's Inspection Routine determines that project takedown is occurring due to the significant changes in location. SWIS updates its records to show that the project has concluded. Upon reaching the equipment warehouse, SWIS recognizes the location assets attached to the signs are inside the geo-fence of a warehouse and disregards further messages until they are moved again.

2.4.2.6 Asset Hardware Failure

This fork begins while workers are filling potholes. At 09:02 AM, the SWIS asset on the upstream Advance Warning Area's "Be Prepared to Stop" sign experiences catastrophic hardware failure. It loses contact with the SWIS server. The work zone is still set up correctly, but the system is unable to verify this is what is currently occurring in the work zone. When the Inspection Routine is run on the project at 09:45 AM, SWIS alerts the crew's supervisor that it has not heard from this asset in the threshold that

the assets have been configured to send messages to SWIS. The supervisor has the option to either suppress alerts regarding the asset for the duration of the project or until a replacement asset can be installed on the sign. In this case, the supervisor chooses the first option. The scenario continues normally.

2.4.2.7 Asset Power Loss

This fork begins in the previous fork at 09:02 AM. Instead of hardware failure, the asset's battery level dips below 20%. When the Inspection Routine Executes at 09:15 AM, a warning is generated for the asset. When the Inspection Routine Executes at 09:30 AM, another warning is generated for the asset. These warnings are not forwarded until their third occurrence. At 09:45 AM, when the Inspection Routine generates its third warning for the device and its battery level is at 13% an alert is sent to the crew's supervisor. The supervisor has the option to suppress the alerts regarding the asset for the duration of the project or until a replacement battery (or asset) can be installed on the sign. In this case, the supervisor instructs his crew to swap out the dying battery on the tracker with a new one. The scenario continues normally.

CHAPTER 3: FUNCTIONAL SPECIFICATIONS

The system described in the previous chapter has many specific functional requirements it must meet in order to work properly. This chapter outlines these requirements and how they relate to each other.

3.1 ASSET TRACKERS FOR TRAFFIC CONTROL DEVICES

The first requirement of SWIS is a mechanism for tracking the location and type of the traffic control assets that make up the work zone. This is one of the fundamental information sources that SWIS will use to provide information to its users. In order for these devices to be effective and efficient, there are some specific requirements that must be placed on them. These are as follows:

1. An adequate number of traffic control devices must be equipped with asset tracking devices to provide the SWIS system with information about a work zone.
2. The asset tracking devices must be capable of retrieving their real-time positioning information
3. The asset tracking devices must be capable of communicating with the outside world wirelessly:
   a. The asset tracking devices must be capable of using this communication to transmit its position to a centralized system.
   b. The asset tracking devices must also transmit a regular "heartbeat" message to provide the central system with status information.
   c. The asset tracking devices must be capable of transmitting information regarding the status of the device to the central system.
      1. This information must include but is not limited to health status, logged malfunctions, cellular signal power.
   d. The asset tracking devices must be capable of being accessed remotely to change operational parameters and install software upgrades.
4. An asset tracking device must be capable of being attached to multiple different traffic control device types.
5. An asset tracking device must be capable of being removed from the traffic control device.
6. The mechanism for attaching an asset tracking device to a traffic control device must be capable of withstanding being struck by a vehicle at high speed without injuring the occupant.
7. The asset tracking devices must be self-sustaining, requiring no interaction from work crews to be deployed.
8. The asset tracking devices must be self-powered.
9. The asset tracking devices must have an extended operational life that allows them to operate continuously for the life of a traffic control asset.
10. The asset tracking devices must be capable of operating in an outdoor environment in all weather conditions.
11. The asset tracking devices must be capable of communicating with drivers via local wireless communication to provide additional advanced warning when entering a work zone.

3.2 SERVER FOR ROAD CONSTRUCTION PROJECT DATA

The second requirement for SWIS is a means to host and interpret road construction project data. This centralized system takes the form of a server. If the aforementioned asset trackers are the nervous system of SWIS, the server is the brain. In order for this server to be effective and efficient, the following requirements must be fulfilled:

1. Users spread throughout the state of Minnesota must be able to access SWIS regardless of where they are.
2. The SWIS server must have the capability to intelligently warehouse road construction project data.
    a. The SWIS server must be capable of hosting data critical to its comprehension of road construction projects.
3. The SWIS server must be able to autonomously monitor projects without an official Traffic Control Plan.
    a. The SWIS server must support manual input for an unofficial Traffic Control Plan.
    b. The SWIS server must be able to generate an impromptu project if no corresponding road construction project record exists for a work zone being set up.
    c. The SWIS server must support the inspection of a work zone based on MUTCD rules
4. The SWIS server must be able to autonomously monitor projects with a Traffic Control Plan.
    a. The SWIS server must support the automated ingestion of AutoCAD files containing work zone Traffic Control Plan once it is imported by a user.
    b. The SWIS server must support the inspection of a work zone based on the layout described in the corresponding Traffic Control Plan.
5. The SWIS server must have the capability to interpret Asset Tracker data as the live representation of a work zone.
    a. The SWIS server must be able to determine what state a work zone is in so that it may prevent fallacious inspections from being performed.
    b. Asset Trackers may send their location in areas other than a work zone. Therefore, the SWIS server must be able to determine when an Asset Tracker is in the bounds of a work zone and when it is not.
6. The SWIS server must have the capability to interpret Road Project meta-data.
    a. The SWIS server must be able to reconcile a work zone in the process of being set up with its corresponding road construction project record, if the record exists.
    b. The SWIS server must be able to autonomously detect and gracefully handle changes in the layout of a work zone. This includes the conclusion of a road construction project.
7. The SWIS server must have the capability to interpret and utilize road geometry information when monitoring projects.
8. To further mitigate the risk of fallacious inspections being executed, the SWIS server must perform sub-inspection "sanity checks" to determine if a work zone should be inspected.

CHAPTER 4: SYSTEM ARCHITECTURE AND PROCESSES

In this section, the overall system architecture and individual algorithm processes of SWIS are presented.

4.1 SYSTEM ARCHITECTURE

In this section, the system architecture at varying "views" of SWIS is presented, from an overall view of sources of information, to what occurs when SWIS receives messages from assets in work zones.

4.1.1 System Overview

Figure 4.1 shows how information from projects throughout the state is gathered, and can be interacted with.

Figure 4.1 SWIS System Overview
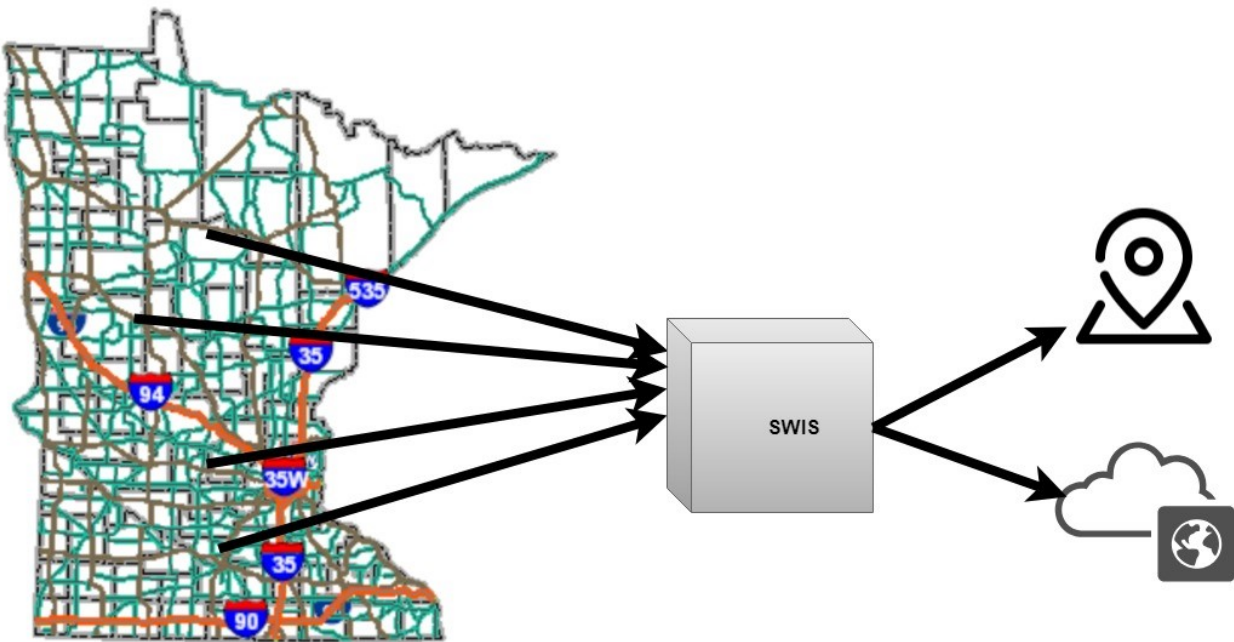
Data from work zones across the state is transmitted to SWIS, which is always listening. Once data from work zones are gathered and formatted by SWIS, users are able to interact with it in the system through its official web-based client. Users can also access SWIS work zone data through the information providers and entities that the system is configured to push information to.

4.1.2 External Sources of Information

Figure 4.2 shows how external sources of information interact with SWIS. This interaction can be described as pushing data from an origin to a destination or pulling data from a source to a destination.
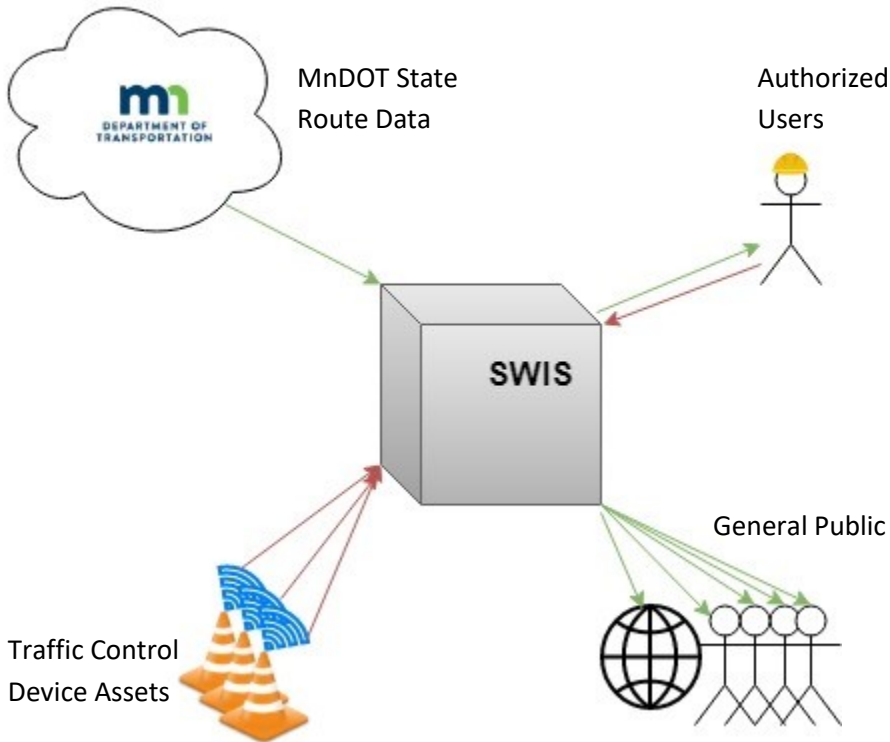

Figure 4.2 External sources of information

Data in SWIS is readable by the general public who may navigate to the system's client page and services that have been configured to pull data from the system. This data is generated by SWIS using the following:

- Traffic Control Device (TCDs) Assets: Symbolized by the orange cones, this hardware is responsible for sending data to SWIS. Assets will either be placed onto a TCD or built into TCDs. Assets are embedded with GPS sensors, and will transmit their position, the type of Traffic Control Device they are on, and metadata about the beacon itself to SWIS. This metadata includes the asset's identification information, and its battery level. There can be none, one, or many assets reporting their locations to SWIS at any given time. The system can also send commands to the assets, such as an order to go into low power mode.

- State route data: Symbolized by the cloud with the MnDOT logo, SWIS will query state government entities for data such as milepost, speed limit, road geometry, and Annual Average Daily Traffic (AADT) to describe a project in the scope of the route it is on.

- Authorized SWIS users/Project Supervisors: Symbolized by the stick figure with an orange hat, project supervisors are responsible for entering and editing project data within the system and responding to violations in traffic control device layout or alerts that have been raised by SWIS.

Additionally, one group of users can see the SWIS website and interact with it to a limited degree.

- General public: User access to and interaction with the server is facilitated by a web browser based SWIS client. Users with no special permissions can view active and historical projects in SWIS.

4.1.2.1 SWIS Asset Tracking Devices

The physical aspect of SWIS, the asset tracking devices that provide SWIS with real-time information, are designed with some key features for them to be appropriate for the application. At the base level, however, they are not much more than the same wireless asset tracking devices used in fleet management systems, freight tracking, and other similar fields. The major components are Global Navigation Satellite System (GNSS) technology for providing positioning information and a cellular data modem for communication with the outside world. In addition to this, the devices have a controller programmed with intelligent power management designed to conserve battery power in the work zone environments in which they are placed. The devices send regular messages to the server so it can be sure they are alive and well. Finally, the devices are capable of being remotely administered over their cellular data connection, communicating with the server to update their parameters or perform software upgrades. All of these functions are handled automatically by the devices without any interaction from workers on site.

In addition to these functions, the devices are capable of broadcasting their ID over Bluetooth to communicate with smartphones in the immediate vicinity. This directs a smartphone with the proper app to use this ID to check SWIS for any messages associated with that asset and prompt the driver, for instance to notify them that they are entering a work zone. The devices also have the capability of detecting when they are struck by a vehicle. This information can be used to notify the work zone crews or other personnel that an incident has taken place. This Bluetooth capability ties back to the original three components of the work zone information system: human factors, driver notification, and cloud-based work zone information. Liao (13) determined through field tests that a WorkzoneAlert app can reliably detect a Bluetooth transmitter placed an average of 127m away from the receiver at posted speeds of 35mph to 45mph in a work zone. Previous work done by Craig et. al (12) determined the most effective messages to provide to drivers through this system. SWIS' asset tracking devices can integrate with the WorkzoneAlert app to provide real time alerts to drivers approaching a work zone.

Critically, the asset tracking devices are also designed to be crash-safe. This means that they will not cause injury to the occupants of a vehicle if they are struck, similar to the beacon lights that are frequently attached to traffic control devices in the field today. Because these devices will be placed on the roadside where a collision is a significant possibility, this is a critical feature of the devices. In their

current version, for SWIS testing and demonstration the SWIS beacons have been incorporated inside MUTCD approved Flashing Barricade Lights that are solar and battery powered, as seen in Figure 4.3.

To summarize, SWIS asset tracker devices (called "assets" or TCDs) are currently placed within beacons and attached to TCDs. In the future, assets will be built into TCDs. They are fully autonomous and will know what kind of TCD they are a part of. These assets then send regular messages to SWIS, which are processed through algorithms described in the rest of this chapter.

Figure 4.3 Example of an enclosure for a SWIS Asset beacon.

4.1.3 Inside SWIS

Figure 4.44 below shows the primary modules of SWIS itself: the Server, System Administrator Client, Project Manager and the User Client. This figure looks inside the "black box" of Figure 4.1 and Figure 4.2.

The SWIS server contains the core database of work zone information. A Dynamic Memory Database (DMD) interacts with the core database to either pull information related to projects or user requests, or archive information for projects that are no longer active. The DMD contains all projects currently or soon to be active in SWIS. The use of a DMD allows for components to access project information faster than querying the entire core database. As explained previously in Section 2.3.1 the DMD is structured by "Project", "Traffic Control Plans" (TCPs) and "Work Zones" (WZs). It is important to reiterate the difference between these three categories and the hierarchical structure of them within the DMD before continuing within the SWIS architecture. A generalized layout of the structure is provided in Figure 4.5, with *N* representing any number of TCPs, WZs, or TCDs.
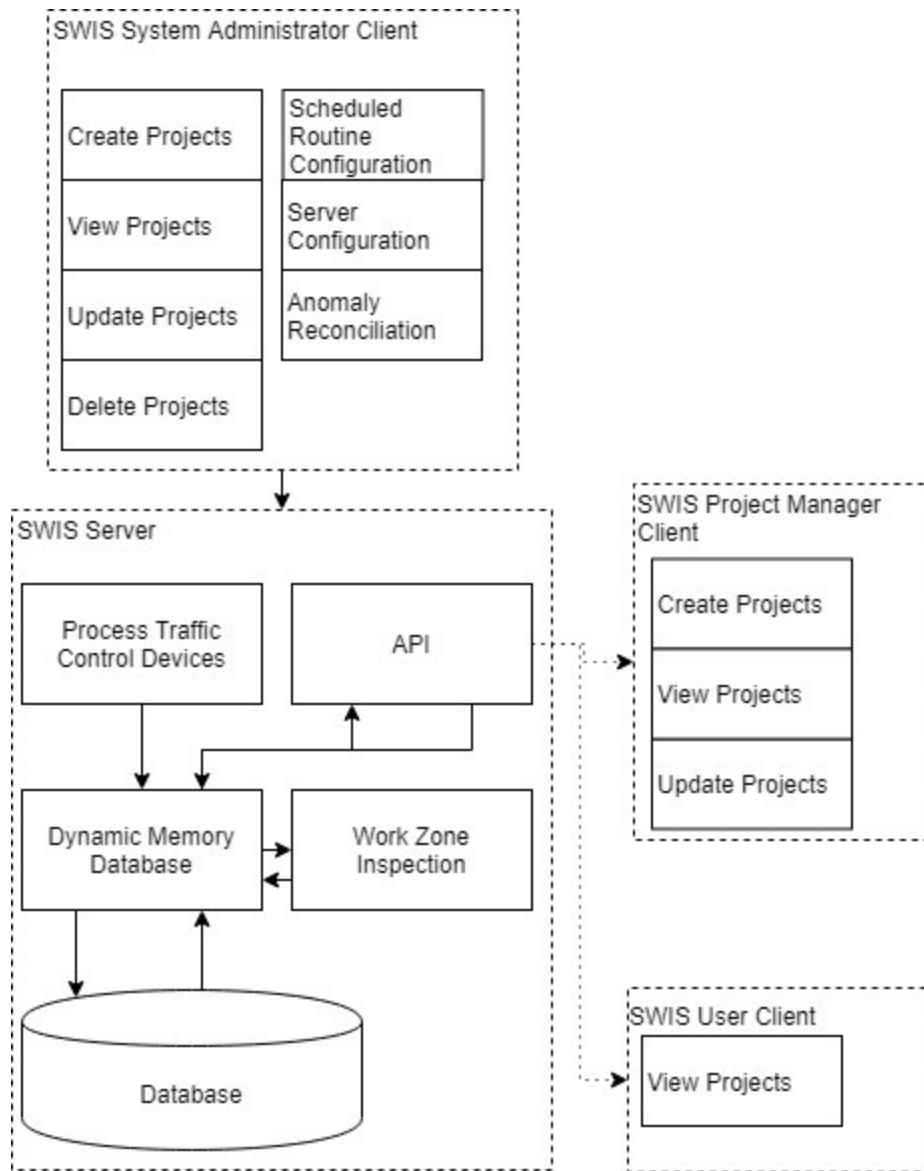
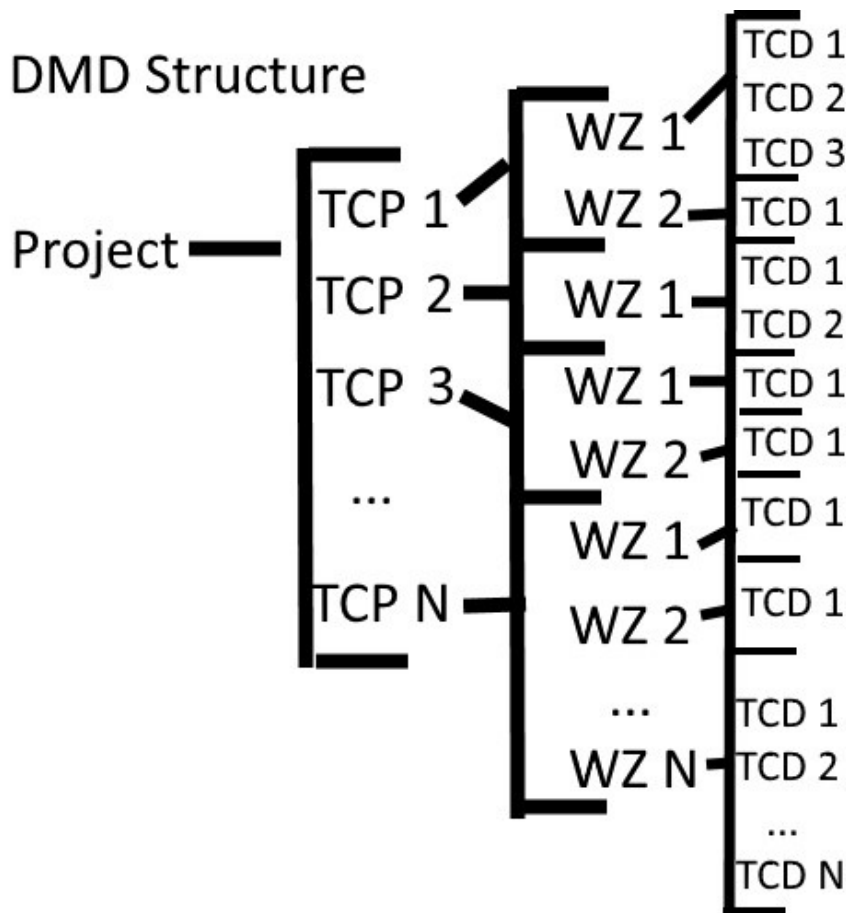**Figure 4.4 Primary SWIS modules and components**

Figure 4.5 Dynamic Memory Database structure

SWIS Projects are assigned to a "route", or roadway, and have a general start date and end date assigned to them either based on when messages are received by SWIS or set up in advance if it is a planned project. Every Project has at least one, but possibly several, Traffic Control Plans (TCPs). These TCPs are active within the project based on the time of day. For example, a small Project that doesn't affect traffic flow much may have only one TCP for the project duration. In Figure 4.5, the Project would only have TCP 1 active. A larger Project, such as on an interstate entering and leaving a downtown area, may have AM peak, PM peak, and Off-Peak TCPs. An AM Peak TCP might be two lanes entering downtown and one leaving. A PM Peak TCP may shift those lanes to two leaving downtown and one entering. Off Peak TCP's may have two lanes in either direction. In Figure 4.5, the Project would use three TCPs for AM, PM and Off Peak. Each TCP dictates where barriers and signage are placed and may either be based on MUTCD layouts or programmed in advance into SWIS by a construction supervisor.

Within TCPs, there are Work Zones (WZs). Each TCP may have one or many WZs at different points along the physical length of the Project. For example, the morning of a Project, one crew could have a WZ repairing potholes along an interstate while a different crew several miles down the road has a WZ reconstructing an off ramp. Because these WZs are along the same route, they fall under the same

Project; because they are active at the same time of day, they fall under the same TCP. In Figure 4.5, this would be represented as Project -> AM TCP -> the two active WZs.

TCDs are categorized under WZs as they send messages to SWIS with their location, through the Pre-Process and Process TCDs algorithms. In Figure 4.5, each WZ has at least one active TCD. More will become active as the project continues to be set up, and TCDs may change between WZs or even Projects.

Various SWIS algorithms connect to the DMD to either log in or gather information. The Process Traffic Control Devices component will continuously input active work zone information, gathered from assets at the worksite, to the DMD. The Work Zone Inspection (and within that, the Sanity Check) component pulls from the DMD to determine if a work zone is in need of inspection and returns the results of inspection to SWIS.

The Applications Process Interface (API) serves as a portal for users to view and interact with SWIS, depending on their level of authorization. Project Managers (and other users with appropriate privileges) can interact with the SWIS system by creating, viewing, and updating projects. The User Client is an interface for users without administrative permissions to view active and historical projects in SWIS. The System Administrator Client shares abilities with the Project Manager client, but also allows for the deletion of projects and additional technical support as needed.

4.2 SWIS COMPONENTS

Two primary components make up the core of SWIS: Process TCDs and Work Zone Inspection. Within Process TCDs is a Pre-Processing TCD routine to ensure messages that are reaching SWIS are legitimate. Also, within Work Zone Inspection is the Sanity Check, described in 4.2.3 . The Sanity Check triggers before the Work Zone Inspection algorithm. The API is also a component of SWIS, allowing users to access to the system, but will be described in Section 4.3 as it is separate from internal SWIS routines.

4.2.1 Process TCDs: Pre-Processing TCDs

Any time a SWIS asset message is received by SWIS, it uses the pre-process TCD algorithm (described in Figure 4.6) to recognize the TCD, to verify that the TCD is legitimate (i.e. not a hacker trying to send a fake message to SWIS), and to check where the TCD is pinging from. If it is a legitimate TCD, but pings in from a warehouse or other recognized storage area, the message is disregarded. The pre-processing algorithm also checks if the TCD has sent a prior message that hasn't been processed yet; if an earlier message exists, it is replaced by the new message to avoid duplicating assets.
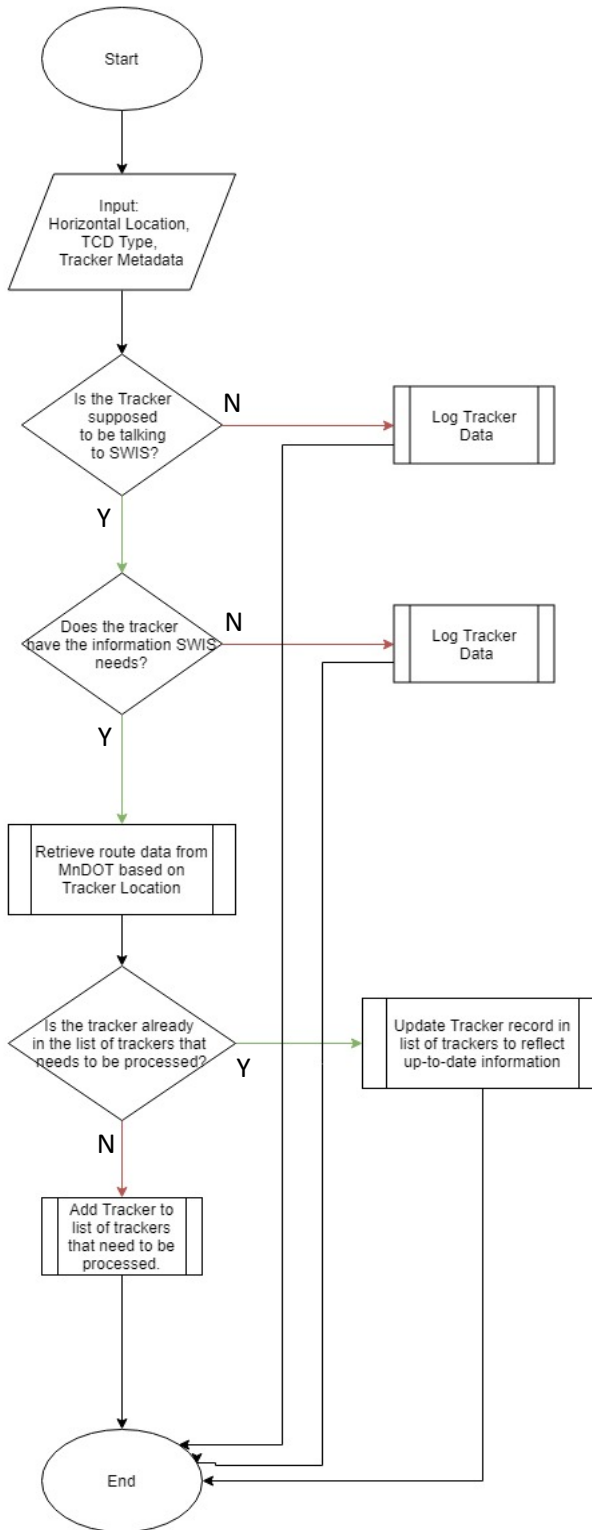
Figure 4.6 Pre-Process TCD flowchart

If the message received is valid, the latitude and longitude of the tracker is translated into a state route and mile-point. It is sent to a queue in the process TCD algorithm.

4.2.2 Process TCDs

In the Process TCD algorithm, SWIS goes through the queue built up by the pre-process routine and attempts to assign the TCD to an existing project. It does this by interacting with the DMD and assigning the TCD to the structure described in Sections 2.3.1 and 4.1.3 . The Process TCD algorithm is depicted as a flowchart in Figure 4.7. This process is set to run every five minutes.

The goal of the Process TCD algorithm is to categorize each TCD message received by SWIS. Each TCD message is checked to see if it is the first time this asset has sent a message to SWIS, or if it has already been categorized and is now sending an updated message. (This differs from the pre-process TCD routine; in that routine, the TCD has not been categorized by SWIS before an updated message has been received.) If it is an asset that has already been categorized by SWIS, any updated information about the asset is logged into SWIS, and the Process TCD moves to the next TCD message in the queue. Updated information may either be a new location within the Project and TCP that the asset belonged to at its previous message, or that it was moved to a new Project on a different roadway. If the asset has moved to a new Project, it will be removed from the old Project and the routine described for assigning asset messages will proceed.

If it is the first time this TCD asset has sent a message to SWIS, SWIS attempts to categorize the TCD following the Project, TCP, WZ structure. This may be as simple as looking at a pre-planned Project that has become active (for example, construction along an interstate is set to begin May 1st. The Project becomes active in SWIS on May 1st though crews do not actually begin until May 3rd. The Project becomes active in SWIS when the first assets are placed.) SWIS looks within its active Projects to see if the geographical location of the TCD fits within the boundaries of an existing Project. If it does, SWIS looks for a TCP within that Project that is active at the time the TCD message was sent, and a WZ within that TCP that fits the location of the TCD. If a Project, TCP and WZ is found that the TCD asset belongs to, the record is updated.

If SWIS cannot find an existing Project that the asset belongs to, it creates a new Unplanned Project, TCP and WZ for that TCD asset. As more TCD assets are placed next to the first asset, the boundaries of the TCP and WZ will adjust through the next algorithm, the Sanity Check, described 4.2.3 .
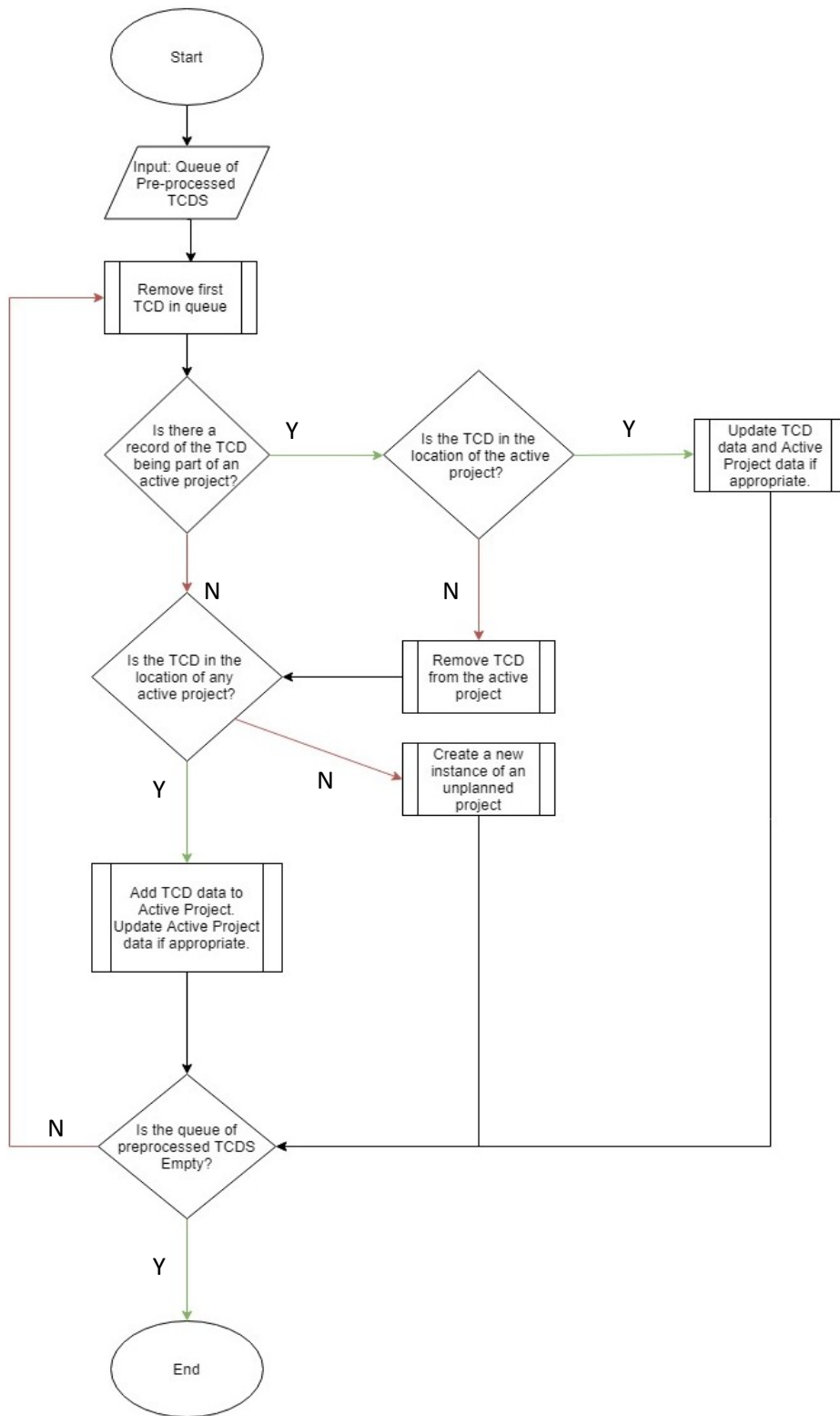
Figure 4.7 Process TCDs function

The process TCD algorithm also checks messages for "rogue" and "unsanctioned" WZs. A rogue WZ is when a TCD appears in a Project boundary but with no active TCP or WZ for it. An unsanctioned WZ is when a TCD comes online within the boundaries of a Project and TCP, but not in a WZ currently active on the TCP. See Figure 4.8 for a visual example of rogue and unsanctioned WZs. These rogue and unsanctioned WZs are flagged for review by the Sanity Check, described in Section 4.2.3 . Y
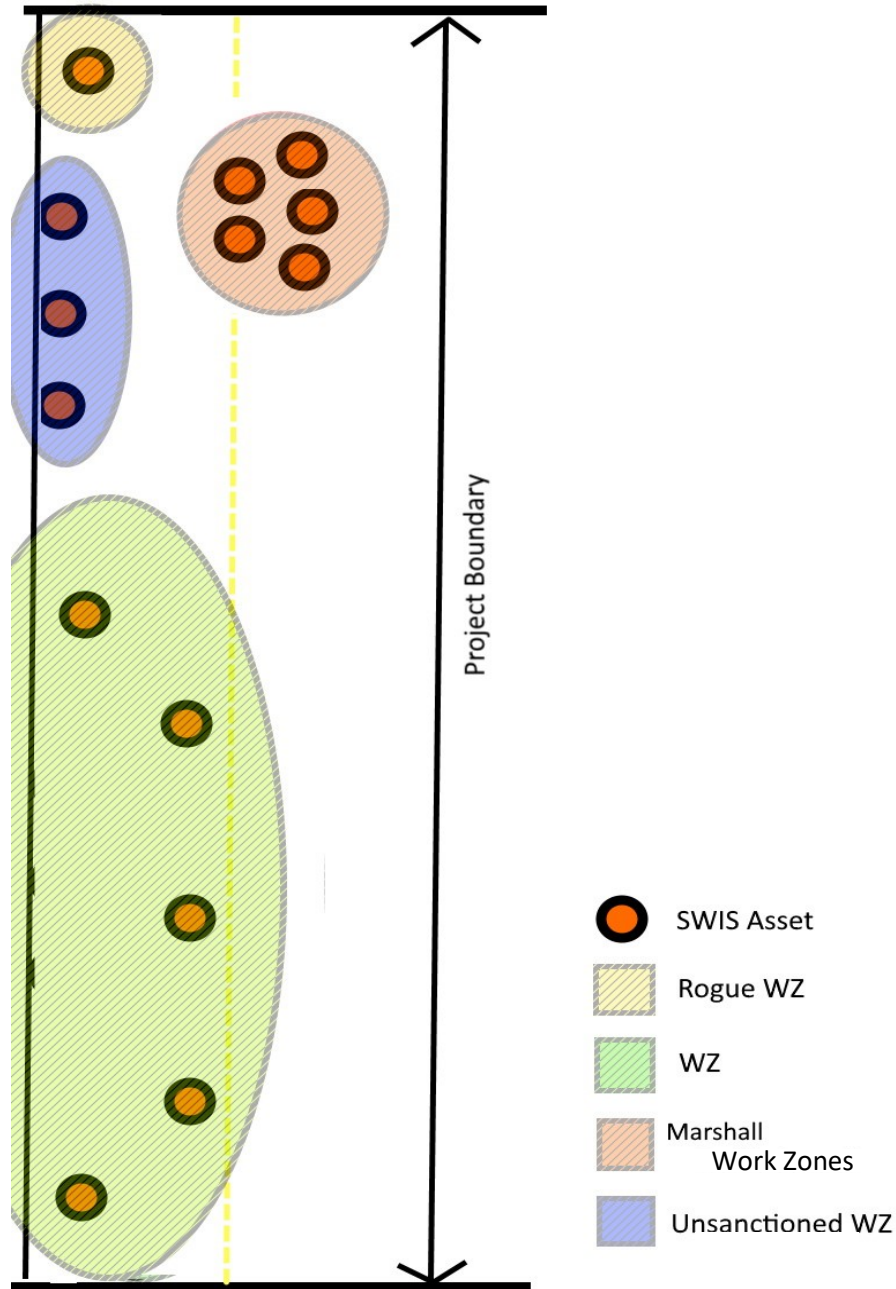
Figure 4.8 Types of Work Zones created in SWIS

4.2.3 Work Zone Inspection: Sanity Check

By default, all Projects are flagged for Sanity Check when they first become active. Any rogue and unsanctioned WZs are also flagged for Sanity Check. If a TCD is added, removed, or moved by more than a set distance, the Project will also be flagged for Sanity Check.

Sanity Check is a complex algorithm that determines if a Project is ready for Inspection, and if it is not, may raise an alert for the crew to examine what is wrong with the Project layout. One of the Sanity Checks is a function called "Marshall Work Zone". This function looks for assets along a WZ that are grouped together (i.e. still in the back of the crew's truck or waiting on the side of the road). If a grouping is found, this function disregards the Project for this pass-through of the Sanity Check and keeps the Sanity Check flag in place. See Figure 4.88 for an example of Marshall Work Zones.

The rest of Sanity Check looks for overlapping Projects and WZs. It does this by examining boundaries of Projects and WZs, after they have been updated by the Process TCD algorithm, adjusting as necessary. For example, if two or more Projects have become active on a stretch of roadway with close or overlapping boundaries, the Projects are grouped together under one common Project. The same process is done with WZs within a project. Especially as not every barrel is given a SWIS asset, WZs that are many miles long may initially appear in SWIS as groupings of Advanced Warning Signs and the initial taper barrels, and the termination taper barrels and End Work Signs. Sanity Check will examine groupings of SWIS asset messages and determine if they belong to the same WZ or if they are different WZs.

Sanity Check will raise an alert to the crew if a rogue WZ cannot be assigned to an existing WZ. It will also raise an alert for unsanctioned WZs. For example, a rogue WZ may have been created around a SWIS asset that fell off the back of the truck and rolled into the ditch, or by an asset being struck by a vehicle and knocked out of its current WZ. Crews will need to retrieve these and replace them or notify SWIS that they are aware of the alert so SWIS will mute it. Unsanctioned WZs may be an unplanned WZ within a larger Project, like a crewmember deciding to set up a few barrels and cones to replace a street lamp light within a larger construction project. As with rogue WZs, an alert will be raised for unsanctioned WZs that the crew can choose to mute if it is expected work. See Figure 4.8 for examples of rogue and unsanctioned WZs. Marshal WZ (groups of closely spaced TCD in no logical order,) are excluded from raising alerts and ignored by the sanity check process.

After a Project is passed through the Sanity Check, it moves into the Inspection Algorithm. If a project does not pass the Sanity Check, it moves back into the Process TCDs algorithm while changes to the site based on alerts raised by SWIS are made. Once addressed, they are fed back into Sanity Check. Projects that keep failing Sanity Check must be addressed (by supervisors responding to alerts or violations raised by SWIS) or they will never be inspected.

4.2.4 Automated Work Zone Inspection

After a WZ is flagged for readiness for inspection by the Sanity Check algorithm, it moves to the Automated Work Zone Inspection routine. An important component of SWIS is the ability to
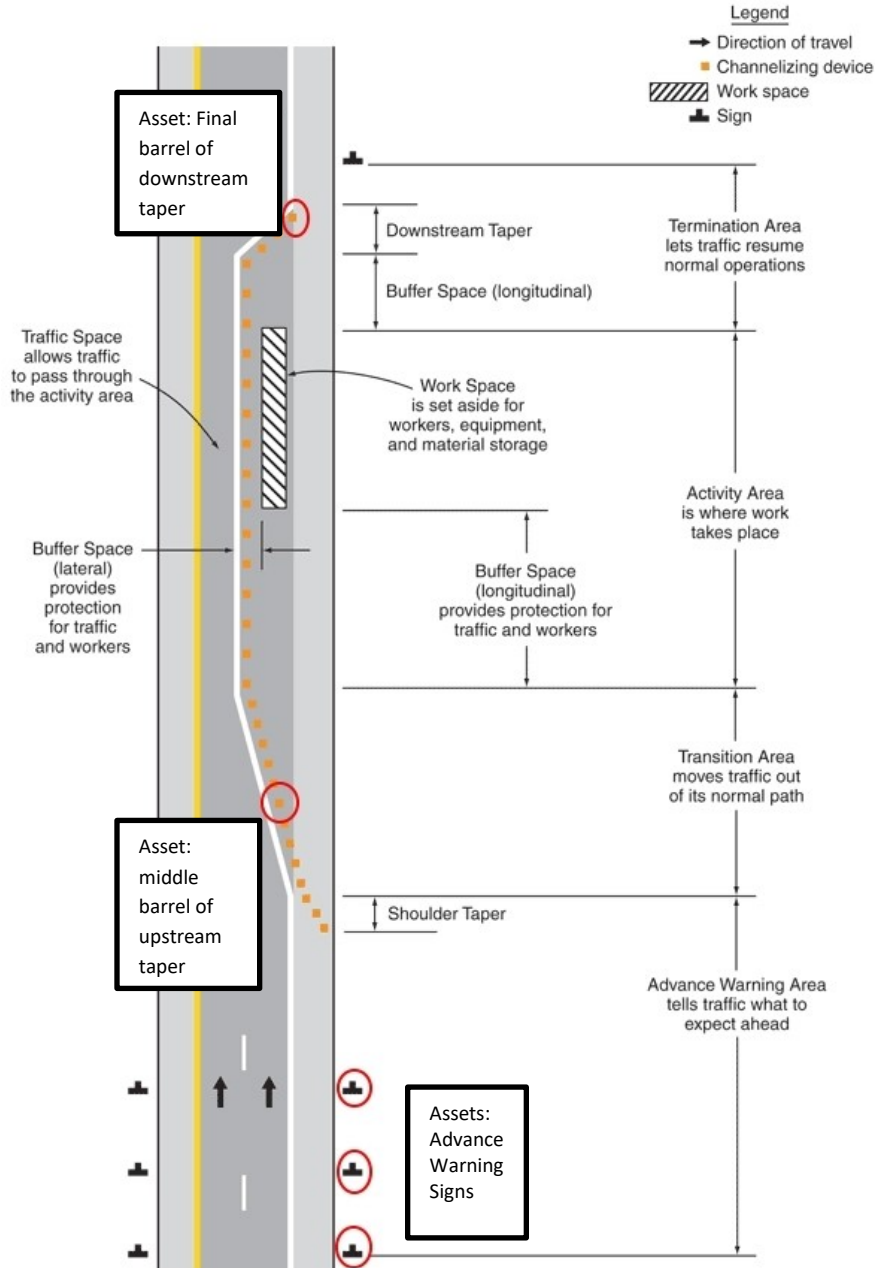

Legend
→ Direction of travel
▪ Channelizing device
▨ Work space
⚓ Sign

Asset: Final barrel of downstream taper

Downstream Taper

Buffer Space (longitudinal)

Termination Area lets traffic resume normal operations

Traffic Space allows traffic to pass through the activity area

Work Space is set aside for workers, equipment, and material storage

Activity Area is where work takes place

Buffer Space (lateral) provides protection for traffic and workers

Buffer Space (longitudinal) provides protection for traffic and workers

Transition Area moves traffic out of its normal path

Asset: middle barrel of upstream taper

Shoulder Taper

Advance Warning Area tells traffic what to expect ahead

Assets: Advance Warning Signs

Figure 4.9 Minimum set of tagged traffic control devices for system to determine the MUTCD layout in use

automatically inspect some aspects of the layout of WZ TCDs with only the information from certain tagged assets. There are two main tracks for doing this, one when there is no formal traffic control plan in the system, and one where a formal TCP is available. When there is no formal traffic control plan, the

automated inspection process involves a heuristic for selecting the traffic control layout from the assortment of options in the MUTCD to determine whether it is set up correctly. The layout selection process requires that a minimum set of assets be tagged to provide the system with sufficient information to select the correct layout. These include all signs, the flagger's pole/stop sign (for flagger operations), the channelizing device at the center of the driving lane within the upstream taper (or at the beginning of a lane shift), and the last channelizing device of the downstream taper (or end of a lane shift). These essential assets are highlighted with red circles in Figure 4.9.

In addition to being tagged, all tagged assets must be aware of what type of TCD they are. For signs, this means that the MUTCD ID of the sign (e.g. W20-1 for a Road Work Ahead sign) must be part of the information sent by the tracking device to SWIS. Channelizing devices (drums, cones, etc.) may send only their type and do not need to say specifically whether they are in the upstream or downstream taper.

In addition to the information from the assets, SWIS also needs to acquire additional information about the road on which the assets are located. After the asset is placed on the appropriate route based on a digital map of roads, SWIS must retrieve the road type (number of lanes and whether it is divided or undivided), posted speed limit, and Average Annual Daily Traffic (AADT) of the road from an information system. Currently this is possible for Minnesota roads using the Geographic Information System (GIS) maintained by MnDOT and could theoretically be implemented in other states with a similar information system.

With this information, SWIS can now begin searching through the potential layouts as shown in Figure 4.10. These layouts are organized into a tree similar to their layout in the MN MUTCD. At the highest level, a branch of the tree can be chosen based on the type of road. In the MN MUTCD, there are different sections for each of the road types of: two-lane, two-way roads, multi-lane undivided roads, and multi-lane divided roads. Once this selection is made, the number of layout possibilities is greatly reduced by approximately one half to two thirds.

Following the selection based on road type, the AADT of the road is checked to see if it is a "low-AADT" road. If the AADT is below 400, or between 400 and 1500, a special subset of "low-AADT" layouts can be examined to determine if the layout in the field matches one of them using the layout test described below. If not, the search continues to allow for the possibility that a more general layout was used despite the low AADT of the road.
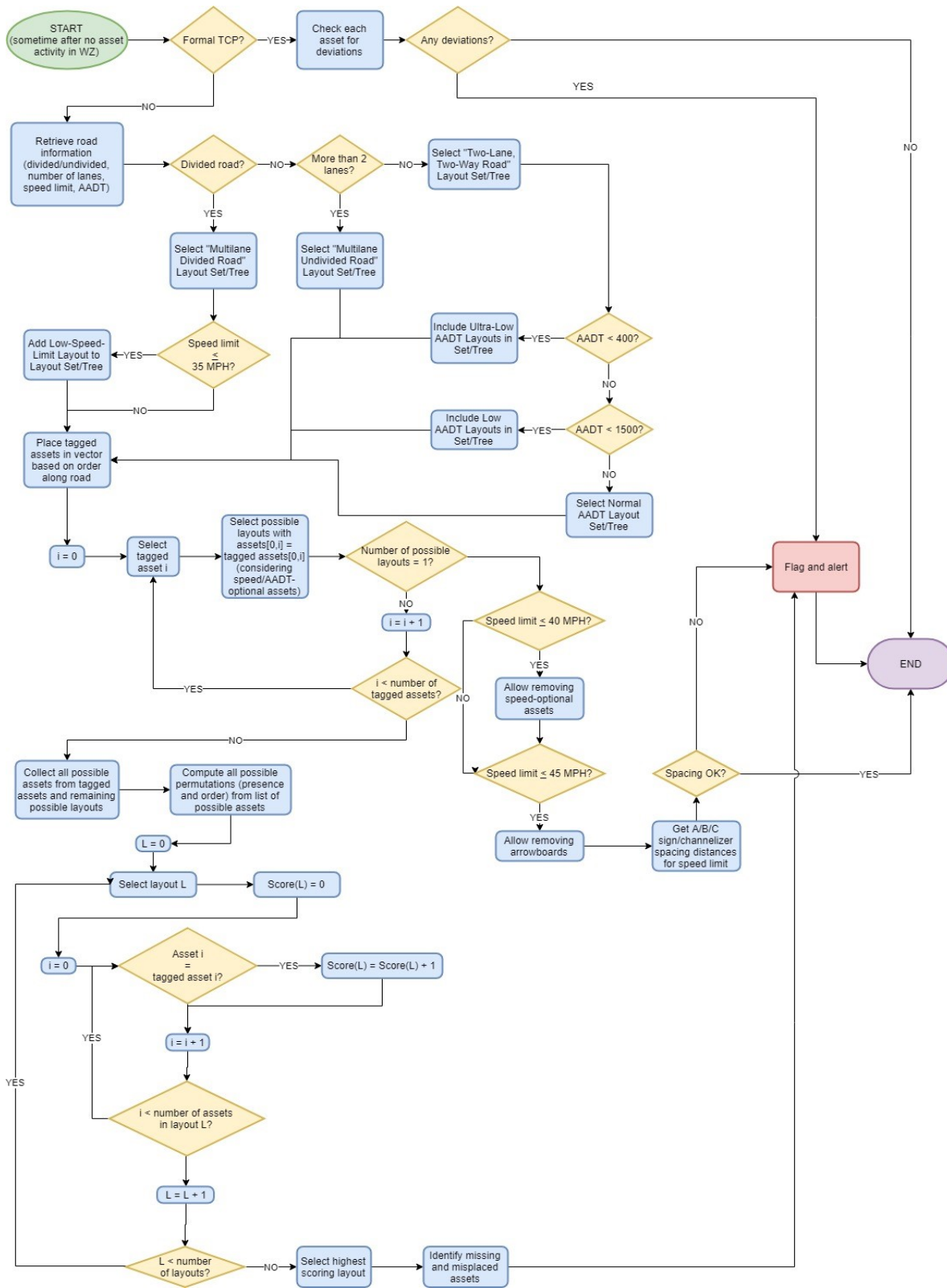
Figure 4.10 SWIS Inspection algorithm

Once the search has been refined by road type (and whether or not the road has a low AADT), to find the correct layout, all signs in the work zone are placed into a vector in the order in which they would be encountered by the driver. This vector is specific to the direction of travel on multilane roads. The tree of layout options is stored in the system based on the order of these signs, with each sign position leading to a number of branches on the tree depending on what sign is in that place. Cases of optional signs for low AADT or low-speed roads also included as options for following a certain path through the tree, which require checking the AADT or speed when these decisions are encountered. The two parameters that determine which is the appropriate MUTCD layout for a specific roadway are the AADT and normal speed limit of that roadway before the work zone implementation. The AADT describes how many drivers will be influenced by the work zone and determines if TCDs need to be added to deal with potential queues and/or vehicles having intersecting paths. The speed is the main factor that determines the spacing between TCD, especially in the advanced warning area. Speed also influences the number of TCD in the advanced warning area; higher speeds lead to more warnings leads to a longer advanced warning area. As each sign is examined, it triggers a test that will direct it along a branch.

When the signs are laid out in the correct order, it is relatively easy to search through the tree, as each sign encountered will have a possible option at that point in the tree. The system may then continue along the path until all signs have been processed, all options evaluated, and a single layout remains. Each layout contains objects representing the signs and channelizing devices that should be part of that layout, which will be the same as those encountered while the system searched through the tree. Each asset also has a set of options for the distance from the upstream sign at which it should be placed, based on the speed limit of the road. Once a layout is selected, both the order of signs and the actual distances between the signs are evaluated (within an allowable distance error threshold) to determine if the layout is correct. If the layout is incorrect, the violation is flagged in the system and highlighted in the interface. Manual inspection of the site is then required.

In situations where the signs are not laid out in the correct order, the process is more complicated. If a decision in the tree is encountered for which no option fits the actual sign in that location, it triggers a more exhaustive search of permutations of the actual layout through the possible remaining options in the tree. This is achieved by generating all of the possible sign permutations given the signs in the field, as well as any signs not in the field that are allowed by the remaining layout options, then testing them against the possible options until a matching layout is found. Because of the relatively small number of signs that would be encountered in work zones that are inspected using this methodology, which by definition are fairly small, all possible permutations of the work zone would not be especially large. This may still fail in some situations, resulting in one of several layouts still remaining as a possibility despite running out of options to test, however those situations would generally involve a traffic control layout that is incorrect for several reasons, like mixing signs from different layouts. If the search is successful, the sign order, omission, or addition mistake is recorded, distances between assets are tested, and the problems with the layout are flagged in the system and highlighted in the GUI.

In cases where there is a formal traffic control plan that can be associated with the work zone in the field, which can be done based on the stored traffic control plans in the system database, their intended

location in the real world, and the project schedules, the inspection process is much simpler. In these cases, any deviation from the traffic control plan beyond a small distance threshold is flagged as a violation. This greatly simplifies the search for larger work zones, which using the aforementioned methodology might cause an excessively large search space that may take a very long time to work through. In addition to this, a formal traffic control plan may have one or more approved deviations from the MUTCD because of special conditions on the road. Because the process for planning a work zone requires many people to approve of the plans, however, it can be assumed that these deviations are safe. This assumption helps avoid additional difficulty in the layout selection process.

4.3 SWIS API

The SWIS API acts as an intermediary between project data on the server and project data in the user interface. Primarily, the API allows for authorized users of SWIS to create new projects and retrieve active (present), past, and future projects. This is done through three access points: retrieving active or inactive projects and creating projects.

4.3.1 Retrieve Active Project API

The retrieve active project API access point is used when a user first navigates to the SWIS user interface or when a project has been updated and its data needs to be pushed to the user interface. For the first case, a request is sent to the SWIS server to return all active projects. After verifying that the user is authorized to view projects, SWIS will return all active projects through the API. For the second case, the ID of the project is included in the request to the server. Once the user is authorized, SWIS will return data corresponding with the ID of the project. Figure 4.11 depicts this process as a flowchart.
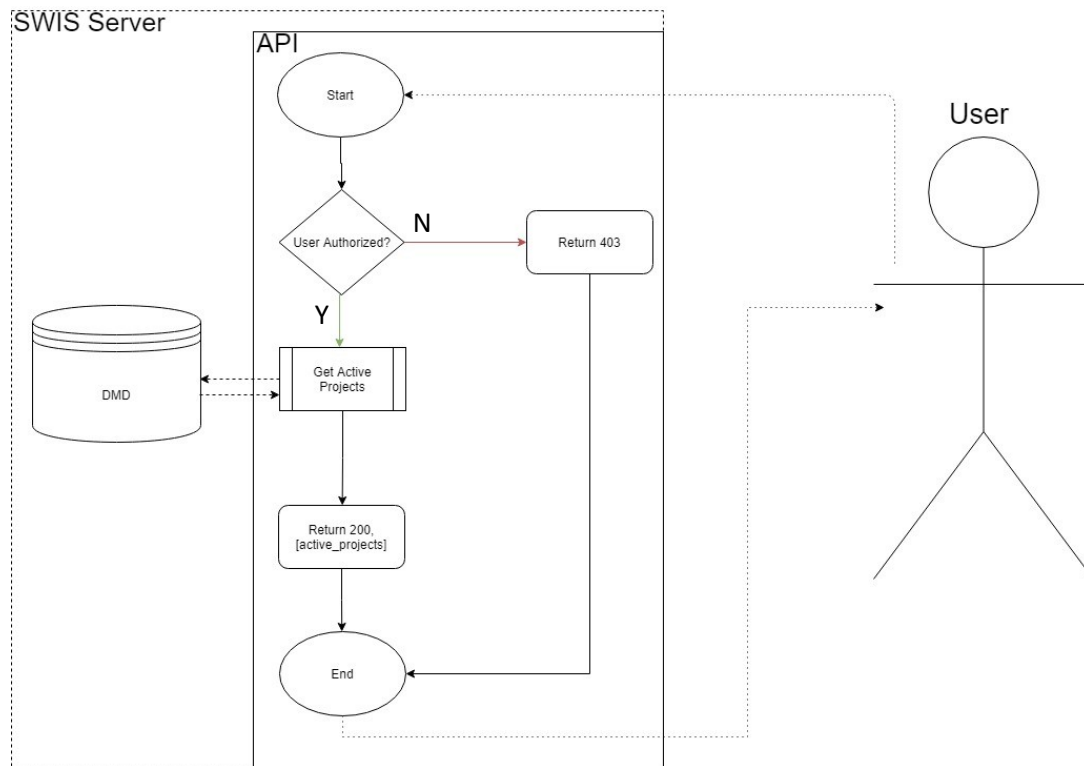
Figure 4.11 Retrieving an active project by an authorized user with SWIS API

4.3.2 Retrieve Inactive Project API Access Point

The retrieve inactive project API endpoint is used when a user wishes to view projects within a certain date range, past, present or future. In the SWIS user interface, this is possible in the chronological view, wherein users select a range of dates past, present or future to view. The user can also specify project level criteria such as name, location, or whether the project was planned or unplanned. A request is sent to the SWIS server once the user specifies the date range within the chronological project view. After verifying that the user is authorized to use this functionality, SWIS determines if the date range passed by the user includes active projects, inactive projects, or both. If the date range only includes active projects, SWIS searches for them in the DMD. If the date range only includes inactive projects, SWIS searches for them in the core database. If the date range includes both active and inactive projects, SWIS searches for the projects in both databases. Once the list of all projects within the date range is retrieved, they are filtered by the project level criteria specified by the user. Once filtering is complete, SWIS will return all projects that meet the criteria of the request. Figure 4.12 shows this process as a flowchart.
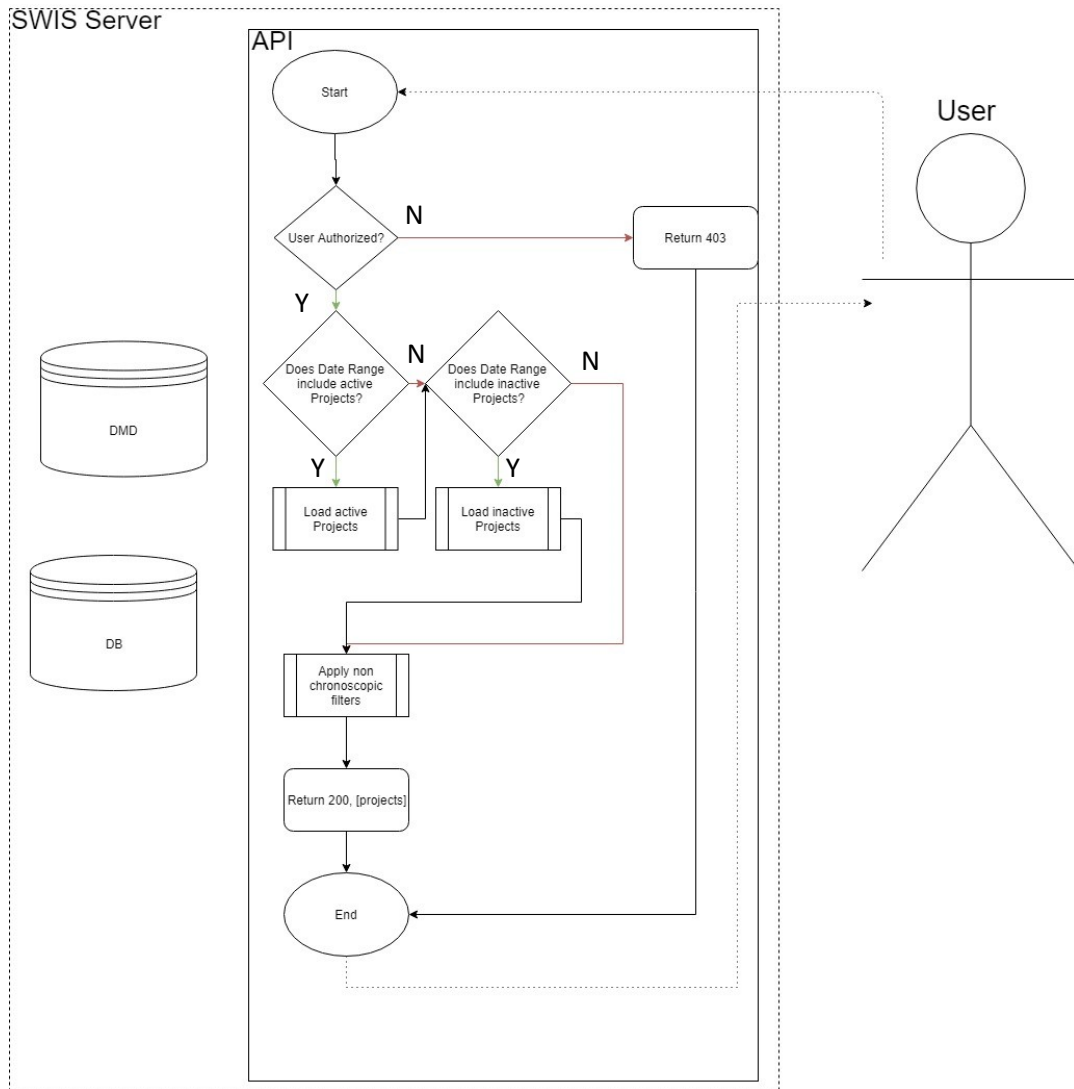
Figure 4.12 Retrieving a planned project with SWIS API

4.3.3 Create Project API Endpoint

The create project API endpoint is used when a user creates a project within the SWIS user interface. After verifying that the user is authorized to create new projects, SWIS will then check if the project should be loaded into the dynamic memory database or saved directly to the database by seeing if it is scheduled to begin in the next 30 days. If this is the case, the project is saved in the dynamic memory database. If this is not the case, the project is saved in the database. Once this is done, a message is returned to the user through the API that the project has successfully been saved. Figure 4.13 shows this process as a flowchart.
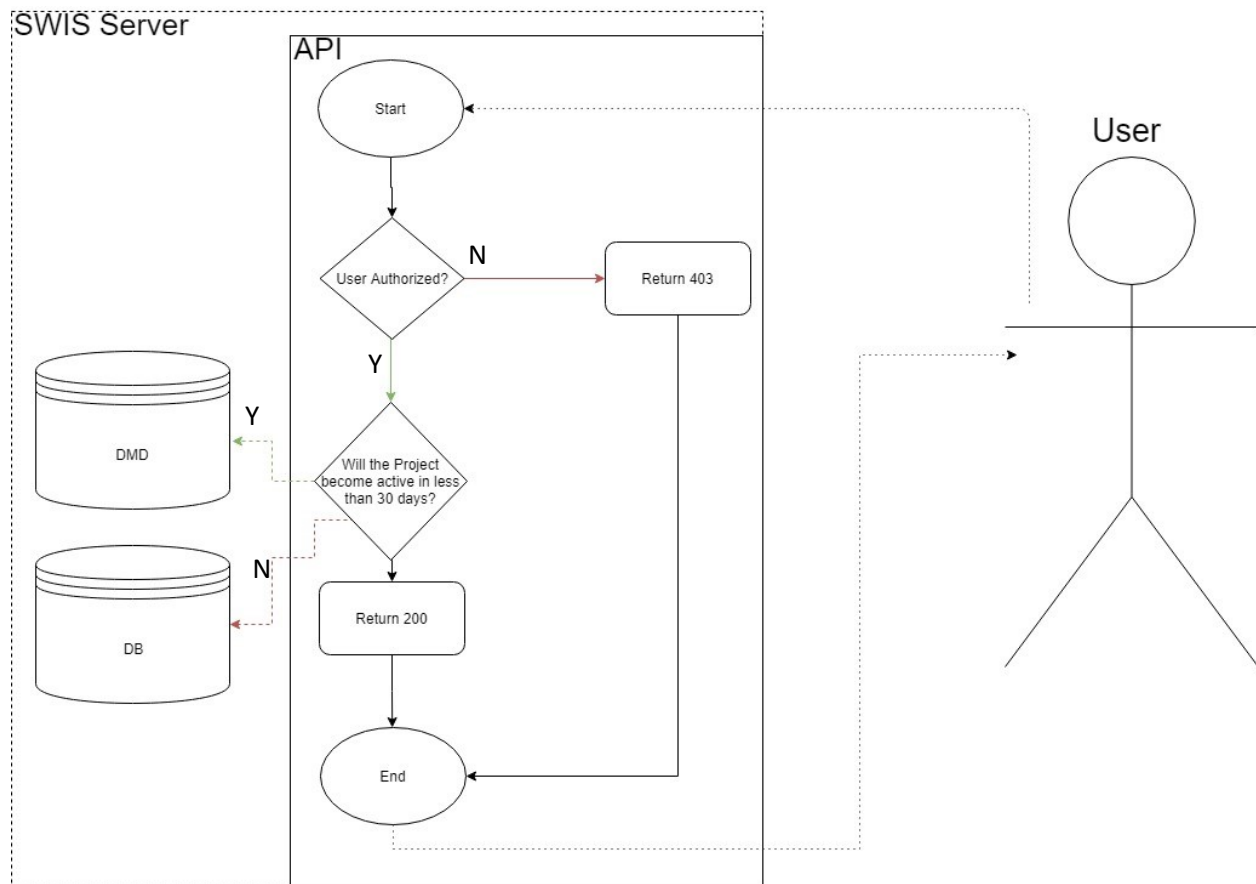
Figure 4.13 Creating a project with SWIS API

CHAPTER 5: USER GUIDE AND EXAMPLE SCENARIOS

This section will discuss the administrative and installation guide to SWIS, as well as examples of use scenarios and a general user's manual for the web interface.

5.1 ADMINISTRATIVE AND INSTALLATION GUIDE

SWIS is a client/server Internet of Things (IoT) driven system. The client component is written in JavaScript while the server and Internet of Things components are written in Python. Data pertaining to projects and system configuration are stored in a SQL database which is acted on by the SWIS server. The client is responsible for displaying project data for users and the server is responsible for work zone layout inspection, communication with deployed assets (IoT location aware beacons), as well as hosting and transmitting project data. The location-aware beacons are responsible for describing the layout of active work zones. Please see Appendix A for a full administrative and installation guide.

5.2 EXAMPLE USE SCENARIOS

Three use case scenarios are presented, highlighting the functionalities of the SWIS web interface.

5.2.1 Scenario One – Real-time project view

This scenario is from the viewpoint of a user logged into the SWIS web interface, with authorization to edit a work zone. Figure 5.1 shows the general SWIS web interface, after a user has logged in (if required, depending on the level of permissions granted.) At this point, no work in the area of the map shown in the user interface is occurring, so no TCDs have appeared in SWIS.
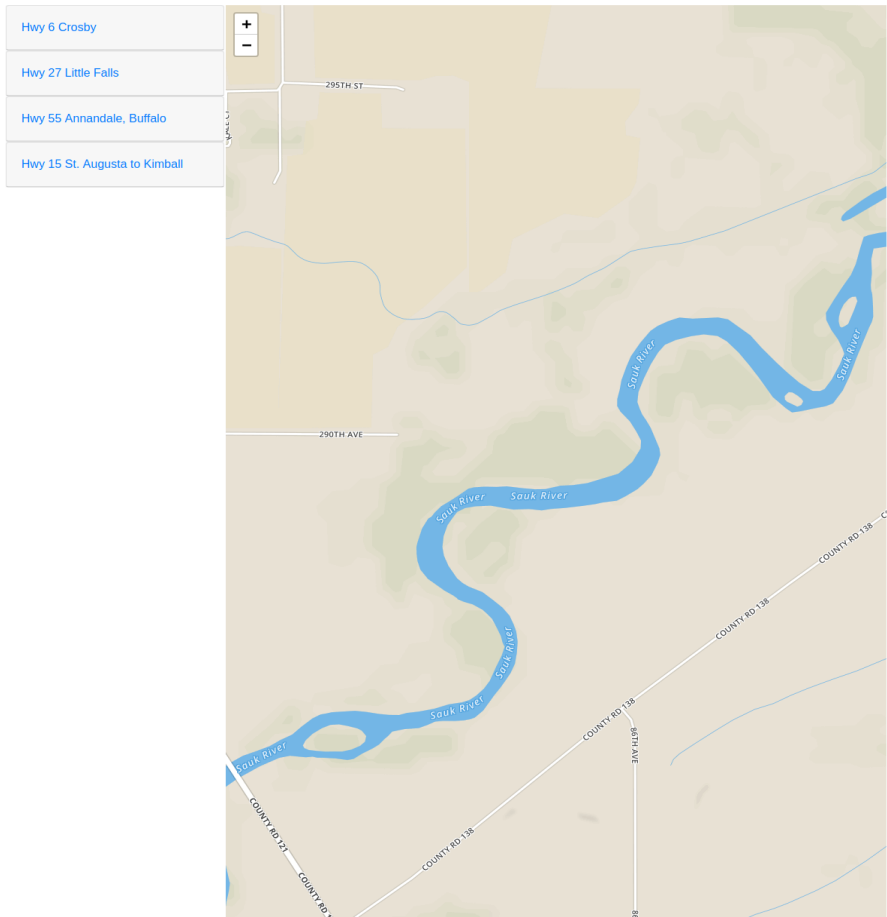
Figure 5.1 SWIS Web Interface

The list of currently SWIS projects can be seen to the left of Figure 5.1. For this use scenario, a new project is beginning in Stearns County, on CSAH 138. TCDs have been dropped by the crew, and begin to appear in SWIS both as an active Project to the left ("Stearns County CSAH138") and beacon icons on the map, as shown in Figure 5.2.

Statewide Work Zone Information System

v7.10

Hwy 6 Crosby

Hwy 27 Little Falls

Hwy 55 Annandale, Buffalo

Hwy 15 St. Augusta to Kimball

Stearns County CSAH138

Description

Project on route Stearns County
CSAH138 created by SWIS

Start Date

2019-05-06

End Date

2019-05-09

Location

route	milepoint
Stearns County CSAH138	start: 0.0000000 end: 3.74311

⊟ Traffic Control Plans

  ⊟ T:2019-05-06_2019-05-09

Source

origin	creator
SWIS	

  ⊟ Work Zones

    ⊟ WZ:0.0000000_3.42308

Location

route	milepoint
Stearns County CSAH138	start: 0.0000000 end: 3.42308

  ⊟ Assets

W20_1
Milepoint: 002+00.777

W20-4
Milepoint: 002+00.918

W3-4
Milepoint: 003+00.055

W20-7
Milepoint: 003+00.196

Figure 5.2 New project appearing on SWIS

As the crew continues to place beacons, they appear in SWIS. Figure 5.3 shows the project with all beacons placed and active in the SWIS system.

Figure 5.3 New project on SWIS, all beacons active

Users may select beacons once they are active in SWIS, to see more information about any violations SWIS has detected. Figure 5.4 shows a beacon selected, with an active violation ("Work Zone Boundary Violation"). The selected beacon is circled in red, and the menu on the left has changed to reflect the

45

selected beacon. Figure 5.5 shows a user double clicking a beacon, creating a pop out menu with more information on the status of the device.
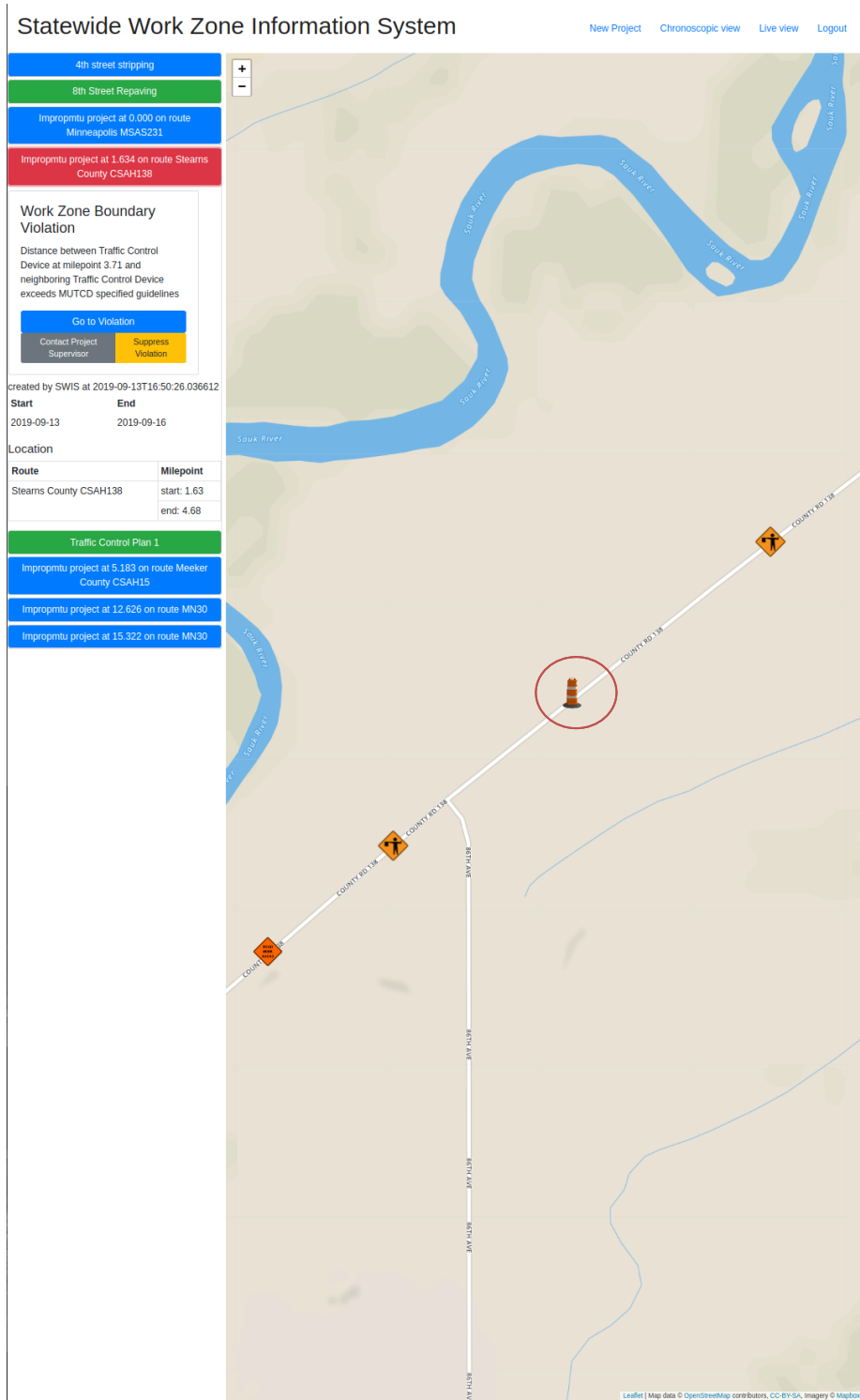

Statewide Work Zone Information System

New Project   Chronoscopic view   Live view   Logout

4th street stripping

8th Street Repaving

Impropmtu project at 0.000 on route Minneapolis MSAS231

Impropmtu project at 1.634 on route Stearns County CSAH138

Work Zone Boundary Violation

Distance between Traffic Control Device at milepoint 3.71 and neighboring Traffic Control Device exceeds MUTCD specified guidelines

Go to Violation

Contact Project Supervisor   Suppress Violation

created by SWIS at 2019-09-13T16:50:26.036612

Start	End
2019-09-13	2019-09-16

Location

Route	Milepoint
Stearns County CSAH138	start: 1.63
	end: 4.68

Traffic Control Plan 1

Impropmtu project at 5.183 on route Meeker County CSAH15

Impropmtu project at 12.626 on route MN30

Impropmtu project at 15.322 on route MN30

Leaflet | Map data © OpenStreetMap contributors, CC-BY-SA, Imagery © Mapbox

Figure 5.4 Beacon selected; violation listed

46

Figure 5.5 Details about beacon

5.2.2 Scenario Two – Different views of SWIS

If a user does not know the title of the project, or wishes to see projects around the state, they may zoom out to a higher-level view. Figure 5.6 depicts all five active projects in this example of SWIS. The circles indicate a project site; the number indicates the number of beacons at that site. The selected project, still Stearns County CSAH138, is green, while the unselected projects are yellow.
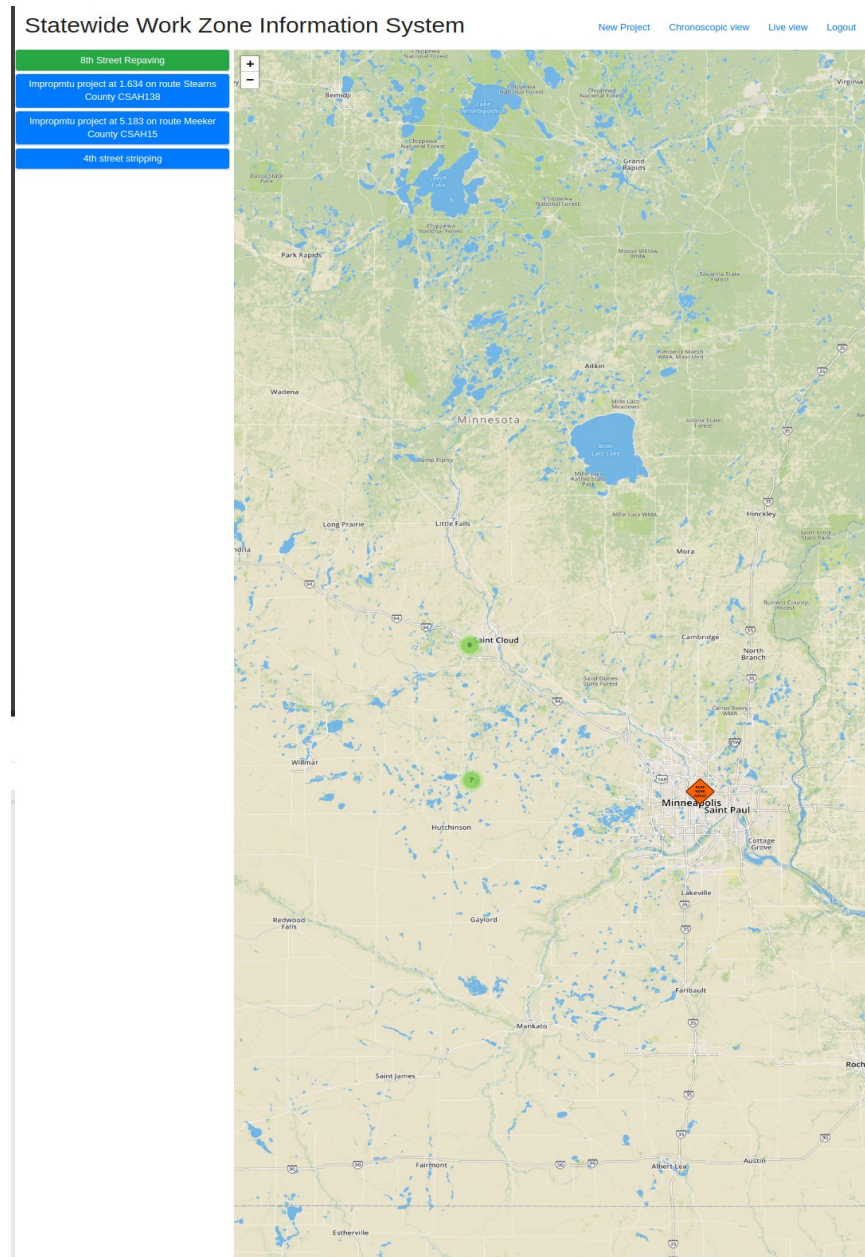
Figure 5.6 Zoomed out view of SWIS

As users zoom into a project of interest, the circle will split into smaller groups of beacons. When zoomed in all the way on a project, beacons will appear individually, as in Figure 5.3.
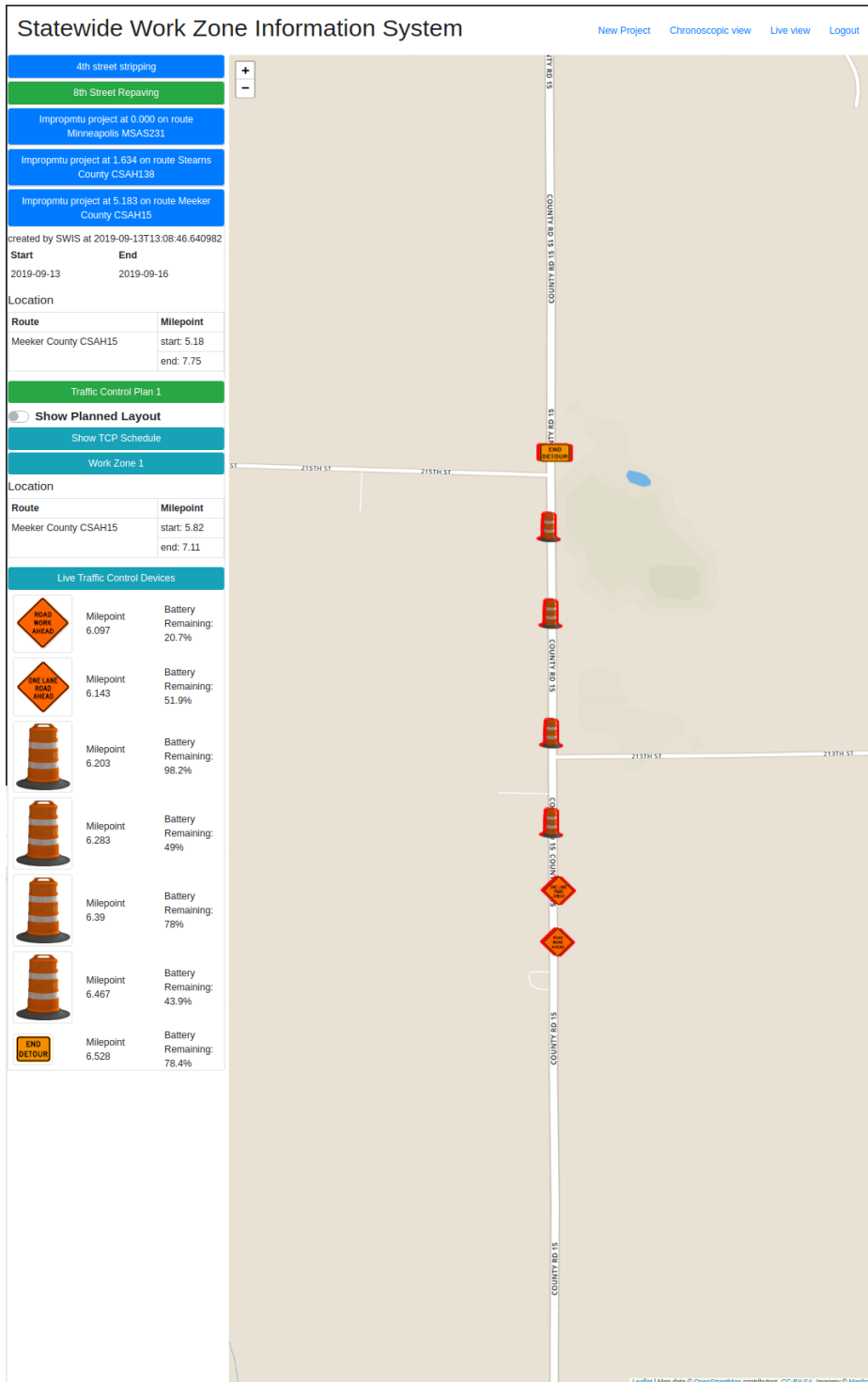
Figure 5.7 Zoomed in view on a project

In addition to real time project views, SWIS users can access the chronological view to see historical project data stored in SWIS. Figure 5.8 depicts the chronological view, titled "Chronoscopic View" in the GUI option.
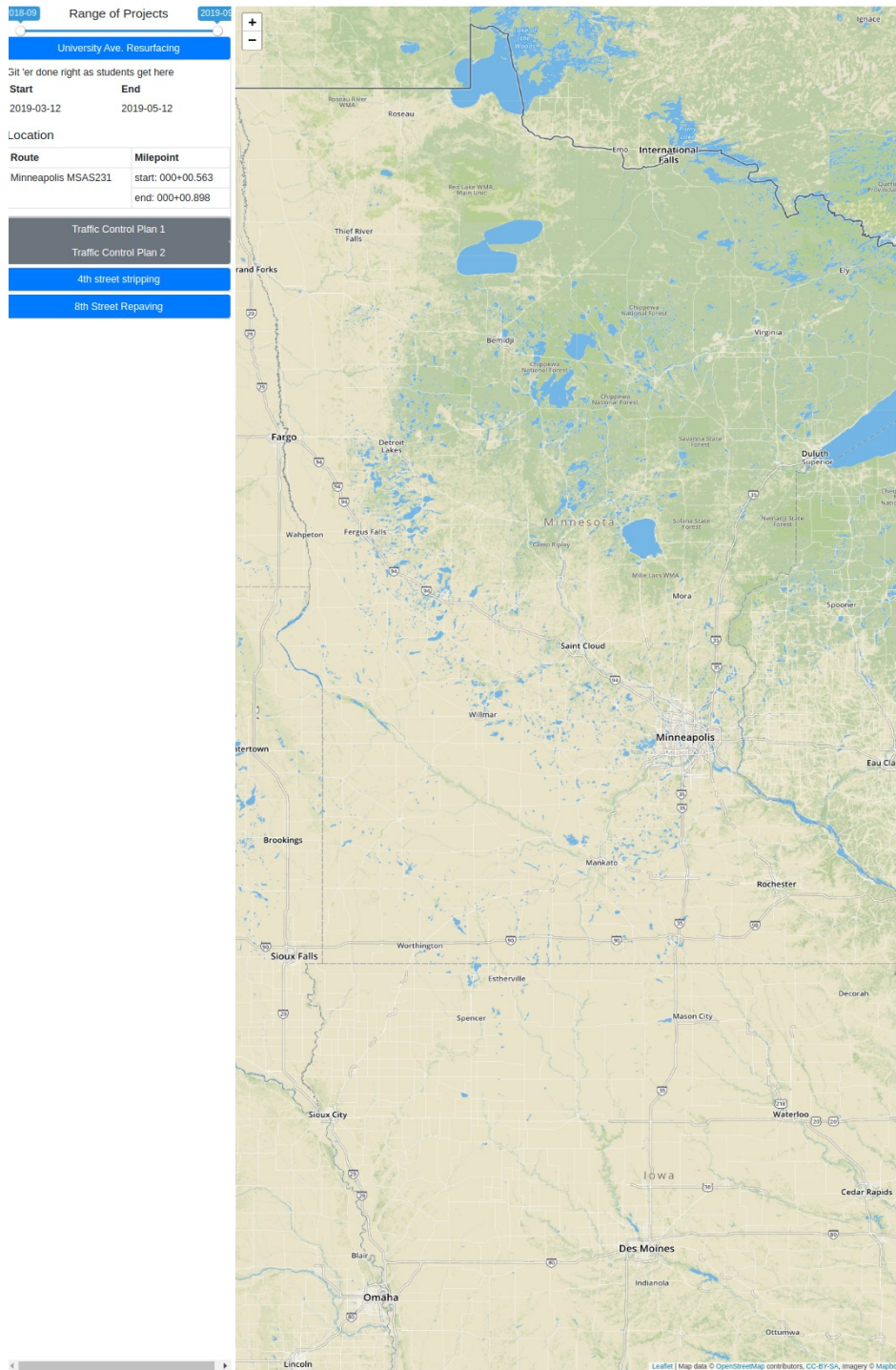
Figure 5.8 Chronological "Chronoscopic" view

In the chronological view, users can move the blue slider above the projects list to a desired date range. As the slider is moved, the list of projects active in that time range will appear. Figure 5.9 shows a user selecting a historic project. Note the beacons are not tracked, as the project is no longer active.
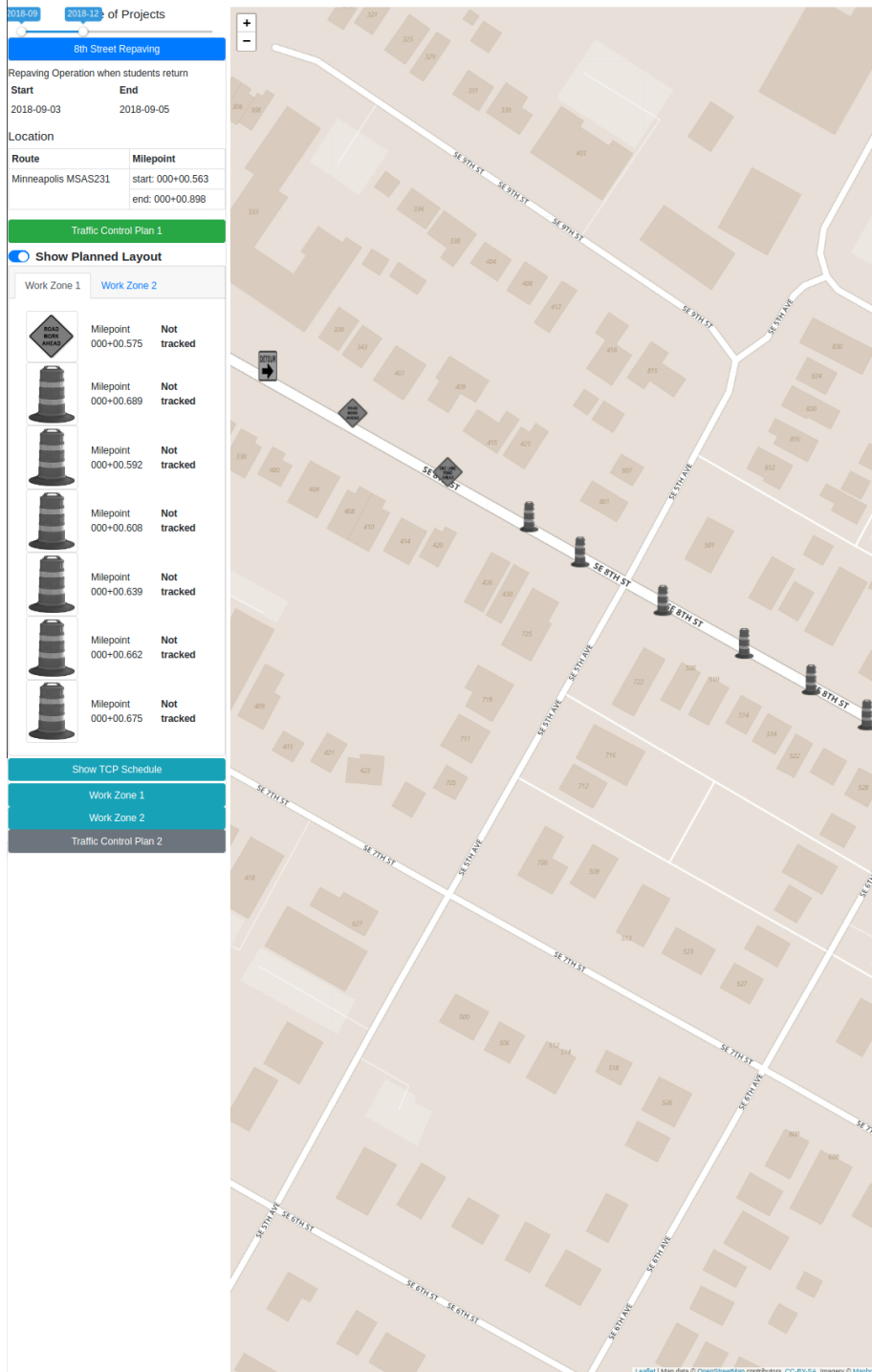
Figure 5.9 Chronological "Chronoscopic" view, date range narrowed

5.2.3 Scenario three — Creating a Project in SWIS

Users with appropriate permissions can create projects directly in SWIS. Figure 5.10 is the project creation screen, where users can enter the project name and description, and add traffic control plans and work zones to the project layout.

Figure 5.10 New Project Creation Screen

When creating a new TCP, users will select the start and end date of the project, then add beacons to the project by clicking "Edit TCP". Users will select whether or not this TCP is the default condition for the roadway. The default condition toggle indicates that the TCP being created symbolizes the road's default traffic control. Users will set the schedule for the project, year and month active, days of the week active, and any days that are to be excluded from the TCP. Users can select "validate schedule" to see a pop up calendar verifying the days the TCP will be active. Users then create the work zone layout by selecting TCDs to place on the map. These may be dragged and dropped onto the map, and then finely adjusted by milepost. When placing the start and end TCDs, users will select "set start TCD" and "set end TCD" respectively. Once the work zone layout is complete, users select "save project". Note that users are responsible for the work zone's design and compliance with MUTCD standards; SWIS does not check compliance.

CHAPTER 6: CONCLUSIONS AND FUTURE WORK

This report describes the design of a real-time, remote system for organizing, monitoring, and inspecting roadway work zones. The need for such a system arose from the development of wireless, driver-warning beacons that broadcast safety advice to vehicles approaching a work zone. Such warning beacons rely on a cloud-based repository, relating their IDs to appropriate warning messages sent to drivers' cellphones. The original concept of these Bluetooth beacons required that their location and registration in the system be carried out by the work zone crew. MnDOT engineers raised the concern that any such method would meet resistance from work crews, and advised a creating beacons that could be deployed without any extra work on behalf of the crew. To address this concern and capitalize on the recent advancements of IoT devices and wireless connectivity, the research team designed and developed completely autonomous beacons that determine their location through GPS technology and transmit it over regular cellular networks. Knowing the device locations and movement enabled remote monitoring and inspection possibilities. SWIS started as a simple cloud-based database of work-zone beacons and evolved into a fully functional work zone operation and control application.

The currently delivered system has all the features described in this report. The most advanced concepts are its ability to automatically decipher the work-zone boundaries and MUTCD or pre-approved layout, and conduct automatic inspections for safety and operational compliance. SWIS also serves as a provider of traveler information on roadway work zones, which is a major piece of information needed by 511 and other systems, which currently deliver information to users as the systems are manually updated.

While SWIS was built with considerable attention paid to complying with traffic engineering and traffic operations practice, it will not be considered a finished product until it is tested in actual practice. Following system demonstrations provided to MnDOT and other DOTs, the development team will seek to conduct a large field operational test where several real work zones will be outfitted with SWIS beacons and have their assets tracked and inspected by the system.

Tests and deployments during system development have helped eliminate hardware and software issues. However, since only a small number of beacons have been constructed and testing has taken place in urban areas, a claim cannot be made that all issues have been detected and resolved. The envisioned field operational test will address potential issues related to GPS accuracy/drift, cellular network availability, undocumented deployment practices, and accuracy of the state's road database. SWIS success will depend on addressing all of these issues in order to retrieve route, mile-point, and speed information, as well as to gain acceptance from the industry.

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APPENDIX A

INSTALLATION AND ADMINISTRATIVE GUIDE

Data Standards

- JSON: The system uses JavaScript Object Notation (JSON) to transmit data.
- WGS84: This geodetic datum is used by the System's beacons to describe their location and the client side map to express location
- NAD83: This geodetic datum is used by SWIS's functions to retrieve route data from MnDOT and is used by MnDOT Temporary Traffic Control Plans to express work zone setup
- REST: The SWIS server follows a Representational State Transfer (REST) architecture
- ISO 8601: The system expresses date and time in the format described in ISO standard 8601 so that it is in a readable unambiguous format.

Server Set Up

This is a guide for setting up the SWIS server.

OPERATING SYSTEM

The SWIS server was written to be run on a machine running a Linux Kernel. The server can be run on kernels derived from Windows and Unix systems, but procedures may vary slightly. The machine should have a minimum of 2 GB of RAM and 16 GB of hard drive storage space. SWIS's Server has a GUI, but it is not used in the instillation and is accessed remotely, meaning the host can be set up heedlessly.

Once the Linux Kernel derived operating system is installed on the server and connected to the internet, obtain the hostname of the machine. It is required for configuration of the server in the following steps.

INSTALLING CRITICAL PACKAGES

Before downloading the SWIS source code, the newly configured machine will need some packages installed. From anywhere in a terminal, run the following commands:

sudo apt-get update && sudo apt-get upgrade

sudo apt-get install git python3-pip python3-dev python3-venv libpq-dev postgresql postgresql-contrib

CLONING THE SWIS REPOSITORY GIT CLONE

Download the SWIS package from github in terminal by navigating to the directory you wish to install SWIS in and typing the command:

git clone <URL-Of-SWIS-Repository>

CREATING SWIS VIRTUAL ENVIRONMENT; INSTALLING SWIS DEPENDENCIES

Next, set up a python virtual environment so that dependencies using the python package manager (pip) can be isolated and managed. From terminal, type the command:

python3 -m venv </path/to/SWIS/virtual/environment>

Once created, the virtual environment will need to be activated. From terminal, type the command:

source </path/to/SWIS/virtual/environment>/bin/activate

Once activated, navigate to the setup directory within the SWIS directory that was cloned in the previous step. From that directory, type the command:

pip3 install -r requirements.txt

This command will install the rest of the dependencies necessary to run SWIS in the virtual environment, including Django, djangorestframework, and the psycopg2-binary.

Initializing and Pre-Populating the SWIS Database

Once the dependencies for the server have been set up, the system's database can be initialized. From terminal, type the following commands.

sudo su - postgres

psql

These commands start a shell session from which a database for SWIS can be created. Typing the next command will create SWIS's database.

CREATE DATABASE swis;

Once the database is created, it will need a user account allowed to connect and interact with it. This is done by executing the command:

CREATE USER <name_of_user> WITH PASSWORD '<password>';

After creating this user, it will need some of its default parameters modified. This is done through the following commands:

ALTER ROLE <name_of_user> SET client_encoding TO 'utf8';

ALTER ROLE <name_of_user> SET default_transaction_isolation TO 'read committed';

ALTER ROLE <name_of_user> SET timezone TO 'UTC';

Finally, the user will need to have database access rights. This is done by typing:

GRANT ALL PRIVILEGES ON DATABASE swis TO <name_of_user>;

Now that the database has been created, navigate to SWIS's settings.py file. In the DATABASES section of the file, change the user and password fields to match the credentials specified in the postgres shell session. Navigate back to the top of the SWIS directory and type the command:

python3 manage.py migrate

The database has now been initialized for the SWIS server. To ensure that conflicts do not occur with previously existing content navigate to the top of the SWIS directory and begin a python shell session. This is done by running the command:

python3 manage.py shell

Once inside the shell session, type the following python commands:

from django.contrib.contenttypes.models import ContentType

ContentType.objects.all().delete()

quit()

Once cleared we can populate the database with icon and project data. Run the following command from the setup directory within the SWIS directory:

python3 manage.py loaddata devicedump.json Icons.json ttc.json

Creating an Administrator Account to Access the Server GUI

To create a user who can log into the admin site, run the following command from the top of the SWIS directory and fill in the prompted information:

python3 manage.py createsuperuser

Starting the SWIS Server

Navigate to SWIS's settings.py file. In the ALLOWED_HOSTS list, enter the host/domain name of the server obtained in step 4.2.1. Exit the file and start the server by running the command:

python3 manage.py runserver

SWIS should now be accessible from the domain name specified. To access the client, follow the domain name with/SWISApp. To access the admin GUI of the server, follow the domain name with /admin.