



# Portable, Non-Intrusive Advance Warning Devices for Work Zones with or without Flag Operators

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John Hourdos, Principal Investigator  
Minnesota Traffic Observatory  
Department of Civil Engineering  
University of Minnesota

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*Prepared by:*

John Hourdos

Minnesota Traffic Observatory  
Department of Civil Engineering  
University of Minnesota

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## Executive Summary

Highway work zone safety is a major concern for government agencies, the legislature, and the traveling public. Studies have shown that drivers can disregard or ignore work zone traffic control devices, and other driver warning information systems. Many of the crashes near work zone areas occur when drivers who have failed to take heed of other traffic warning and control measures upstream of the work zone area intrude into the work zone. This project operating under the premise that if a sufficient, obvious and directed warning is delivered to such drivers, dangerous situations such as these could be reduced, and thereby reduce risk of serious accidents. This project aimed to develop and test a low-cost rapidly deployable Intelligent Drum Line (IDL) prototype that sends an audible warning to alert motorists traveling at dangerous speeds near highway work-zones.

In cooperation with MnDOT engineers, the IDL system developed is comprised of two instrumented work zone drums. The drums, integrate four main subsystems; sensor, audible warning, visual warning, and communications. These subsystems are under the control of the Central Processing Unit (CPU) and powered by an appropriate 12V battery. The sensor subsystem is responsible for measuring the speed of the oncoming vehicles and for detecting the location of the vehicle in respect to the each of the drums. The audible warning system is comprised of a powerful air horn mounted inside the drum and designed in such a way that the sound force is mainly directed toward the roadway while sound is suppressed in all other directions. The horn produces 120db warnings 5 feet from the drum in the road direction while the sound level does not exceed 85db in any other direction. The visual warning is delivered through a number of emergency flasher units mounted on the outside of the drum and appropriately directed toward the approaching vehicles. The communication between the IDL system drums and other components is achieved with the use of XBEE IEEE 802.15.4 radios operating in a preselected channel. Prototypes of the IDL system were developed that can operate in two separate modes, single- and dual-drum versions. The cost of the single-drum prototype is estimated at around \$1,100 while the second drum costs an additional \$800 since it does not include a radar sensor. These costs are based on single over-the-counter components and can be reduced to approximately half if sufficiently large numbers of components are purchased specifically in the case of the flashers, which ended up being approximately 50% of the price.

The system was tested only under simulated conditions, with vehicles ranging from small to large. The conditions were simulated since the drivers were aware of the system beforehand and were not located upstream of an actual work zone. Limited testing was conducted in case the drivers were unaware of the system, but again, not in conjunction with actual work zone operations. Based on the recommendations of the test subjects, the dual-drum version is recommended since the presence of the second drum reinforces the warning and therefore produces a more successful operation.



**IDL Testing and Demo at MnROAD**



# Chapter 1. Introduction

Highway work zone safety is a major concern for government agencies, the legislature, and the traveling public. Studies have shown that drivers can disregard or ignore work zone traffic control devices, and other driver warning information systems. This in turn has led to serious accidents when unprepared drivers intrude into work zone areas during an evasive maneuver to avoid a crash, or as a result of a crash next to the work zone area. On average over the last five years, there have been over 1,150 roadside work zone related deaths. Mohan and Guatam (2002) estimated over 26,000 lost day injuries resulted in a total cost of \$2.46 billion alone. Highway work zone fatalities per billion dollars spent cost at least four times more than in total U.S. construction. Many of the crashes near work zone areas occur when drivers who have failed to take heed of other traffic warning and control measures upstream of the work zone area intrude into the work zone area. This project operating under the premise that if a sufficient, ‘obvious and directed’ warning is delivered to such drivers, dangerous situations such as these could be reduced, thereby reduce risk of serious accidents. The aim was in developing and testing a low-cost rapidly deployable “Intelligent Drum” Line prototype that sends an audible warning to alert motorists traveling at dangerous speeds near highway work zones.

## 1.1 Project Scope and Objectives

The scope of this research project is limited to the development of a working prototype of the Intelligent Drum Line (IDL) system that can be field tested under challenging conditions by actual work zone crews and heavy vehicle operators. Developing a device that can pass FHWA crash worthiness tests or a system that can be directly put to production was outside the scope of this project.

The objective of this project was to work closely with MnDOT maintenance personnel to assure that the developed system will be something useable in the field, rugged, and cost effective. The challenge was great since other teams have attempted similar ideas but failed especially in the cost effectiveness part. A major effort in this project was to search and discover cutting edge components that can deliver the desired functionality at a cost that fits the task. The resulting prototype developed and described in this report is the outcome of several trials. Although it is not perfect it is succeeded in proving the concept and highlights the few remaining places where cost effective technology is missing. Hopefully this proof-of-concept prototype will be the catalyst for future technological advancement.

## 1.2 Report Organization

There are five chapters in this project report. Chapter 1 describes the problem addressed, the scope, and the objectives of the overall research project. Chapter 2 describes the concept of operation of the IDL system as well as describes alternative designs that were not promoted to the prototype stage. Chapter 3 describes the result of the intense market search looking for components for the IDL as well as the testing and evaluation of these components. Chapter 4 describes the final prototype, providing details of all components as well as directions on how the system is build and can be replicated. Finally, Chapter 5 describes the remaining issues with the device and proposes potential solutions this project schedule and budget did not allow to explore.

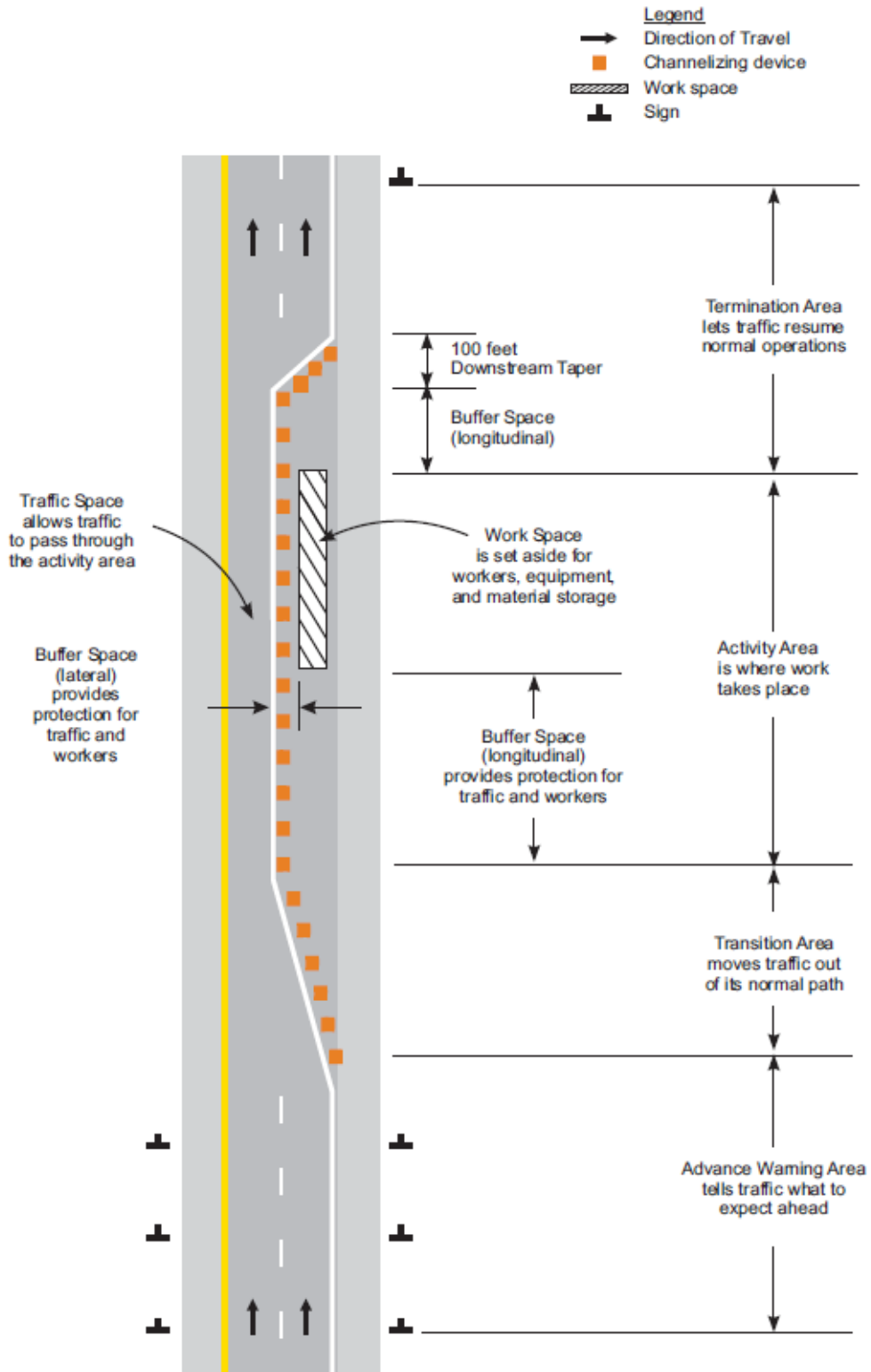
## **Chapter 2. System Design and Functional Requirements**

### **2.1 IDL Design Premise**

Work zones vary in temporal, spatial, and operational characteristics. This project started with a focus on improving the safety of work zone flag operators. Flag operators are predominately involved in small, short duration, moving work zones on two to four lane highways. Most of the effort involved in this project as well as the final prototype was aimed at the aforementioned work zone types. Regardless, different versions of the device could be developed to operate on bigger longer lasting work zones.

In the majority of work zone crashes, the vehicle was driving at speeds that were higher than the ones advised and higher than ones that would have allowed safe stopping or control of the vehicle when it approached the taper line. To explain this better, figure 2.1 referenced from the MN MUTCD, shows the important elements of a work zone. As a vehicle approaches the work zone the first element it passes is the signs along the Advance Warning Area where information of the downstream lane drop or shift is given. This area in the case of work zones with flag operators can range from 250 to 1200 feet depending on the posted speed limit prior to work starting. At the beginning of this area an Advanced Flagger Sign (figure 2-2) is deployed and in effect is the only warning to the drivers that they approach a work zone. Given the plethora of signs drivers encounter all the time it is not a surprise that many times they do not notice the sign and continue driving with the same speed.

With the premise that the drivers often miss the advance information regarding the work zone and fail to slow down as they approach the taper line and the flag operator, the IDL system will provide additional means for attracting the driver's attention. The purpose of the system is to detect vehicles driving at unsafe speeds and target them with active visual and auditory warnings attracting their attention and prompting them to reduce speed prior to reaching the work zone. In addition, given that the device aims to primarily serve small, temporary, possibly moving work zones it also needs to be easy to relocate by a single person charged with the task of moving the various channelizing devices.



**Figure 2.1 Component Parts of a Temporary Traffic Control Zone (Mn MUTCD)**



**Figure 2.2 Advanced Flagger Sign**

## **2.2 Technical Approach**

The warning system described herein consists of two or more primary subsystems: advance drum with speed detection capability and one or more secondary drums for warning message reinforcement. Each of these subsystems can be further divided into sensor, communication, and computation components.

The warning system described herein serves two purposes. First, it is used to collect data that can be used to describe driver compliance with the posted speed limit and to execute threat assessment algorithms. The second purpose is to selectively activate visual and auditory warnings that target the vehicle classified as a threat.

### ***2.2.1 IDL System Requirements***

The primary functional requirements for the IDL system is to provide work zone operators with a cost effective safety system that produces additional and targeted alerts to oncoming vehicles that display signs that they did not notice the Advance Flagger Sign. A successful IDL system will attract the attention of all approaching drivers and prompt them to slow down while simultaneously increase their level of awareness in regards to the upcoming work zone. Given this goal, a specific set of top-level functional requirements can be defined.

#### 2.2.1.1 MUTCD Compatibility

If the IDL is to be deployed, the system must meet MUTCD standards and specifications. Part of these standards is to pass FHWA crashworthiness test. When the device progresses beyond the level of a prototype specific design elements will be implemented to ensure the final system meets the aforementioned criteria.

#### 2.2.1.2 Operational Requirements

From an operational point of view, to be embraced by traffic and highway maintenance engineers, the cost of acquiring, powering, and maintaining the IDL system must be compatible

to that of an automated flagger assistance device or a temporary dynamic speed display system. Specifically, the system must satisfy the following requirements.

- **All Weather Operation.** Although relatively few temporary work zones operate during poor weather conditions it is still possible that poor weather and visibility conditions may develop. An effective system will provide the same level of operation in all weather conditions, and as such, the IDL speed detection and alert subsystems shall operate regardless of weather or visibility conditions.
- **Initial Purchase and Operations Cost.** The IDL system should cost less than the cost to procure and operate an automated flagger system. In addition, given that the system will be deployed in advance of the work zone and be exposed to high-speed traffic it should be expected that soon or later will be hit by a vehicle. The replacement cost of the system should be lower than the replacement cost of a dynamic speed display.
- **Maintenance Requirements.** The system should be designed to be low maintenance. In general the system should require no more attention other than recharging the battery that provides power and replacing it when it becomes depleted.
- **Rough Handling Requirement.** The system should be rugged enough to withstand the same rough handling as other Drum Channelizing devices. All the components should be rigidly placed inside the drum or safely secured and protected if located in the outside of it. There should be no parts that can be detached or misaligned if they fall on the ground from a height equivalent to a maintenance truck cargo bed.
- **Reliability.** The IDL has to be reliable in its warning operation and produce reliable warnings to all speeding vehicles even if it must err on the conservative and some target warnings are directed to vehicles that may not be speeding.
- **Modular Design.** The IDL system should be built with a modular, open architecture. Following these guideline assures the DOT that the system will be upgradeable should improved sensors, computers, alert systems become available.

The next section describes the functional requirements for the IDL system.

#### 2.2.1.3 Functional Requirements

The purpose of the IDL system is to support operations of temporary moving work zones by detecting approaching vehicle speed and if this speed is higher than the desired threshold, target that vehicle with active visual and auditory warnings. This objective dictates several first level functional requirements for the IDL system.

- The warnings need to be such that maximize the potential of attracting the driver's attention without requiring averting his/her attention from the roadway.
- The warnings need to reinforce the message that the vehicle is approaching a work zone and that needs to reduce its speed.
- The system needs to operate at an appropriate distance from the work zone that allows the vehicle to safely reduce speed prior to arrival to the taper line.
- The system needs to be self-powered, with enough capacity to operate successfully for more than a whole day.

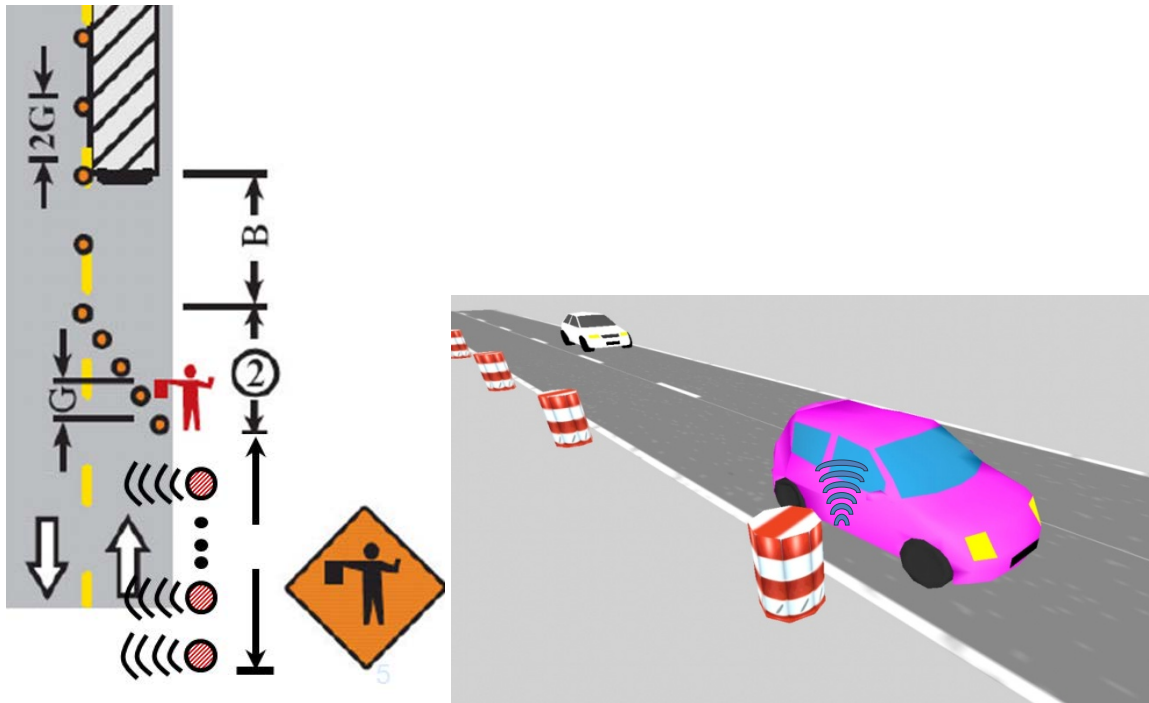
- The system needs to be able to detect speeds of approaching vehicles at a distance that allows the system to generate the aforementioned warnings.
- The system should initiate warnings only in relation to a speeding vehicle and as much as possible minimize the possibility of transmitting a warning to a non-speeding vehicle. This will reduce the noise pollution around the work zone.
- The systems auditory warning needs to be loud enough to penetrate the cab of vehicles as large as a semitrailer or 3-ton truck and be noticeable by the driver.
- The systems auditory warning needs to be directed to the target vehicle and minimize the sound noise directed in all other directions. This would allow for the system to operate in urban settings without causing noise pollution to nearby structures.
- The systems visual warning needs to be noticeable from at least 500 feet distance, bright enough to be clearly visible on a bright sunny day, but also penetrating enough to be effective during low visibility conditions.

Specifically, in regards to temporary moving work zones:

- The system will be used on two-lane roads with speed limits ranging from 50 mph to 60mph. This implies that the system should be able to operate at speeds at least 20 mph higher than that.
- Usually in the intended maintenance operations several Advance Flagger Signs are deployed so as the work zone moves there is always at least one warning sign ~1000 feet upstream of the flag operator position. Considering that the work zone is ~3,000 feet long there will be a need for either the system to advance along with the work zone or multiple sets used as happens now with the warning signs. Therefore, the system needs to be easy to deploy and relocate as the work zone operations progress and allow the operation of more than one system concurrently.
- The system should need only one worker in order to be deployed or relocated. In extend the weight of the system should be such that one person can be able to easily transport one drum for a distance of at least 500 feet.
- The system should be self-contained requiring no assembly on-site.
- The system should require only rough estimates of distances during deployment like the ones that can be made by counting roadway markings.

## **2.3 IDL Conceptual System Design**

Given the aforementioned operational and functional specifications a number of conceptual designs were produced. This section briefly describes the sequence of designs that lead to the final form. The initial envisioned system can be seen in figure 2.3. The idea behind the initial concept was that there would be a number (5-10) of drums deployed in the advanced warning zone each equipped with a simple vehicle detection sensor and an audible warning mechanism. The speed of the vehicle would have been approximated through the detection time difference between the first 2 or 3 drums. The intended result was to generate a sequence of sound warnings resembling the sounds produced by a vehicle traveling over a rumble strip. This concept was quickly abandoned since it violates the functional requirements of portability and deployment by a single person.



**Figure 2.3 IDL First Conceptual Design**

Following discussions with MnDOT maintenance personnel it was decided to reduce the number of drums to at most two. This concept alternative required the use of more sophisticated sensors for measuring the approaching vehicle speed. It also required generating a much more noticeable audible warning since there would be fewer repetitions. Figure 2.4 shows the resulting concept design that moved to the prototype stage.



**Figure 2.4 Dual-drum Version of IDL system**

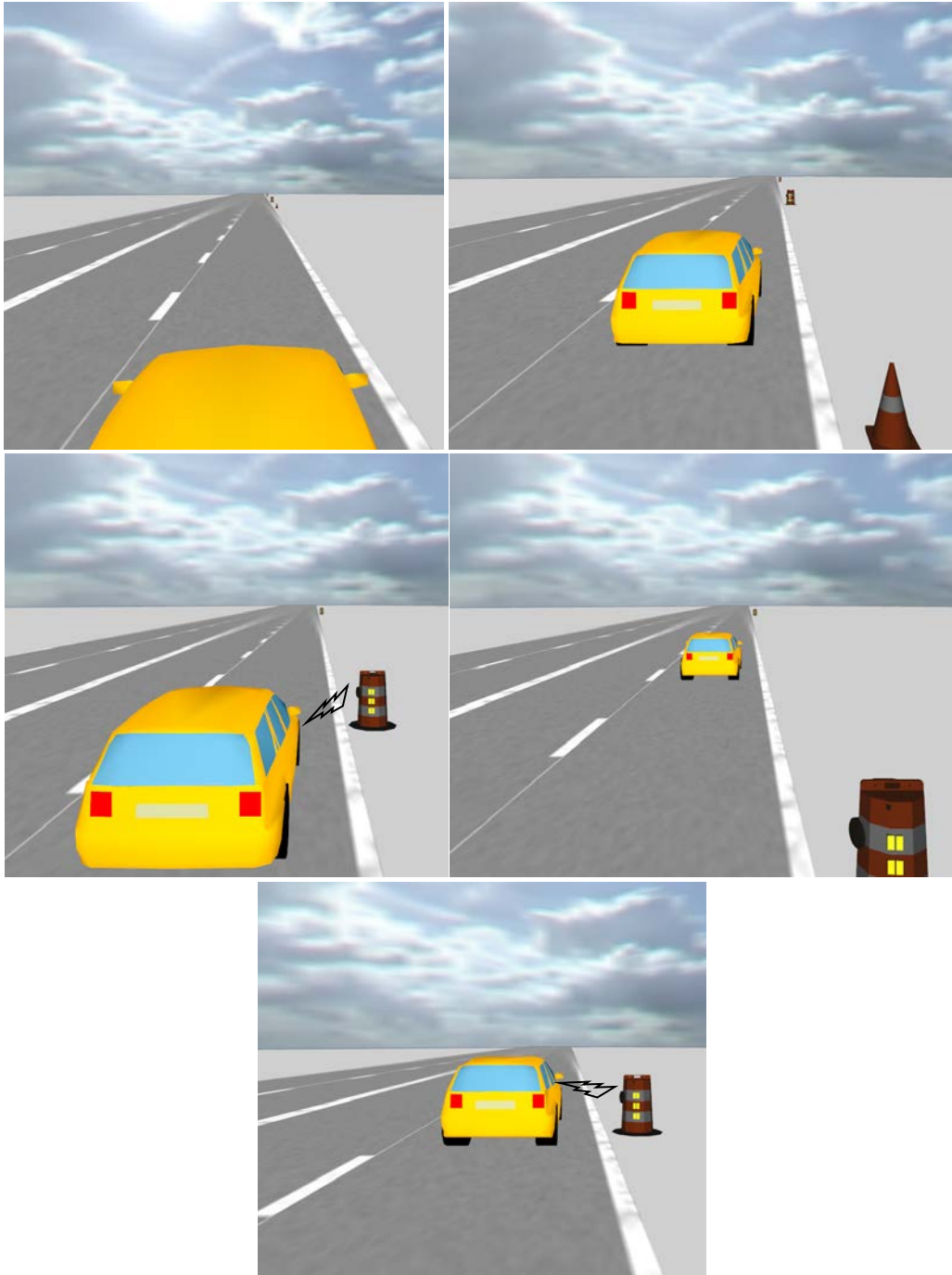
The concept of operation for the resulting IDL system is as follows:

1. The system is comprised by two modified Traffic Drums. The drums are equipped with sensors, communication, and processing components in addition to the auditory and visual warning equipment.

2. The two drums are positioned approximately 300-400 feet apart on the outside of the fog (shoulder) line. The drums should be at least one foot and at most 3 feet away from the fog (shoulder) line.
3. The first drum, in the direction of traffic, is equipped with a vehicle speed sensor. As described in the next chapter several different sensors were tested before selecting a K-Band Doppler radar. The sensor is measuring the speed of the nearest approaching vehicle and transmits the information to the processing unit (CPU).
4. If the speed of the approaching vehicle is higher than the selected threshold three tasks are performed simultaneously
  - a. The visual warning system in the first drum is activated.
  - b. A command is sent over the communication system to the second drum to also activate its visual warning system.
  - c. A countdown is initiated given the vehicle speed and distance. At the end of the countdown the vehicle should be approximately 1 second away from the first drum. At that instance the audible warning is activated.
5. A sensor in the first drum is detecting the presence of the vehicle in front of the drum. As soon as the vehicle has passed the drum the audible warning is terminated. As long as there are no other speeding vehicles following the first drum the visual warning is also deactivated.
6. At the instance when the audible warning in the first drum is terminated a command is transmitted to the second drum that starts a second countdown.
7. Given the last measured speed of the vehicle a calculation takes place in the second drum's CPU estimating the arrival time of the vehicle in the second drum minus one second.
8. At the end of the countdown the audible warning of the second drum is activated and terminated after the presence sensor in the second drum has signaled that the vehicle is no longer in front of the drum.

The aforementioned concept of operations is the ideal one and the one the prototype was based on initially. As it will be discussed later in this document due to the particular speed sensor capabilities, modifications were necessary specifically in the concept of the countdown before the vehicle reaches the first drum. Figure 2.5 shows a sequence of animations showing how the IDL system is viewed from the point of view of the driver.



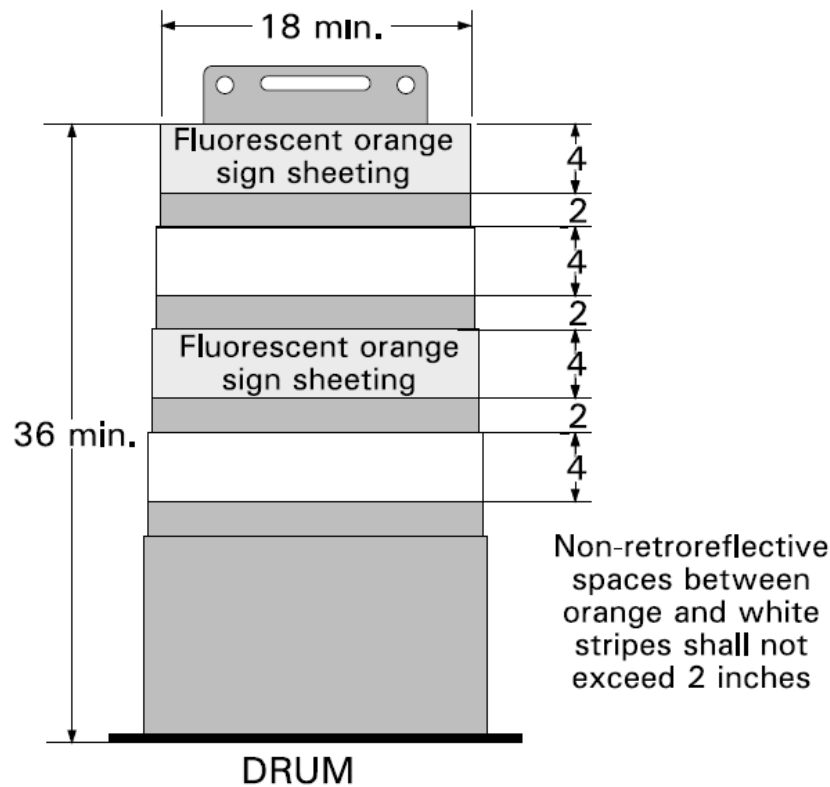


**Figure 2.5 IDL Dual-drum System with Advance Cone Concept of Operation**

# Chapter 3. System Components Testing and Integration

## 3.1 IDL System Subsystems

As discussed in the previous section the IDL system is comprised by four major subsystems; the sensor, the communications, the processing, and the warning subsystems. Each of these subsystems has specific functional requirements depending on the task called to fulfill. The following sections describe the functional specifications for each subsystem and component, the technologies available in the market, the components acquired and tested in the course of this project, and finally the components integrated into the IDL prototype. To provide context for the discussion of the different subsystems it is best to first describe in some detail the actual drum where all the components are going to be mounted and operating from. Figure 3.1 shows the specifications for a MnDOT approved Drum Channelizing Device.



**Figure 3.1 Specifications for a MnDOT Approved Drum Channelizing Device**

Other than the specifications imposed by MnDOT there are no other characteristics the drum is required to have to be a viable components of IDL. All components of the IDL system are mounted on the drum in their intended positions but it is expected that a redesign of the mounting methods would be necessary to proceed beyond the prototype stage. Specifically, the audible warning system would need to be incorporated into the mold of the drum during construction in such a way that components are minimized and detachable pieces are secured and do not detach in the case of a collision with a vehicle. Another part of the drum that will require modifications during construction will be the incorporation of the system battery with the drum

base. Given that the drum will be near the driving lane in roadways with speeds as high as 60mph, the base needs to be sufficiently heavy to prevent the barrel from shifting due to the air currents generated by very large vehicles.

### ***3.1.1 Sensor Subsystem***

In the IDL concept of operation there are two tasks requiring sensing. The first task is the detection of an approaching vehicle and the measurement of its speed. The second task is the detection of the presence of a vehicle in front of each drum for the control of the auditory warning.

Traditional vehicle detection technologies used on intersections and freeways, like inductive loop detectors, machine vision, and others are designed for permanent or semi-permanent deployments. They also require a lot of power. In addition, the cost of such technologies is prohibitive for the scope of the IDL system. Therefore for the purpose of this project more basic sensing technologies had to be selected and evaluated for applicability. The following sections provide a primer on the available technologies to assist the reader in better understanding the later described selected components and their testing.

#### **Active Infrared**

An active infrared sensor sends out infrared light generated by a LED or laser diode and measures the time required to reflect off an object and return to an infrared detector or array of detectors. Speed can be calculated by measuring the time it takes the vehicle to cross subsequent detection zones. These sensors although very accurate are required to be positioned 20 to 25 feet above the road and their cost is currently prohibitively high for the scope of the IDL system. Scaled down versions of active infrared sensors were tested for distance measurement as described in later sections.

#### **Passive Infrared**

All matter above absolute zero emits radiation in the far infrared part of the spectrum. The amount of radiation is a function of the object's temperature, size, and structure. Passive infrared sensors measure this radiation. A non-imaging detector has a relatively wide field of view and can detect a vehicle's presence or velocity (with more than one sensor or detection zone). Passive infrared products are used in many security applications but their range and response time is not optimal for use in the IDL. Additionally, the IDL is required to work under adverse weather conditions and passive infrared sensors can be confused during heavy rain and snowfall. Regardless, their power consumption is very low which is positive.

#### **Ultrasonic**

Ultrasonic air sensors emit a burst of sound pulses at a frequency between 25 and 50 KHz. Distance is calculated by measuring the time it takes for the sound to return after reflecting off the target. Sensors can be overhead or side mounted. There are dozens of ultrasonic emitter, transducer, and integrated sensor manufacturers whose products are used for object detection in commercial and industrial applications and are fairly inexpensive. An ultrasonic detector that also measures the Doppler frequency shift of a reflected signal also exists but is very expensive.

No ultrasonic detector was found that has a reliable range of more than 25 feet during any outdoor environment so although their refresh rate is adequate for speed estimation they would not be effective in speeds above 20mph. Regardless, they are very reliable for vehicle presence detection and their accuracy allows for differentiating between vehicles in adjacent lanes.

### **Magnetic**

Magnetic sensors use a dual-axis flux-gate magnetometer to measure the Earth's magnetic field. When a vehicle approaches the detector, the vehicle distorts the magnetic field and the sensor detects this change. In traditional traffic related application such sensors are packed in plastic canisters and buried in the roadway. The sensor sends vehicle arrival and departure messages to an above-ground receiver via a radio. This sensor technology is passive and consumes very little power which satisfies one of the primary requirements in the IDL system. Unfortunately, the need to have something placed on the roadway renders such a design difficult to deploy and easily destroyable by passing vehicles. There are versions of magnetic sensors that can be mounted on the drum but their range is limited.

### **Microwave**

Continuous microwave devices use the Doppler principle—the change of frequency of a wave reflected from a moving object is proportional to the object's speed—to directly measure the speed of a vehicle. The available systems (TDN-30 by Whelen Engineering, TC-20 by Microwave Sensors, and DRS1000 by GMH Engineering), are configured to be used in an overhead mount or an elevated side mount. Typical power consumption is 2 to 6 watts and cost of a single unit is \$1000 to \$2000. With the proliferation of Automated Speed Warning signs cheaper more versatile sensors have entered the market. Such is the sensor selected for this project to measure the speed of approaching vehicles. Microwave radar sensors are also capable of detecting the distance of the target from the sensor. Unfortunately, this feature requires considerably higher complexity and such sensors are still extremely expensive, in the range of \$3,000 to \$5,000. Although tasked for the automotive industry and therefore bearing favorable characteristics, their cost renders them prohibitive for implementation in the IDL. This could change in the near future.

### **Video**

Video image processing promises the richest data set of traffic measurements including vehicle detection, speed, classification, headway, density, and volume. A camera sends an image to a video processor which digitizes it and applies various detection and tracking algorithms to extract the applicable measurements. Cameras can be side or overhead mounted. The Autoscope Solo (Econolite Control Products) even integrates the camera and processor into one package. Video systems are probably the hardest to install and calibrate correctly of all detector technologies. The lack of portability, high cost, and the high power consumption (20-50 watt range) make them unsuitable for this application. The dirty construction environment and changing road features might also prevent their use.

### 3.1.1.1 Sensor Acquisition and Testing

This project did not start by having a particular sensor technology or manufacturer in mind. Considering the novelty of the concept, the research team was fairly certain that sensors traditionally used in traffic related applications will probably not be of particular use. A market search was conducted to identify sensors that possessed the desired characteristics including appropriate cost for the application. The following sensors were identified across different technologies and manufacturers.

#### **Vehicle Presence Detection and Distance Measurements**

As described earlier, the most appropriate sensor technologies for detecting the presence of a vehicle in the drum's vicinity are Ultrasonic and Active Infrared. Several different models of the aforementioned sensors were acquired and tested. The testing involved indoor accuracy testing as well as outdoor operation in roadways with speeds as high as 65 mph. Specifically, the ultrasonic sensors were tested for interference from wind and other noise generating sources. The sensors were tested under fair and moderate rain conditions. Finally, the different sensors and model implementations were evaluated for their robustness in integrating with the rest of the IDL components.

- Infrared sensors



- Ultrasonic sensors



With enclosure:



**Figure 3.2 Examples of Distance and Presence Sensors**

Following rigorous testing the ultrasonic sensors were selected. These sensors have sufficient long range, are inexpensive, weather-resistant, easy to integrate with our selected control unit and as an added bonus they are made in Minnesota by MaxBotix Inc. The cost of the sensors, depending on the model, ranges between \$40 and \$120.

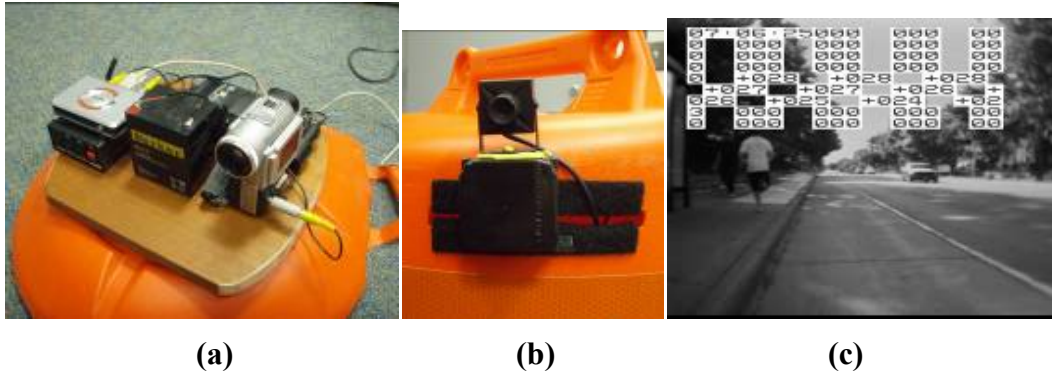
## Vehicle Speed Measurement

Finding an appropriate speed measurement sensor was the hardest part in this project. Early on it became clear that Microwave Radar sensors are the only viable alternative but finding an affordable and robust implementation of such a sensor was very difficult. Most models available in the market were too expensive and/or consumed too much power. The project team even attempted to assemble its own radar unit acquiring only the very necessary parts. That attempt did not prove fruitful and resulted in great loss of effort and time. Although initially not available, in the course of the project the SS300 radar module manufactured by Houston Radar Inc became available in the market. Designed for implementation in Dynamic Speed Advisory signs the sensor is manufactured in sufficient numbers to have a high but reasonable price of around \$500 retail and has the smallest power requirements from all other sensors found in the market. One favorable feature is the ability of the radar to differentiate between approaching or receding vehicles allowing for the IDL to ignore vehicles on opposite lanes. The project team had to collaborate with the manufacturer in order to modify aspects of the sensor operational characteristics to facilitate integration with the rest of the IDL subsystems. The changes implemented are now standard features of all the sensors produced. A picture of the radar unit with the weather proof enclosure can be seen in the following figure.



**Figure 3.3 Doppler Radar Speed Sensor**

Considering the untested nature of the selected implementation the radar underwent a series of tests in order to determine its true operational characteristics. Specifically, a test platform was developed (figure 3) that allowed deployment of an experimental drum on a number of roadways. The test platform provided video confirmation of the radars' operation and accuracy was assured with the use of a handheld police Lidar speed gun. During the test it was determined that the radar operating at full power detects vehicles much farther than this project requires. The test platform was used for calibrating as much as possible the sensor to provide vehicle detection approximately 5 seconds upstream of the first IDL drum. Unfortunately, this measurement is greatly depended on the size of the targeted vehicle. Larger vehicles, representing a bigger target are detected considerably farther than smaller ones. Considerable effort was spent in trying to overcome this negative effect and although the calibration allowed for successful proof of concept testing, modifications in the systems concept are necessary for flawless operation till a more appropriate radar sensor becomes available.



**Figure 3.4 (a) Radar Testing Platform, (b) Radar and Camera, (c) Video Validation**

It is interesting to note that, with the addition of the radar unit, it is possible to produce a one-drum IDL system, where the sole drum has the sound and vision alert systems being activated or primed while the vehicle is still far away. Regardless, as on-site tests and feedback from drivers showed, providing only one time the audible warning may not be sufficient to attract the driver's attention. More details of these test are include later in this document.

### ***3.1.2 Communication Subsystem***

The inter-device communication module was a system requirement for the operation of the original multi-barrel configuration. With the addition of the radar units on the two-drum configuration and the suggestion of the TL to include the sound alert on both barrels this communication capability became unnecessary. Regardless, two requirements prompted the research team to include a communication subsystem that allows information to be transmitted between drums. These requirements are cost reduction and early activation of the visual warning.

The most expensive component of the IDL system is the radar sensor. With the use of an inexpensive communication system, only one radar sensor is necessary mounted on the first upstream drum. The speed of the approaching vehicle, when higher than the threshold, is communicated to the second drum's CPU. Along with the approaching vehicles speed, the fact that it exceeds the threshold is also communicated. This allows for the activation of the visual warning on the second drum more than 600 feet away of the approaching vehicle. This way the driver is encountered with two drums displaying flashing emergency lights in his/hers line of sight.

The solution explored for the communication subsystem utilizes the Zig-Bee communication protocol and radios. These short range, limited bandwidth radios are extremely cheap and require very low power. Two implementations of these radios were tested. The only difference was the operating maximum distance between radios. The first, least expensive model, has a maximum operating range of 400 feet while the next model in cost has a maximum operating distance of 1 mile between receiver and transmitter modules; both on a direct line-of-site situations. The reason for finally selecting the bigger more powerful model was that in order to achieve the indicated maximum operational range the radio antenna needs to be positioned at least ten feet from the ground. Since the IDL drums are considerably shorter this resulted in a considerably reduced realized operational range.

The modules acquired for the project, (Digi-Key XBee Pro 60mW Series 1 (802.15.4)) are self-calibrating and networked, eliminating the need for any configuration before or during deployment. One issue the research team struggled with during testing and implementation of the communication subsystem was a random delay in sending the information as well as loss of information. This problem resulted in a partially successful first full system demonstration at MnROAD. Following several days of testing on real road environments like MN-65 in Isanti County and County Highway 3 in Pine County north of the Twin Cities, it was detected that the problem was not on the communication subsystem but instead was an issue involving the IDL CPU subsystem. Details are described in the next section. Considering that the communication subsystem has a very straightforward and basic functionality, details of its operation are described later in this document when the operation of the working prototype is described.



**Figure 3.5 Wireless XBee Radio Module**

### ***3.1.3 Visual Warning Subsystem***

The operation and characteristics of the visual warning subsystem are simple and straightforward. For the sake of brevity, at this point of the report, only the fact that several different flashing emergency lights were tested before finally selecting the most appropriate ones is pertinent. The final selection is based mainly on the feedback provided by MnDOT maintenance drivers evaluating different alternatives on their ability to produce the most directed and long range visual warning on the upcoming vehicles. Special consideration was given in the emergency light mounting on the barrels to target both large and small sized vehicles. The cub of trucks and semitrailers situates the driver considerably higher from the road plane than the height of a passenger vehicle. Cost was also considered in the selection of components although this aspect will change considerably when the system reaches the production stage. Secure mounting of the emergency lights is an aspect that must also be considered before the system is mass produced.





**Figure 3.6 Examples of Emergency Flashing Lights**

### ***3.1.4 Audible Warning Subsystem***

The audible warning subsystem is the most unique and difficult aspect of the IDL system and from the beginning it attracted much of the attention. As described earlier in this report the original IDL concept involved several (5-10) drums generating a sound experience similar to the one experienced when a vehicle drives over sequential rumble strips. The sound under that pretext did not need to be extremely loud since the large repetitions and the periodicity was the aspects that would attract the attention of the driver. When the system was reduced in at most two drums it immediately became obvious that a much stronger sound source had to be designed. Regardless of the power or number of repetitions, the sound produced needed to be directional, targeting the subject vehicle and generate as little as possible peripheral noise. This way the system could be used near residential areas without generating problems to unintended listeners. Naturally, the sound intensity and directionality requirements are complete opposites and required considerable effort for reaching a robust, low cost, and effective solution. Several different sound sources were explored evaluating their characteristics on the aforementioned two aspects. Since the cost and component availability is of high importance only available off the shelf components were explored. It is possible that a custom made sound device may be more appropriate but this project did not expand on that direction. Quickly, attention was drawn to emergency horns of two types, piezo-electric and air horns.

During the first demo to the TL an electrical horn was utilized since this technology has the fastest response rate. Apart from the fact that the resulting sound was not so penetrating the TL pointed out that the original plan of activating the horn as soon as the vehicle was in front of the barrel is not correct. Considering that speeds of 60 mps equal 88 feet/second, the vehicle is in front of the barrel for a small fraction of a second and then it is gone. To better attract the driver's attention the audible alarm should last for at least one second and be activated while the vehicle is still upstream of the barrel. Therefore given that response rate was not an important issue anymore the research team decided to experiment with air horns like the ones seen in the following figure. The air horns acquired are all accompanied with a small air compressor power by a battery and usually come in pair for producing different tones. In the case of the IDL one horn per barrel is desired. The selected air horns can be purchased for approximately \$50 retail.



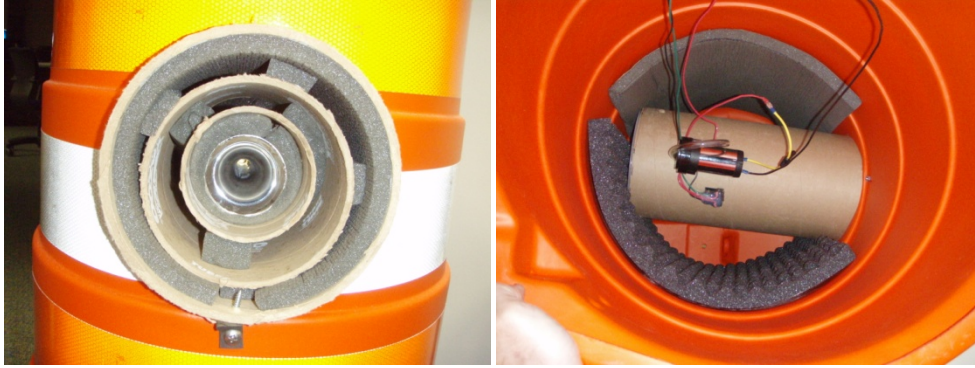
**Air Horns**



**Piezo-Electric Horns**

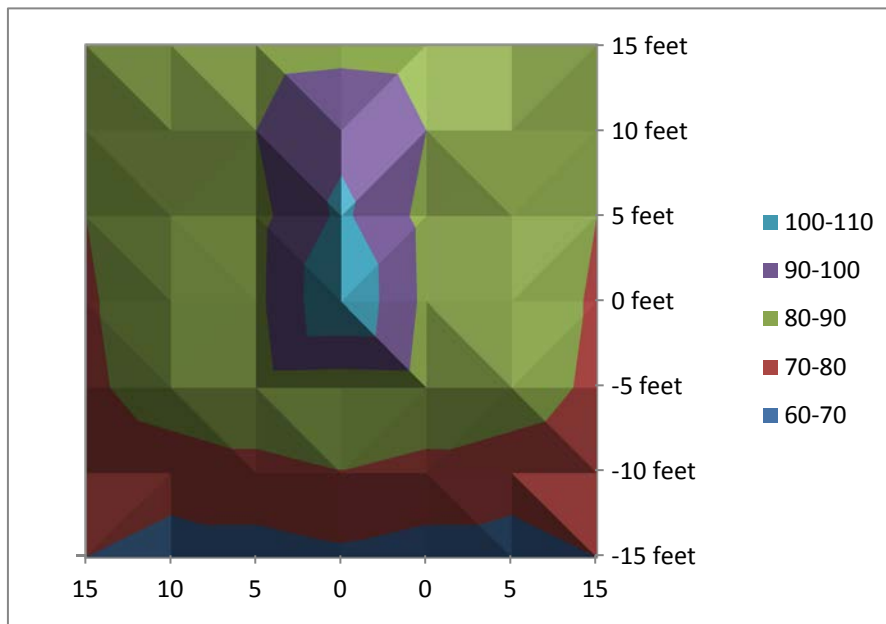
**Figure 3.7 Examples of Audible Warning Sources**

In order to generate as much directional sound as possible and at the same time suppress it in all other directions except the one facing the road, a system of concerting tubes was devised with soundproofing material sandwiched between tubes as seen by the following picture. At the center of the tube system the air horn is mounted also surrounded by soundproofing foam. The air compressor is mounted on the outer tube with the air hose fielded through the tubes and connected to the horn. This arrangement has been adequate for the purposes of the IDL prototype but it is not complying with the specifications of weather resistance (paper tubes) not it is crashworthy. This audible warning solution is a proof of concept and it is envisioned that if the IDL system goes into production the outer tube will be part of the barrel mold and therefore be an inseparable part with the air horn securely mounted inside. The air compressor being the heaviest of the sub system parts can be positioned in the barrel base along with the battery connected with the horn through a longer flexible tube. This way the whole system will be weather resistant (the air horns are designed to be mounted on the outside of vehicles) and all the heavy objects will be safely placed in the barrel base serving as ballast. The electronic parts of both the visual and the audible warnings are located inside the CPU enclosure as described later.



**Figure 3.8 Photos of the Audible Warning Module of the IDL Prototype**

The resulting arrangement of the audible sound system was tested to determine if it possess the desired attributes of directional sound. Tests were conducted measuring the sound level around the barrel. The following figure shows the results of these measurements.



**Figure 3.9 Sound Levels in the Area Surrounding the Drum. Values in dBs**

As the graph suggests, the designed system produces a 100-110 dB sound in the direction of the road while the sound quickly drops down to 70-80 dB 5 feet away in the opposite direction. The presented graph was created with measurements taken around the barrel when no vehicle was present. During the tests at MnROAD it was observed that when a large vehicle is in front of the barrel the peripheral sound increases because the sound wave is reflected back by the vehicle. Given the speeds the system is going to operate at this sound increase last for a fraction of a second and is not deemed important.

### ***3.1.5 Central Processing Unit (CPU) Subsystem***

The final component of the IDL is the Central Processing Unit (CPU). The CPU is the brain controlling all components in each of the drums. In terms of logic and complexity the tasks the system must perform are not a challenge and in the final analysis having an actual processor may not be necessary but since the objective of the project was to explore different designs, allow for easy adaptation of suggestions from the TL and TAP, and in general be flexible on the systems functionality having a programmable unit that depends on software for the systems functionality is appropriate. When the IDL moves beyond the prototype stage, the research team or a private entity can produce a fixed, streamlined version. In the rest of this section we would like to present the current architecture and the alternatives it allowed us to explore.

The central control unit of the IDL system is a BASIC Stamp BS2. The BS2 is a microcontroller developed by Parallax, Inc. which is easily programmed using an easy-to-learn language called PBASIC. It is called a “Stamp” simply because it is close to the size of an average postage stamp. The BS2 is usually used to control and monitor timers, keypads, motors, sensors, switches, relays, lights, and more. All vital components (processor, clock source, memory, power regulator) are provided on the BS2's tiny PCB. The BS2 uses a PIC16F57 processor as the main processing unit and all other vital components (oscillator, memory, voltage regulator) are included; the board even has an RS-232 to TTL converter, allowing connectivity with a PC. The BS2 is powered by a regular 9V battery or in the case of the IDL a 12V-to-9V DC to DC converter. At the early stage of testing the CPU was mounted on a removable tray for easy access as well as allowing mounting wireless cameras giving us visual records of the device operation. The final prototype barrels have the CPU enclosed in a water resistant enclosure mounted internally in the barrel.



**Figure 3.10 Parallax STAMP Microprocessor**

The BS2 functions as the collector of information from all the aforementioned sensors, based on the logic the research team implemented, explained in the next chapter, activates the audible and visual warnings as well as handles the exchange of information between the drums. Although it was very straightforward integrating the ultrasonic, and infrared sensors, as well as the communication radios with the BS2, the integration of the radar unit was a big challenge due to two design characteristics. First, the BS2 as mentioned earlier has an RS-232 to TTL converter for communicating with a PC but for communicating with sensors it uses straight TTL. The radar unit though is also designed to communicate with a PC through RS-232 and it does not accept TTL based communication. Apparently this is not a common issue therefore it was rather

difficult to find in the market the appropriate interface. This though would be a no-problem for an electronics contractor. The second challenge was also affecting the communication of the two devices. The radar by design, in order to conserve energy, deactivates the serial communication port whenever there is no information to be transmitted. This feature does not work well with the BS2 which requires an active line all the time in order to maintain communication. Unfortunately this “feature” of the radar unit was not described in the specifications resulting in considerable time and effort lost in attempting to integrate the radar with the BS2. Finally, two solutions were found one we implemented through code in the BS2 while the company manufacturing the radar considering our problem to be important implemented an option on all their radar that allows for the user to select if they would like to keep the line of communication active in the absence of a detected vehicle.

Considering that the program running at the CPU is the glue that integrates all subsystems together its details are described in the next chapter that describes the IDL prototype. The development of the IDL control logic took the most effort in this project and it was based a lot on in the field trials and testing since it is nearly impossible to test and debug the IDL system inside the laboratory. The output of the radar greatly depends on the target vehicle and like the radio operation it is critical in the operation of the IDL. Both are impossible to replicate in a lab environment.

### **3.2 IDL Component Integration**

The subsystems described in this chapter are all integrated into one functioning systems. Regardless, considering that all components are mounted on the drums care was given in combining components as much as possible to reduce the individual parts forming the prototype. The following picture shows the enclosure containing the CPU, the communication radio, the control board of the radar, and the relays that control the activation of the audible and visual warnings. Details on the board and its components are given in the next chapter that describes the prototype. The electrical diagram of the IDL system is presented in figure 3-12.



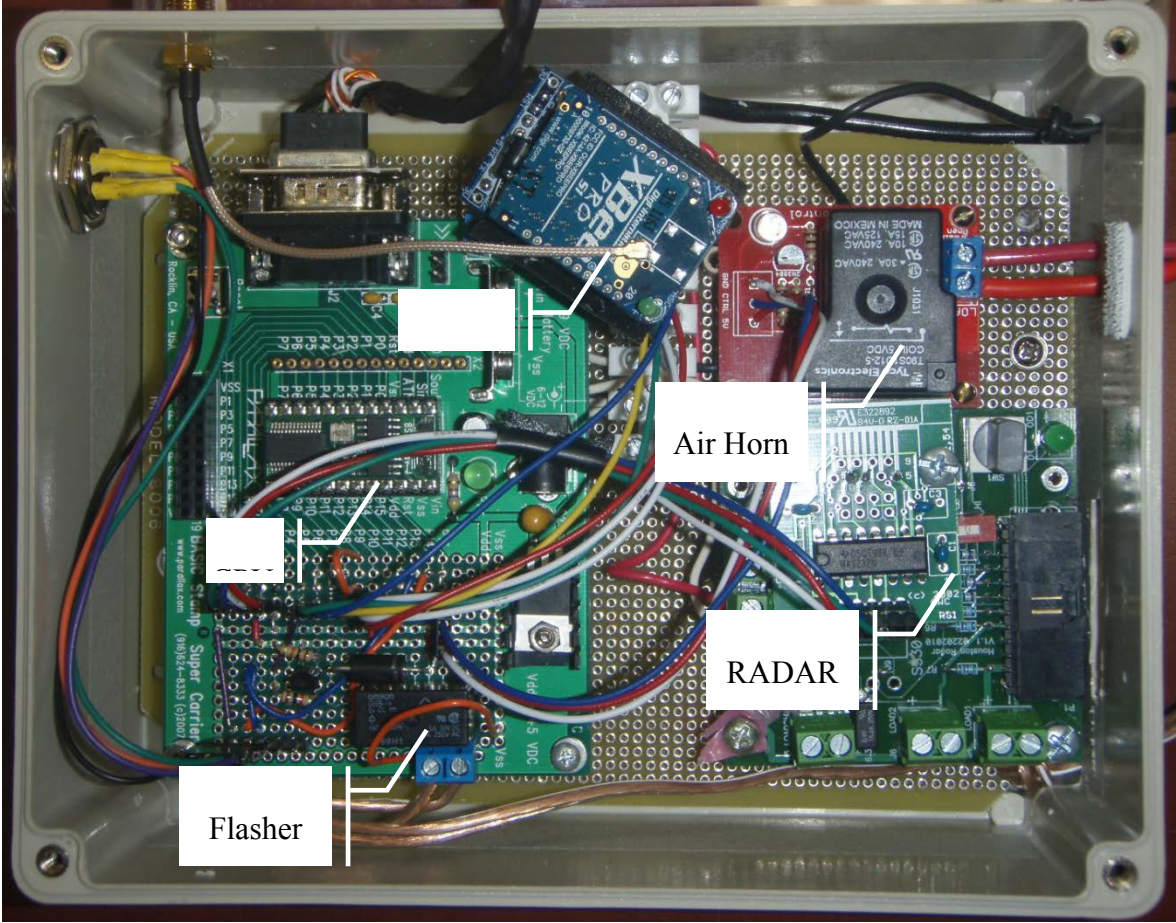


Figure 3.11 IDL System Control Module

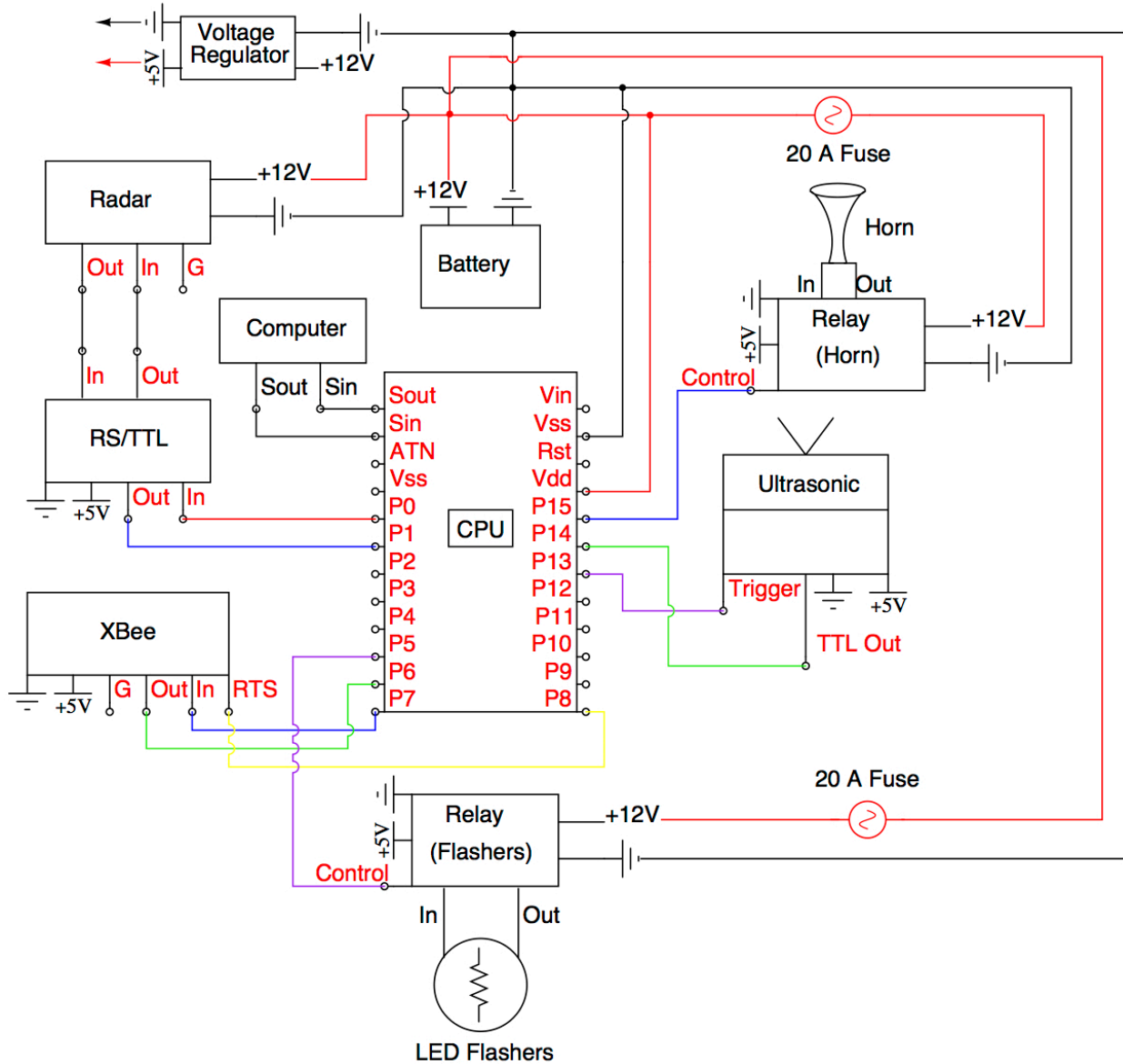


Figure 3.12 IDL System Component and Wiring Diagram

## Chapter 4. IDL Prototype Description and Testing

### 4.1 IDL Modes of Operation

The IDL system underwent several changes over the course of the project for many reasons, some unrelated to the project. In its final incarnation the IDL system has two modes of operation **single-drum** and **dual-drum**. As the name implies the system is comprised by only one drum in the first case and two drums in the second. As already discussed the single-drum version hasn't collected many favorable comments since the drivers stressed the need for a second repetition of the audible and visual warnings. Regardless, in our effort of designing a system that can operate under conditions causing interference to the communication system, in which case the two drums work independently, the single-drum version emerged. As it will be discussed in the following section, the single-drum version allows also the addition of additional drums, forming systems of three, four or more with no change to the basic design. Based on the aforementioned connection between the two versions it is reasonable to begin the description of the final prototype with the discussion of the single-drum version and expand it to cover the two drum version.

#### 4.1.1 Single-drum IDL System

As noted in several places in the preceding document the IDL is a system comprised by the Sensor, Communications, Audible, and Visual subsystems all control by the CPU. It is autonomous by default since it needs to operate unsupervised, in a harsh environment. The method of operation is straightforward and described in the following steps and diagram (figures 4-1 to 4-5):

1. **Continuous Function:** The IDL drum operates at the heartbeat of the CPU which is 24MHz. After power-up and an initialization period (described in the Two Drum section), an infinite loop is performed where the CPU communicates with the radar sensor, validates its correct operation, and retrieves the current measure of speed when a vehicle is detected or reads zero if the road in the direction of the work zone is empty. The radar is providing new measurements of speed approximately every half a second. Every speed measurement retrieved is compared with a threshold set by the operator. As long as the detected speed is below this threshold the aforementioned function continues, otherwise an alarm event is generated. The detected speed is also broadcasted over the radio although in the Single-drum version this is irrelevant.
2. **Alarm Function:** In the case where the radar detects a vehicle approaching the drum with speed higher than the set threshold an Alarm Event is generated and the IDL enters the alarm function. The following functions are invoked:
  - a. **Visual Warning Activation:** As soon as a speeding vehicle is detected the CPU activates the visual warning system. The emergency strobes are activated and stay activated till the vehicle passes the IDL drum and if no other speeding vehicle is following it.
  - b. **Vehicle Approach Countdown:** Given the vehicles reported speed a countdown commences tracking the vehicle till it is approximately one second away from the drum. Ideally this function would have available a measurement of the vehicles distance when detected and would require no



assumptions or concept modifications. Unfortunately, in the course of this project, it was impossible to find radar that will provide speed and distance measurements in a cost effective package. There is a gap in the market between the speed only Doppler radars and the Speed & Distance radar sensors. The cost of the first ranges from \$500 to \$1500 per sensor while the second starts at \$3,000. The speed and distance radar are now entering the automotive market, offered as options to several current models, and have started to be mass produced. It is possible that in a few years their price will fall to the \$500 level and therefore become cost effective in use with the IDL system. In the absence of distance information the research team produced two working prototypes, one with a less than perfect operation and one that violates the concept of “system should be comprised by at most two parts”. These two alternatives are described here:

- i. **Assumption of Detection Distance:** In the less-than-perfect version of the prototype, the distance of the vehicle from the drum at the time of detection is assumed to be 300 feet. Field measurements have shown that this is the average distance the IDL detects most vehicles with the exception of very large semi-trailers. The semis being a much bigger target for the radar can be detected at a much greater distance of 600 to 1000 feet. The less-than-perfect operation in the case of large semis results in a premature trigger of the audible warning. In most cases considering that when the audible alarm is activated the semi is still in the detection zone of the radar, a new alarm condition is activated generating a second audible alarm which may target the semi or may start just after the semi has passed the drum. In either case the IDL fails to target the speeding vehicle and produces one unnecessary audible alarm. As it will be discussed later the operation of the second drum is not affected by this problem.
- ii. **Advance Presence Sensing Cone:** The second solution developed to cope with the lack of distance information from the radar involves an additional piece in the IDL system. Given that the objective is to activate the audible alarm one second before the target vehicle reaches the drum, the research team mounted a ultrasonic sensor and a radio on a tall highway work zone cone. The cone is placed approximately 90 to 110 feet upstream of the IDL drum. The vehicle detection device mounted on the cone transmits to the IDL barrel the presence, or not, of a vehicle ~100 feet away. This information is part of the Continues Function (a) described earlier. When the IDL drum enters the alarm stage in addition to entering a countdown tracking the vehicle as it approaches, it continuously receives presence information from the advanced cone. When the target vehicle is detected in the advanced cone and in extend be approximately 1 second away from the IDL barrel the audible alarm is activated.
- c. **Audible Warning Activation:** Regardless of the actual method of triggering the audible warning, the IDL drum CPU activates the audible warning. The audible warning stays active till one of two conditions become true.

- i. The ultrasonic presence sensor mounted on the IDL drum reports the presence of a vehicle in a distance from the drum less than 6 feet.
- ii. The audible alarm has been active for more than 7 seconds. This threshold condition was selected to terminate the audible warning system in the case the vehicle presence clause fails. Even in the Less-than-Perfect incarnation of the IDL it is almost impossible to have activated the audible alarm while the speeding vehicle is more than 7 seconds away from the drum while in the less rare case where semitrailer passes the drum before the system starts detecting vehicle presence in its vicinity the false audible alarm does not exceed 7 second. The threshold of 7 seconds has been selected based on field tests but is not an absolute number. If the IDL is deployed in a residential area where the loud horn sound could be more of a nuisance the threshold can be lowered to as low as 2 seconds without affecting much the systems' operation.

The termination of the audible alarm, assuming no other speeding vehicles are currently been tracked by the radar, also terminates the visual warning.

While in the alarm state the IDL continues to receive information from the radar. The radar is programmed, in the presence of multiple vehicles, to report the speed of the strongest target which, except of extremely rare cases, the vehicle closest to the IDL drum. If while tracked, but not yet closer than 1 second away from the IDL drum, the vehicle decelerates to a speed below the threshold, the countdown is canceled and the IDL exits the alarm state. This situation has been frequently observed since the speeding vehicle is exposed to the visual warning while ~300 feet away from the IDL drum. If its speed was not too much above the speed limit selected by the work zone crew, there is enough time to decelerate and render the audible alarm unnecessary.

As soon as the targeted vehicle is closer than 20 feet from the IDL drum it exits the radar's field of view. At this instance if there are other vehicles following closely the first speeding vehicle are starting to be tracked by the radar. Barring the extreme case where the following speeding vehicle is tailgating the first at headway of less than 0.5 seconds (44 feet at 60mph) the IDL restarts the countdown function targeting the new speeding vehicle. In the case of headway around 0.5 seconds between vehicles there is no need for an additional audible alarm since the following vehicle is so close that it is exposed to the alarm targeting the first.

#### ***4.1.2 Two Drums IDL System***

The design of the IDL system follows a hybrid design principle. Essentially the same control code exists in all drums regardless of which drum is first or second or if a second drum even exists. The only difference between the first and second drums is that the second "preferably" is not equipped with a radar. "Preferably" because the radar is the most expensive part of the IDL system and having a second one greatly increases the overall price. Regardless, the IDL system's programming does not change and in the case a radar exists in the second drum, the system ignores it when it operates in the Two Drum mode.

The work zone crew needs to be aware of two things when they deploy the IDL as a two drum system.

1. Deploy the drum with the radar upstream of the drum with no radar.
2. Activate the upstream drum first and the downstream drum second.

The program running in both drums is identical but contains two separate sections. During initialization the active section is selected and the drum enters the Lead Drum or the Second Drum mode. Specifically, the following functions take place during initialization.

1. **Communication Subsystem Test:** The operation of the radios is validated. If the radio for some reason is malfunctioning the Lead Drum defaults in Single-drum operation. If the radio of the Second Drum fails and the drum is not equipped with a radar the user is alerted of the malfunction through the visual warning system. It flashes for two seconds, pauses for one second, and again flashes for two seconds. This is repeated as long as the unit is powered and the radio does not validate and successfully communicate with the Lead Drum. There are two reasons why the second drum radio may fail. One, it may be physically damaged in which case if it cannot be repaired in the field it is deactivated and removed. Two, there may be interference preventing the communication with the lead drum. In this case simply carrying the second drum closer to the lead drum it may resolve the problem. If the second drum is moved as close as 100 feet downstream of the lead drum and still does not work, it is deactivated and removed from the work zone. If the second drum is equipped with a radar then it defaults to a single-drum operation and alerts the user accordingly. If the problem is not resolved then the second drum is allowed to work independently.
2. **Sensor Subsystem Test:** Following the communication system test, the radar and ultrasonic sensors operation is validated. In the case of the Lead Drum, if the radar does not report to the CPU the system uses the visual warning system to alert the user of the malfunction. It flashes for two seconds, pauses for one second, and again flashes for two seconds. This pattern and the radar validation are repeated as long as the unit is powered and the radar does not validate. The same applies to the second drum if it is equipped with a radar and the radio has failed. If no indication is returned to the user that means that the Ultrasonic sensor is malfunctioning. Since the ultrasonic is essential to the systems operation the device is not allowed to start-up if this component is malfunctioning. The user may try to repair or replace the drum if one of the same type (with or without radar) is available. We recognize that the present User Interface system is not optimal and better interfaces need to be devised but for the purposes of testing and validating the IDL system prototype they are adequate.
3. **Mode of Operation Selection:** Following the successful pass of the communication and sensor system validation checks each drum enters the Lead or Second drum mode selection. The process is simple, since the Lead (upstream) drum is activated first, as soon as the tests finish the radio goes into a listening mode. If the radio does not receive any communication for 10 seconds the system defaults into the Lead Drum mode. The device uses the audible warning system to report back to the user its mode of operation. Specifically, it sounds the horn once for 1.5 seconds and enters the Continues Function loop described in the previous section. The downstream (second) drum is activated second and therefore by the time it reaches the radio listening state the Lead drum already

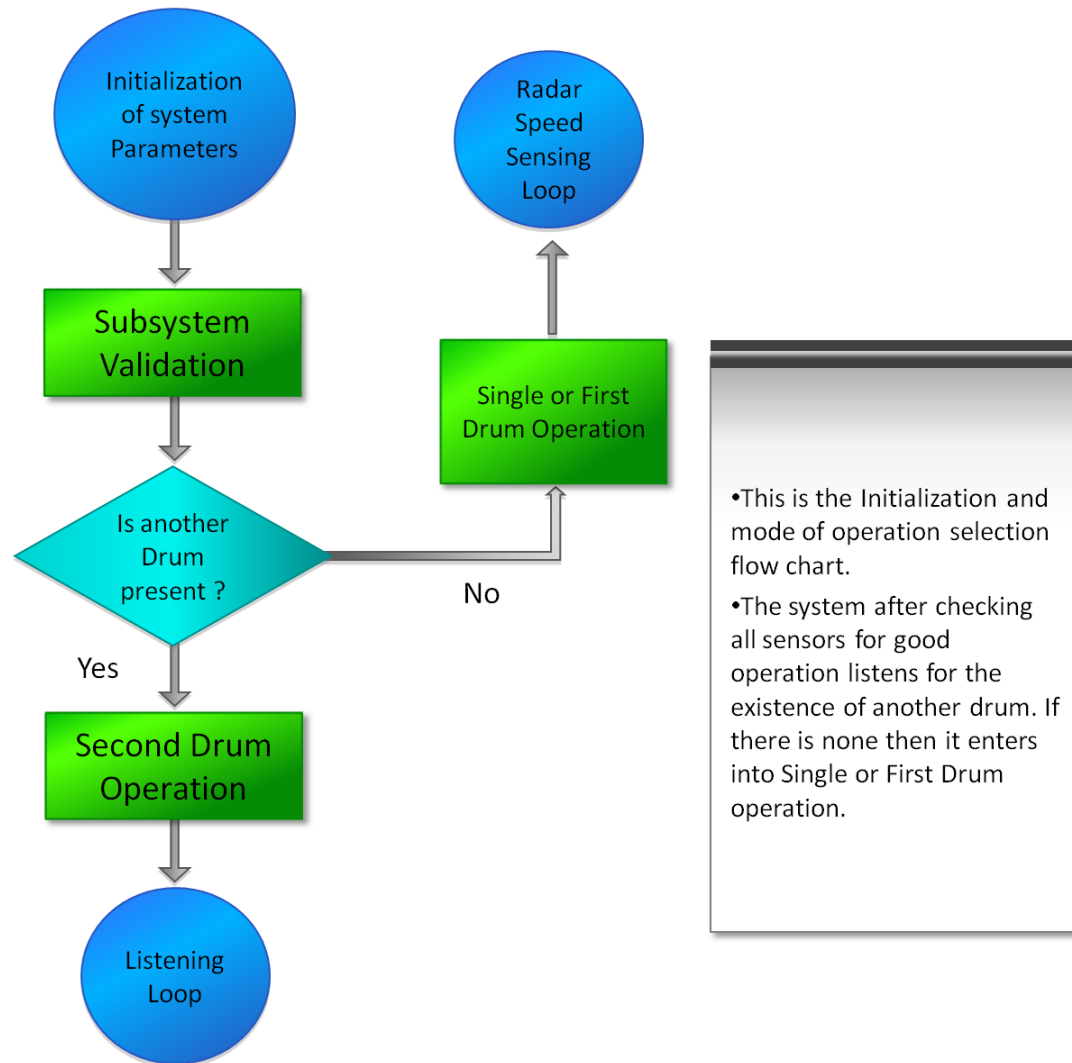
has started transmitting information. Detecting the presence of a Lead Drum simply by the existence of relevant radio communication the drum enters the Second Drum mode of operation. The result is transmitted to the user through the audible warning system. The horn sounds for 1.5 seconds twice one second apart.

The upstream IDL drum as soon as it is activated enters the Lead Drum mode which is identical to the single-drum mode described in the previous section. What it was not highlighted in the previous section is that the Lead Drum regardless if it stands alone or is part of a pair always broadcasts Functional State information over the radio. Specifically, the lead drum transmits the following:

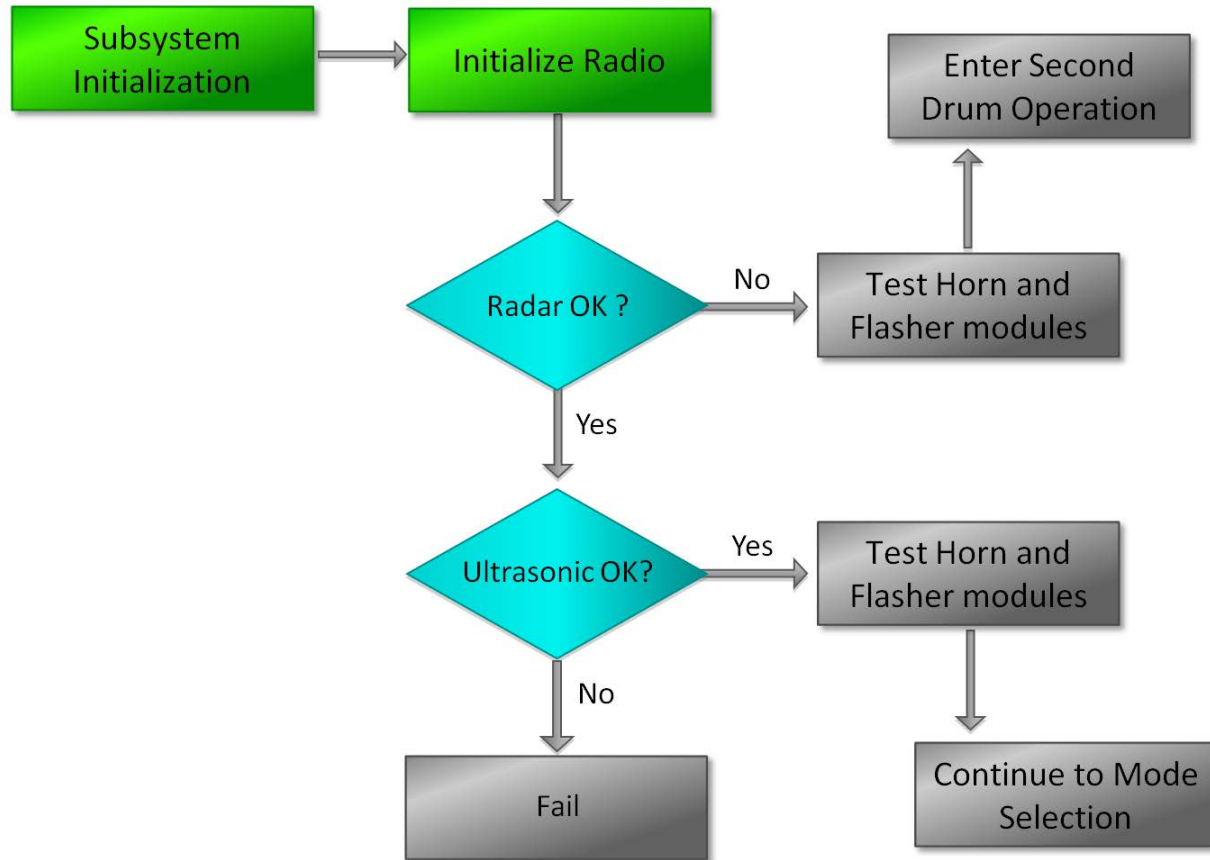
1. **Continuous Function:** in addition to the functionality described in the previous section the lead drum while no speeding vehicle is detected it broadcasts the measurement read from the radar sensors over the radio or if no vehicle is detected it transmits "Speed: 0". This information is received by the Second Drum but invokes no action.
2. **Alarm Function:** in addition to the functionality described in the previous section the Lead drum transmits the following information:
  - a. **Violation Detected:** Code "X 2 Violation" along with the speed of the speeding vehicle is transmitted. The second barrel receiving this information, stores the speed for later use.
  - b. **Visual Warning Activation:** Code "X 7 FLASHHH ON" is transmitted. The second drum upon receiving this information it activates its Visual Alarm subsystem. Barring any interference the flashers in both barrels are activated virtually simultaneously.
  - c. **Audible Warning Activation:** while the Lead drum is in vehicle approach countdown the Second drum remains idle receiving speed information when available. The Lead drum audible warning is activated following the procedure/alternatives described in the previous section. Regardless, as soon as the speeding vehicle is in front of the Lead drum and the horn is deactivated the following code is transmitted "X 5 Blast OFF". Given that the speeding vehicle is in front of the Lead drum when this code is transmitted the distance from the Second drum is known as selected by the user when the drums were deployed. Given that the speed of the violating vehicle is known from step 2 the travel time of the vehicle from the Lead drum to the Second drum is calculated by the second drum's CPU. A countdown is activated with the TT info minus one second. At the end of the countdown the audible warning of the Second drum is activated and remains active until the vehicle passed in front of it.
  - d. **Visual Warning Deactivation:** The flashers on the Second drum are deactivated as soon as the horn stops unless the Lead Drum has detected another speeding vehicle in which case the flashers remain active till both drums have ended their alarm functions.
  - e. **Canceling Alarm State:** If the speeding vehicle after is detected lowers its speed before reaching the Lead drum and therefore the horn does not sound, as soon as the Lead drums flashers are deactivated the following code is transmitted "X 6 FLASH OFFFFF" which when received by the Second drum it cancels the visual warning.

As described earlier the benefits of having the second drum are twofold. First the visual warning is reinforced in the field of view of the driver since both drums are flashing as soon as the speeding vehicle is detected. This translates to a flashing drum approximately 300 feet downstream and a second flashing drum up to 700 feet away depending on the users selection of deploying the second drum. The second advantage is the double hit with the audible warning which reinforces the message.

During field tests different distances between the two drums were tested. For the second drum to be more effective the distance from the lead drum must be more than 250 feet while it was considered that 350 to 450 feet may be the optimum. The radios have exhibited good reception with no interference or dropped packages up to 2000 feet so there is no limiting factor there. What hasn't been tested was the range of the radios if there is no direct line-of-sight between them, a case possible if the IDL system is deployed along a very sharp curve. We do not anticipate a problem there but it would be necessary to perform further tests in various environments especially urban where there could be a concrete building in between.



**Figure 4.1 IDL Operation Flow Chart: Initialization Stage**



**Figure 4.2 IDL Operation Flow Chart: Subsystem Checking and Mode of Operation Selection**

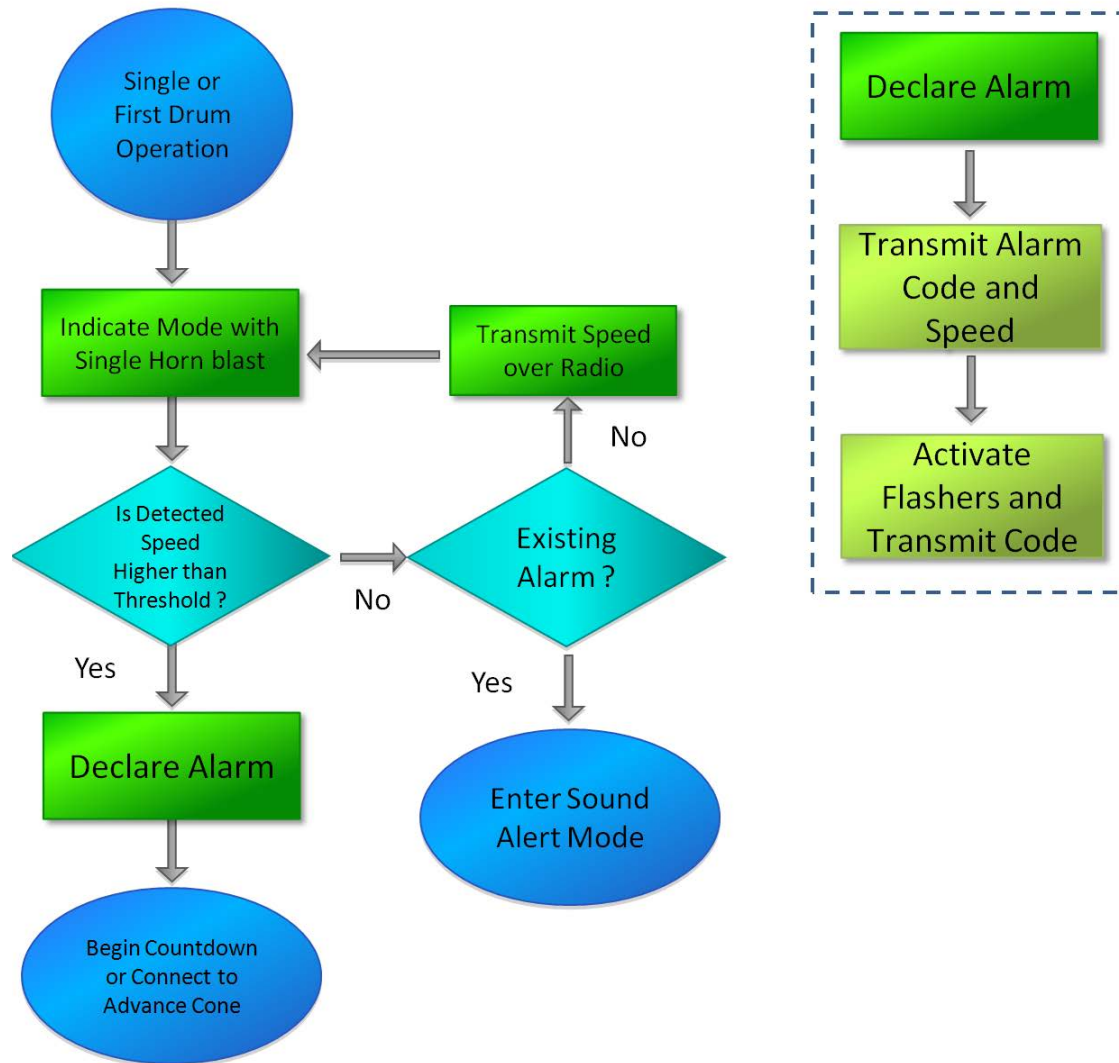
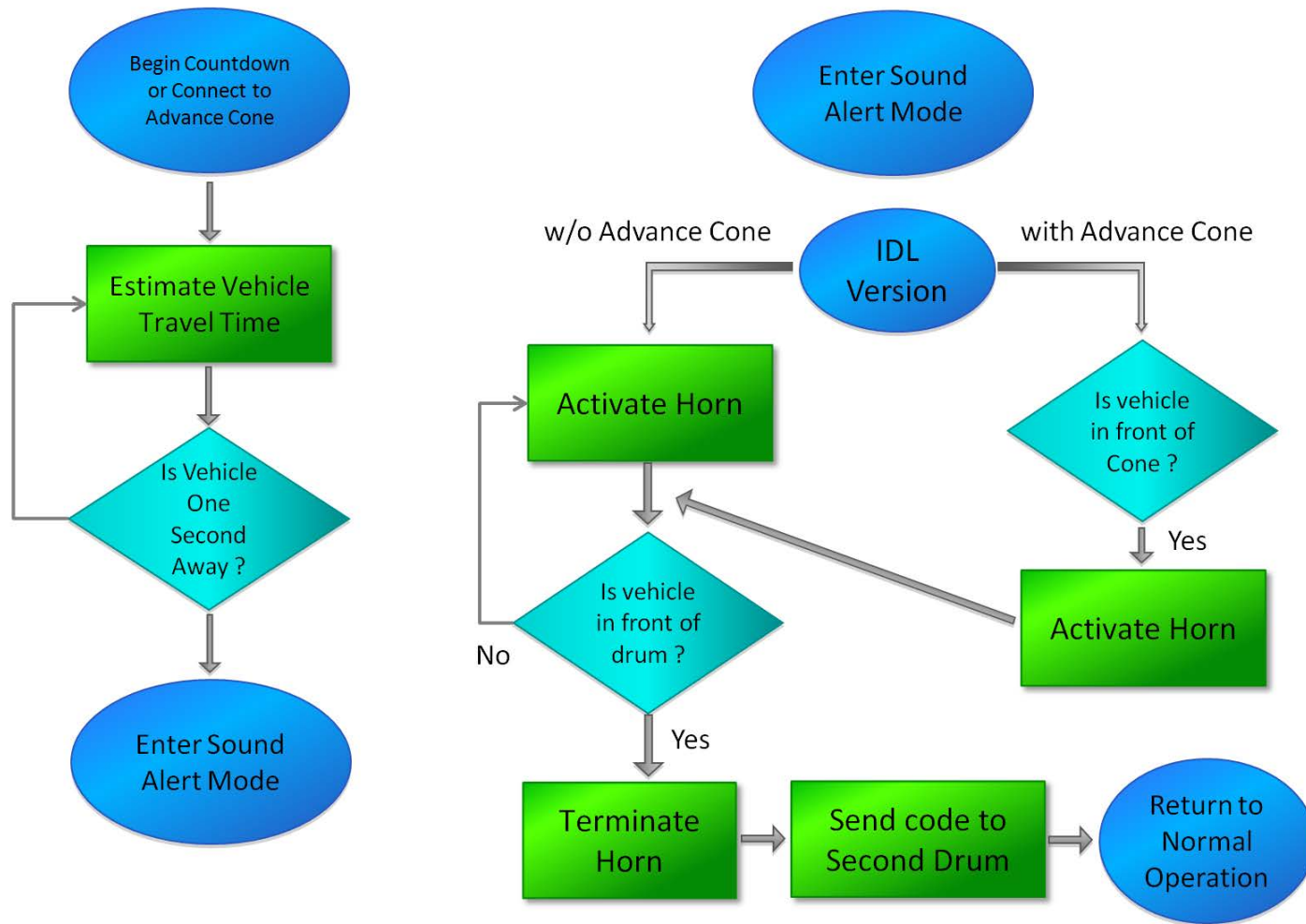
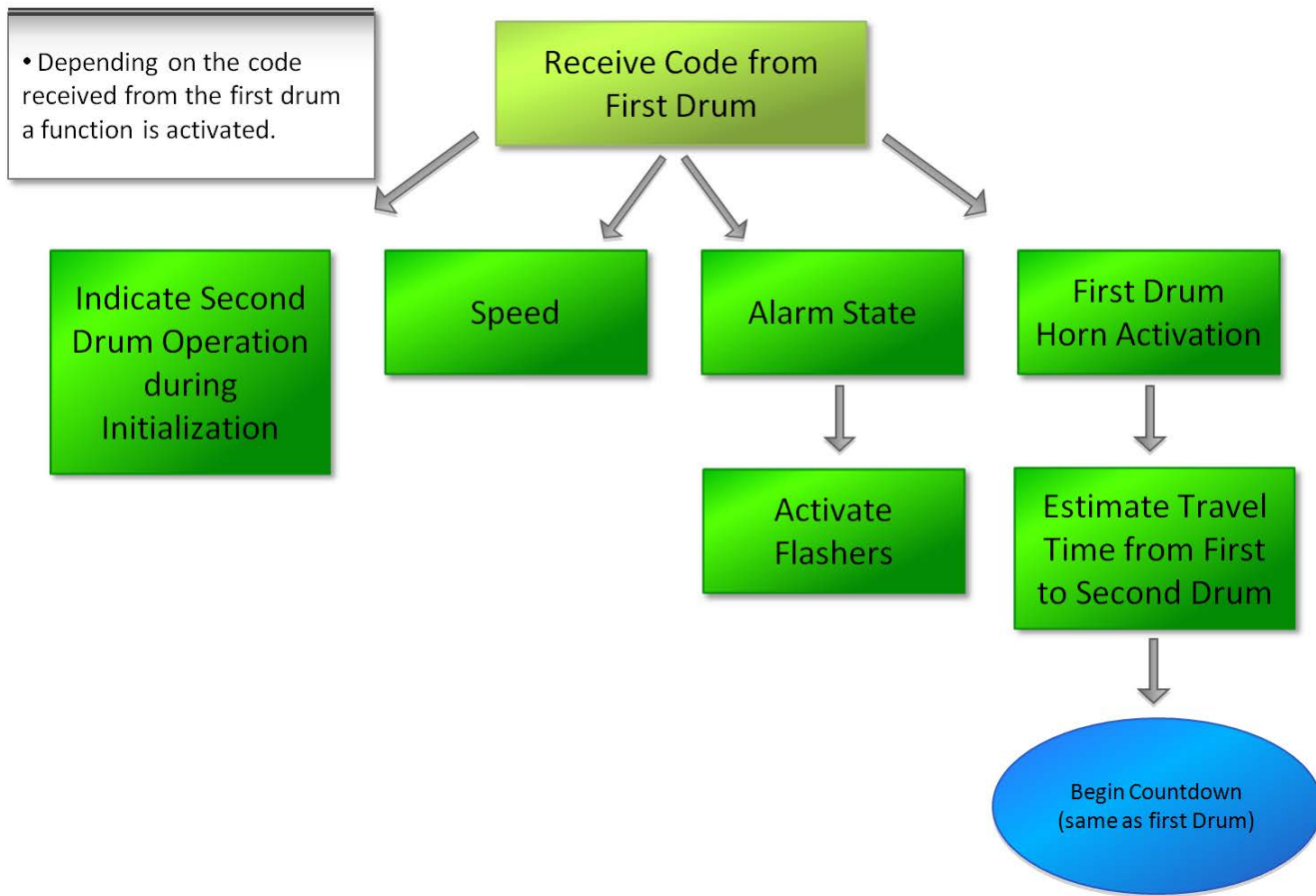


Figure 4.3 IDL Operation Flow Chart: Continuous Function and Speeding Vehicle Detection





**Figure 4.4 IDL Operation Flow Chart: Audible Alert Subsystem**



**Figure 4.5 IDL Operation Flow Chart: Second Drum Operation**

## 4.2 Prototype Testing

The IDL prototype was tested in three locations around the Twin Cities; the MnROAD facility of MnDOT involving test vehicles ranging from small to large, TH-65 in Isanti Co which is a road segment with legal speed limit of 55mph but real speeds usually reach 65mph or higher and traffic ranging from small vehicles to very large semi-trailers, and a remote segment of Co Road 3 in Pine Co, MN. The later was a remote location where the audible alarm system was tested for endurance. The most extensive tests were conducted on MnROADS where several of the systems bugs and issues were detected and resolved. Specifically, the system version operating with the help of the advance vehicle detection cone was only tested in MnROAD due to time constraints.



**Figure 4.6 MnROAD Testing of IDL**

The initial tests at MnROAD involved three types of vehicles; a passenger vehicle, a light truck, and a heavy 3-ton truck. Speeds up to 85mph were tested to prove that the system is fast enough to activate the warnings before the vehicle passes the drums. At speeds near or greater than 85mph it was reported that the audible warning is heard but for a very brief period since the vehicle is in the vicinity of each drum for less than a second. In such situations the two drum version is necessary since the single-drum can hardly be adequate.

The first field operational test at MnROAD also generated a change on the visual warning component. Specifically, the drivers reported that the then selected flashers were not visible from the vantage point of a truck driver. Subsequently, the flashers were replaced with different units that have considerably more power and range.

In all situations it was reported that both the audible and visual alarms were successful in attracting the attention of the drivers. Since these drivers were aware of the system beforehand such tests are not proper examples of the systems success. Further tests under real conditions are

required with equipment independently measuring the speed behavior of the targeted vehicles generating a statistically correct sample identifying the effect the IDL system has in reducing the speed of oncoming vehicles. Two reasons prevented the execution of such tests. First, the project schedule and issues in perfecting the hardware consumed too much time. Second, in order to conduct tests under realistic deployments of the IDL system a crashworthy version of the drums is necessary. The project budget did not allow for the production of such units.

At the time this document was composed there are discussions regarding demonstrations and further testing of the IDL system in MnROAD and elsewhere.

### 4.3 System Cost

Given that the system prototype developed utilizes single item purchases of over-the-counter components the reported costs do not reflect the costs of manufacturing the device (ordering bulk streamlined components). Specifically, the cost of the visual warning system can be greatly reduced if flasher components instead of finished products are used. Regardless, in this section we report the final components used in the IDL system along with their current costs in the market. When applicable the component manufacturer is included.

1. Drums (2): \$35-\$50 each including the base
2. Advance Cone (1): \$25
3. 12V Battery (2): \$15 each
4. Air horn (2):\$35 to \$50 each depending quality (metal or plastic)
5. Flashers (6 to 9): \$5 to \$50 each depending on quality.
6. Doppler Radar (1): \$300 to \$500 retail. Specifically the SS300 unit manufactured by Houston Radar Inc. <http://www.houston-radar.com/SS300-OEM-doppler-speed-sensor.php>
7. Ultrasonic distance sensors (3): \$50 to \$100 each in single item quantities and depending on model. Specifically the indoor and outdoor models of the MaxBotix sensors were used <http://www.maxbotix.com/products.htm>.
8. XBEE IEEE 802.15.4 radios (3): \$30 to \$50 plus ~\$5 for an external antenna. <http://www.digi.com/products/wireless-wired-embedded-solutions/zigbee-rf-modules/point-multipoint-rfmodules/xbee-series1-module#overview>
9. CPU and electrical components (2): \$45 for the microcontroller and approximately \$30 to \$50 in additional components. For the development of the prototype the STAMP microprocessor from Parallax Inc was used <http://www.parallax.com/Store/Microcontrollers/BASICStampModules/tabid/134/CategoryID/9/List/0/SortField/0/Level/a/ProductID/1/Default.aspx>. Retrospectively, this is neither the most appropriate nor the cheapest microprocessor available. It offered flexibility during the development and has the most flexible development environment. It is suggested that in further developments of the IDL another AVR processor is used streamlined for the final design.

The final cost of the IDL prototype (dual-drum version) ranges between \$1,000 and \$2,000 with the selection of the appropriate flasher units deciding the final cost even on a retail price basis.

## **Chapter 5. Conclusions and Recommendations**

The main objective of this project was to design a warning system for the protection of moving, temporary work zone operations. The system scope is not to alert the work zone crew but it is directed to the drivers of vehicles approaching the work zone at speeds that are higher than the posted or selected speed limit. The goal is to alert the drivers who may have missed the advanced flagger sign and can pose a danger to the work zone crew if they do not reduce their speed. The solution proposed in this project involves a device that can measure the speed of approaching vehicles, determine if it exceeds a predefined threshold, and if it does direct a clear message towards the speeding vehicle involving both visual and audible warnings.

### **5.1 Conclusions**

In cooperation with MnDOT engineers, the Intelligent Drum Line (IDL) system developed is comprised by two instrumented work zone drums. The drums, as described in this document, are comprised by four main subsystems; the sensor, the audible warning, the visual warning, and the communication subsystems. These subsystems are under the control of the Central Processing Unit CPU and powered by an appropriate 12V battery. The sensor subsystem is responsible for measuring the speed of the oncoming vehicles and for detecting the location of the vehicle in respect to the each of the drums. These are accomplished through microwave radar for the speed and several ultrasonic sensors for the position. The audible warning system is comprised by a powerful air horn mounted inside the drum and designed in such a way that the sound force is mainly directed toward the roadway while sound is suppressed in all other directions. The horn produces 120db warnings 5 feet from the drum in the road direction while the sound level does not exceed 85db in any other direction. The Visual Warning is delivered through a number of emergency flasher units mounted on the outside of the drum and appropriately directed toward the approaching vehicles. The communication between the IDL system drums and other components is achieved with the use of XBEE IEEE 802.15.4 radios operating in a preselected channel. The radios have a reported distance of 1-mile which exceeds the requirements for the operation for the IDL system. Prototypes of the IDL system were developed that can operate in two separate modes, single- and dual-drum versions. The cost of the single-drum prototype is estimated to around \$1100 while the second drum costs an additional \$800 since it does not include a radar sensor. These costs are based on single over-the-counter components and can be reduced to approximately half if sufficient large numbers of components are purchased specifically in the case of the flashers which ended up being ~50% of the price.

The system was tested only under simulated conditions with vehicles ranging from small to large. The conditions were simulated since the drivers were aware of the system beforehand and there were not located upstream of an actual work zone. Limited testing was conducted in case where the drivers were unaware of the system operation but again not in conjunction with actual work zone operations. Based on the recommendations of the test subjects, the dual-drum version is recommended since the presence of the second drum reinforces the warning on the drivers and therefore produces a more successful operation.

## 5.2 Recommendations

1. The IDL system needs to be streamlined if it is going to be produced for actual work zone operations. Specifically, the produced prototype is definitely not crashworthy. To pass FHWA crashworthiness tests the following aspects need to be streamlined:
  - a. The battery of the system needs to be incorporated inside the drum base and a power conduit mechanism devised that connects with the drum body without making a rigid connection with the base. The air compressor of the air horn system also needs to be situated in the drum base connected with the air horn with a detachable, flexible pressure tube. These two components are the largest and heaviest in the system and pose a danger if they are thrown away with force. Incorporated inside the drum base will safely be run-over by the vehicle.
  - b. The air-horn needs to be situated inside an enclosure that is part of the drum and therefore non detachable. Although the air horn has no significant mass it is best to remain with the drum body even when hit by a vehicle. The enclosure needs to be part of the drum mold and allow for the appropriate soundproofing material. This is the aspect that requires the cooperation with a drum manufacturer.
  - c. Preferably the radar and ultrasonic sensors should also be mounted in appropriately designed sockets on the drum. Although they have no significant mass, such mounting will offer the greatest protection to the components as well as prevent them to be detached during collision.
  - d. The flashers preferably need to be mounted internally with only the actual LEDs mounted on the surface of the drum. This way cheaper component can be used as well as produce a more streamlined version preserving the external smooth shape of the regular drum. Example of such mounting can be found in the flasher units mounted on curve warning signs and flashing LED stop signs.
  - e. The actual system controller as well as the radio can be either situated in the case of the drum or in order to simplify connections to the sensors be situated inside an appropriate enclosure inside the top of the drum. Specific details of such enclosures are out of the expertise of the authors and are better discussed with experts in drum manufacturing.
2. Pass FHWA crashworthiness tests so the system can be allowed to be tested in actual roadway work zones.
3. As briefly mentioned in the previous section, the selected microprocessor used in the current prototype may not be the most appropriate. Switching to a different microprocessor during the present project would have generated considerable additional delays and it was deemed unnecessary in the proof-of-concept objective this project had. If the IDL system moves to an implementation and testing phase it will be simple to select a more appropriate microprocessor with no change in the system design and improve its operation.
4. This project involved only the design and proof of concept of a work zone speed warning system. It did not include a human factors study focusing on the positive and possibly negative effects it can generate when it is used in practice. As pointed out, in the tests of the IDL system, the test drivers were aware of the system and therefore not surprised by the loud audible warning. Although we do not anticipate any serious side effects the acceptance from regular drivers needs to be investigated. A proper human factors study combined with a roadway safety study will produce definitive results regarding the effect the system has on the oncoming traffic.

## REFERENCES

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