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Advanced LED Warning System for Rural Intersections: Phase 2 (ALERT-2)

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February 2014

Research Project
Final Report 2014-10

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16. Abstract (Limit: 250 words)

This report presents findings of the second phase of the Advanced LED Warning System for Rural Intersections (ALERT) project. Since it is the next generation of the same system, the second phase system is referred to as the ALERT-2 system while the first system is referred to as the ALERT-1 system. The ALERT systems demand use of four basic Intelligent Transportation Systems (ITS) technologies: LED-based signs, renewable energy, non-intrusive sensors, and wireless communication. Use of these four basic technologies remained the same for both phases of the system. In the first phase, the data showed that the ALERT-1 system reduced vehicle speeds on the main approach, increased STOP wait time on minor approaches, and eliminated roll-throughs for vehicles on minor approaches when a conflict existed in the intersection. However, when no conflict exists in the intersection, an increase in roll-throughs for vehicles on the minor approaches was observed. The ALERT-2 system was redesigned to mitigate this increased roll-throughs. With respect to technological advances, the ALERT-2 system improves many aspects of the basic technologies, providing higher system reliability, easier installation and maintainability, and better self-sustainability through redesign of the renewable energy application. To assess the driver behaviors at the test site, 13 moths worth of video data and a survey of local residents were collected. This report describes the system development, implementation, and analysis of the video and survey data.

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Advanced LED Warning System for Rural Intersections: Phase 2 (ALERT-2)

Final Report

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Executive Summary

According to Minnesota's recent Intersection Green Sheets [1], 94,373 intersection-related crashes occurred during the last ten years in the state of Minnesota, and 43 percent (40,616 crashes) of them occurred at Thru/Stop intersections. Digging deeper, when the Minnesota crash data was isolated only to fatal crashes, 77% of all fatal crashes occurred from Thru/Stop intersections. According to the National Highway Traffic Safety Administration (NHTSA) study [2], of the 787,236 intersection-related crashes studied, about 96 percent (756,570 crashes) had critical reasons attributed to drivers, while the vehicle- or environmental-attributed critical reasons were less than 3 percent of these crashes. Among driver-attributed critical reasons, the most frequent critical reasons were inadequate surveillance (44.1%), followed by false assumption of other's action (8.4%) [2]. These studies led to the AASHTO Strategic Highway Safety Plan's recommendation [4] to "Provide an automated real-time system to inform drivers of the suitability of available gaps for making turning and crossing maneuvers."

This report presents findings of the second phase of the Advanced LED Warning System for Rural Intersections (ALERT) project. Since it is the next generation of the same system, this system is referred to as the ALERT-2 system. The ALERT system demands use of four basic Intelligent Transportation Systems (ITS) technologies: LED-based signs, renewable energy, non-intrusive sensors, and wireless communication. Use of these four basic technologies remained the same for both phases of the system. In the first phase, the data showed that the ALERT-1 system reduced vehicle speeds on the main approach, increased wait time, and eliminated roll-throughs for vehicles on minor approaches when a conflict existed in the intersection. However, when no conflict exists in the intersection, an increase in roll-throughs for vehicles on the minor approaches was observed [8, 9]. The ALERT-2 system was designed to mitigate this increased roll-throughs by redesigning the sign system. In ALERT-2, the two stop signs in the minor road approaches were turned into LED blinker STOP signs. The LED blinking was activated when a vehicle passes by the corresponding STOP Ahead sign and terminated when the vehicle arrives at the STOP sign. With this added feature, a vehicle approaching the intersection from the minor road is first presented with an activated blinker STOP sign.

For evaluation of the new design, the ALERT-2 system was installed at a completely different location from the ALERT-1 installation to eliminate the potential learning effect of drivers on the dynamic warning system. The site chosen is located at the intersection of Lismore Road and Lakewood Road, Duluth, Minnesota. Lismore Road is the major road with a through condition while Lakewood Road is the minor road with a stop condition. The speed limit of both roads is 55 mph (88.5 km/h). The Annual Average Daily Traffic (AADT) for Lismore Road is 970 vehicles per day, while Lakewood Road's AADT is 570 vehicles per day. A severe vertical curve exists on the west approach of Lismore Road, which significantly reduces the available intersection sight distance for vehicles stopped on either the north or south approaches of Lakewood Road.

To assess the effectiveness of ALERT-2, 13 months worth of video data were collected. The on-site video recording system consists of two network cameras, two illuminators, a PoE (power over Ethernet) switch, and a PC video server. The first camera records vehicles on the minor road entering the intersection; the second camera records the traffic on the major road. In addition, signal event loggers were installed to record activation of blinker signs and detector signal events. A total of 54,596 vehicles entering the intersection were analyzed through the video processing software developed and electrical actuation events recorded.

The roll-through percentage measured after ALERT-2 installation was 1.16% when an intersection conflict exists and 16.22% when no intersection conflict exists. This data agrees with the findings of the ALERT-1 study in that most roll-throughs occur when no intersection conflict exists. The roll-through percentage of before ALERT-2 installation was 28.15%, and this number included both conflict and no-conflict cases (it is not separable for before data). After installation of ALERT-2, this number decreased to 17.38%, which is the sum of 16.22% (no-conflict cases) and 1.16% (conflict cases). Based on this data, the ALERT-2 system was able to decrease the roll-throughs by 10.8%. However, it should be noted that this is actually a 22% improvement over the roll-throughs of ALERT-1 since it was increased by 11%. The minor road wait time at stop signs was 2.5 seconds for no-conflict cases and 3.91 seconds for conflict cases, resulting in a 56% increase in conflict cases. The analysis of average vehicle speeds on the major road showed a decrease of 3.89 mph in the conflict case. This decrease translates to 0.93 seconds of difference in time from the moment the driver passes the blinking sign to entering the intersection, thus increasing the gap time. The minor road wait time and the major road speed reduction are similar to that of ALERT-1.

In the ALERT-2 mail-in survey, 92% of the responses were either “strongly agree” or “agree” that the system improved the safety of the intersection. In the ALERT-1 survey, this number was 72% [9], i.e., ALERT-2 improved 20% over ALERT-1 on the question of improved safety. Another important result obtained was that 98% of responses were “strongly agree” or “agree” that the vehicle activated blinker STOP sign obtained their attention. This survey result clearly rebuts the concerns that blinker STOP signs may not be able to grab a driver’s attention as much as the design intended. Finally, 87% of the responses rated the effectiveness of the ALERT-2 system as “excellent” or “good.” In ALERT-1, 79% of the responses rated the system as “excellent” or “good” [9].

In conclusion, data analysis discussed above showed that the ALERT-2 system kept or improved all of the benefits of the ALERT-1 system while mitigating the roll-through problem of the ALERT-1 system when no conflict exists. In addition, the ALERT-2 system improved many of the non-apparent technological aspects of the ALERT-1 system, providing higher system reliability, easier maintainability, and better self-sustainability.

Chapter 1: Introduction

According to the Minnesota's 2011 Intersections Green Sheets [1] (an Excel spreadsheet of crash data published by the Minnesota Department of Transportation), 94,373 crashes occurred at intersections during the last ten years in the state of Minnesota, and 43% (40,616 crashes) of them occurred at Thru/Stop intersections. A Thru/Stop intersection typically consists of a major road that carries through-traffic with higher traffic volumes and a minor road that carries lower traffic volumes. The major road intersects the minor road, and the minor road approach is typically controlled by a stop sign. Digging deeper, when the Minnesota crash data was isolated only to fatal crashes, which are defined as the crashes that resulted in at least one fatality, about 77 percent of all fatal crashes occurred from Thru/Stop intersections. In order to better understand the cause of intersection crashes, the National Highway Traffic Safety Administration (NHTSA) studied the National Motor Vehicle Crash Causation Survey data and published the results in September 2010 [2]. According to this documentation, of the 787,236 intersection-related crashes studied, about 96 % (756,570 crashes) had critical reasons attributed to drivers, while the vehicle- or environmental-attributed critical reasons were less than 3 percent of these crashes. Among driver-attributed critical reasons, the most frequent critical reasons were inadequate surveillance (44.1%), followed by false assumption of other's action (8.4%) [2]. This result parallels with another study in Minnesota that drivers' inability to recognize the intersection was cause for only a small fraction of the crashes; instead, gap selection was the predominant problem [3]. These studies suggest that providing automated and timely surveillance, warning, or gap-assist information to drivers approaching the Thru/Stop intersection is one of the keys to reduce intersection-related crashes. This strategy is recommended by the AASHTO Strategic Highway Safety Plan, NCHRP-500, Objective 17.1 D1 – Provide an automated real-time system to inform drivers of the suitability of available gaps for making turning and crossing maneuvers [4].

Over the past several years, states and local agencies, industry, and university researchers have independently designed several different types of low-cost countermeasures to reduce un-signalized intersection crashes, and many of them are already installed or in a planning stage for evaluation. These countermeasures typically involve providing advance warnings or gap information to drivers, utilizing Intelligent Transportation Systems (ITS) technologies, such as speed feedback signs, LED blinker signs or LED flashers activated by intersection approaching traffic. In order to provide information and a guideline on these ITS-inspired efforts, FHWA published a documentation titled, "Stop-Controlled Intersection Safety: Through Route Activated Warning Systems" in 2011 [5] and provided information on example implementations of Missouri, North Carolina and Minnesota. More comprehensive resources on state DOT's efforts in intersection conflict warning systems are available in the web site managed by the ENTERPRISE pooled fund program [6].

In Minnesota, two different approaches of intersection conflict warning systems have been independently developed and deployed for evaluation [7-9]. The differences between the two approaches are mainly in power delivery, use of traffic detection technologies, and communication technologies between the signs and detectors. The first approach, which is referred to as the Rural Intersection Conflict Warning System (RICWS), uses utility AC power, inductive loop detectors for vehicle detection, and wired communication between detectors and signs [7]. The second approach, which is referred to as the **A**dvanced **LE**D Wa**r**ning System for **R**ural In**t**ersections (ALERT), more aggressively adopts recent ITS technologies, utilizing solar-powered renewable energy, LED integrated signs, non-intrusive vehicle detection systems, and wireless communication between devices in order to achieve ease installation and maintenance [8, 9]. It should be noted that the ALERT system was originally called ALWS (Advanced LED Warning System) but later changed to the present name ALERT to use a name that is easy to relate and remember.

The RICWS approach is more conservative and focuses on providing higher reliability, thus only utilizing proven Commercial Off-The-Shelf (COTS) products, but at a higher cost of installation and maintenance. The ALERT approach, on the other hand, is more focused on lowering the cost of installation and maintenance (typically one third of RICWS) by utilizing recent technologies in renewable energy, non-intrusive detectors, and wireless communications, but perhaps at a lower reliability of power delivery, due to battery and solar panel's dependency on weather conditions. In general, the ALERT system is preferred in rural intersections because of lower installation and maintenance costs, while RICWS is preferred in the urban intersections because AC utility power is easily available and solar panels are less desirable because of street clutter.

This report presents the second phase of the ALERT research project. In the first phase, the system was designed to assist drivers on the minor road to determine a sufficient gap to safely complete their turning maneuver, and assist drivers on the major road in their recognition of a potential conflict at the intersection. The findings of the first phase (ALERT-1) is that the system positively influenced in changing driver behavior by reducing vehicle speed on the major road, and increasing the wait time and eliminating roll-throughs for vehicles on the minor road when a conflict exists at the intersection [9]. However, an unintended consequence, an increase in roll-throughs by vehicles on the minor approach, was observed when no conflict existed at the intersection [9].

The observation that roll-through events increased when no conflict existed presented a unique dilemma to the research team. In effect, drivers were treating the system as a de-facto traffic signal. Through discussions with colleagues, this behavior was hypothesized but never actually observed. The dilemma can be summed up in the following question. Should these types of systems be deployed knowing that they may encourage the willful disregard of a regulator device, namely the STOP sign? There are three suggested solutions for this dilemma. First, accept the trade-off between an apparent improvement in intersection safety and the compliance with a STOP sign. Second, replace the STOP sign with a YIELD sign. Or third, add a feature to the ALERT-1 system that mitigates the de-facto traffic signal effect. For the phase two project, it was determined the best solution was to add a feature to the ALERT-1 system to mitigate the de-facto traffic signal effect. This feature was the dynamically activated blinker STOP signs which were wirelessly activated when vehicle presence is detected at the respective STOP Ahead sign. This modification was based on the study that flashing LED stop signs have been shown to be effective at reducing roll-throughs [10]. With this added feature, a vehicle approaching the intersection from the minor road is first presented with an activated blinker STOP sign after passing the STOP Ahead sign. The blinker STOP sign is turned off as the vehicle arrives at the intersection. The driver is then presented with the "VEHICLE APPROACHING" blinker warning sign which is located on the other side of the intersection and activated by an approaching vehicle on the major road.

Video data have been collected through an on-site video recording system. In the ALERT-1 system, two analog video cameras were used, which required digitization and produced poor image quality. In the ALERT-2 system, video quality was improved by deploying an IP-networked digital video recording system that consists of two network cameras, two illuminators, a PoE (Power over Ethernet) switch, and a PC video server. The PoE capability is important since there is no need to run separate cables for power and data. The digital video streams from two network cameras were directly transferred through the on-site Ethernet without digitization, and high quality images were recorded into a high-capacity hard disk on the video server. Availability of high-quality video helped automate the video analysis through image processing algorithms, resulting in analysis of more vehicle data than ALERT-1. Another important pieces of equipment used in the ALERT-2 system but not used in the ALERT-1 system was event-data loggers. These are standalone battery-powered devices that are able to record signal actuation events up to 32,510 readings. Several of these devices were installed on sign and detector units, and the collected data provided information on when the intersection was in conflict or no-conflict. The electrical event data was also used to verify whether a vehicle detection reliably triggered activation of the corresponding blinker signs.

The rest of this report are briefly described. Chapter 2 describes the project site, the ALERT-2 sign system design, power demand computation for battery sizing, and ALERT-1 /ALERT-2 comparison on power consumption. Chapter 3 describes microcontroller hardware, embedded firmware flow charts, and wireless transceivers, which are related to controls of the system. Both the lab and on-site tests were conducted before installation of the ALERT-2 system, and they are described in Chapter 4. Installation of the system at the site is described in Chapter 6. Chapter 7 includes all analysis results of the video data and mail-in survey collected. Chapter 8 concludes this report and provides future recommendations.

Chapter 2: System Design

2.1 System Design Goals

The design objective of the ALERT-2 system was to develop a low cost, low maintenance, easy to install, self-sufficient, and effective dynamic intersection conflict warning system powered by renewable energy. All component selections and the design choices are made based on this design objective.

2.2 Project Site and System Layout

2.2.1 Project Site

The project site chosen for the ALERT-2 system evaluation is at the intersection of Lismore Road and Lakewood Road, located north of Duluth, Minnesota. Lismore Road is the major road with a through condition, and Lakewood Road is the minor road with a stop condition. The speed limit of both roads is 55 mph (88.5 km/h). The Annual Average Daily Traffic (AADT) for Lismore Road is 970 vehicles per day, while Lakewood Road is 570 vehicles per day. A different site from the first phase of this study (ALERT-1) was chosen to eliminate any bias from “pre-conditioned” drivers. Figure 1 shows a satellite view of the chosen intersection.

Figure 1: Satellite view of the ALERT-2 study intersection [11].

A severe vertical curve exists on the west approach of Lismore Road which significantly reduces the available intersection sight distance for vehicles stopped on either the north or south approaches of Lakewood Road. Figure 2 shows the view of eastbound drivers in advance of the intersection with a blind vertical curve.

Figure 2: Sight restriction of the intersection for drivers traveling from the west side of Lismore Road.

2.2.2 System Layout

The original intersection layout had a “BLIND INTERSECTION AHEAD” sign for warning drivers traveling eastbound on Lismore Road that there is limited visibility due to the vertical curve. Figure 3 shows the original layout of the intersection before installation of the ALERT-2 system. The “BLIND INTERSECTION AHEAD” sign was located 775 ft (236.22 m) west from the intersection. The size of this signs was 36 in (91.4 cm). This sign was removed from the intersection upon installation of the ALERT-2 system. The intersection layout after installation of the ALERT-2 system is shown in Figure 4 and is described next.

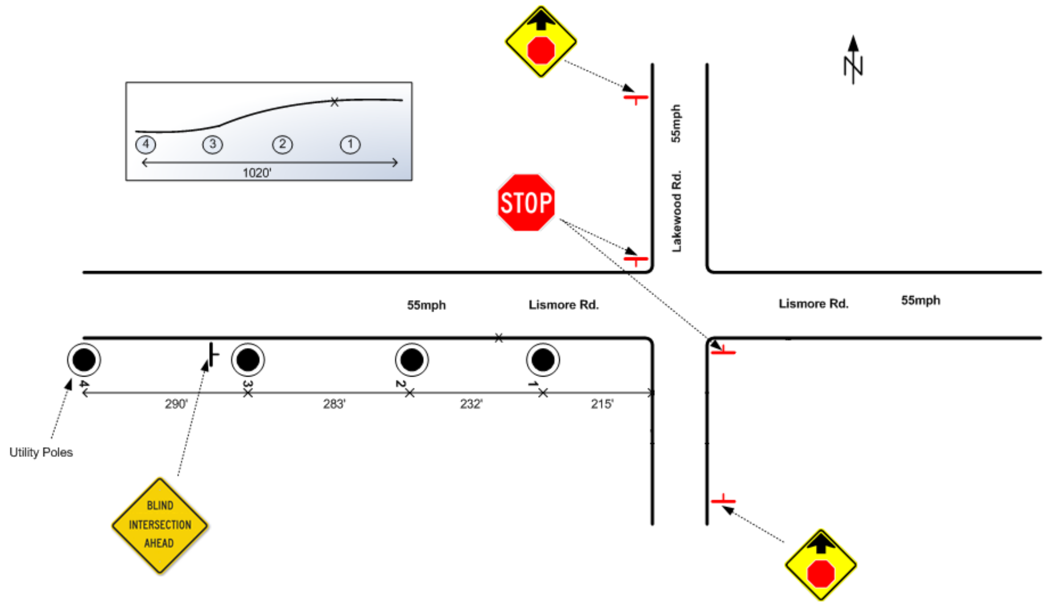


Figure 3: Intersection layout before installation of ALERT-2.

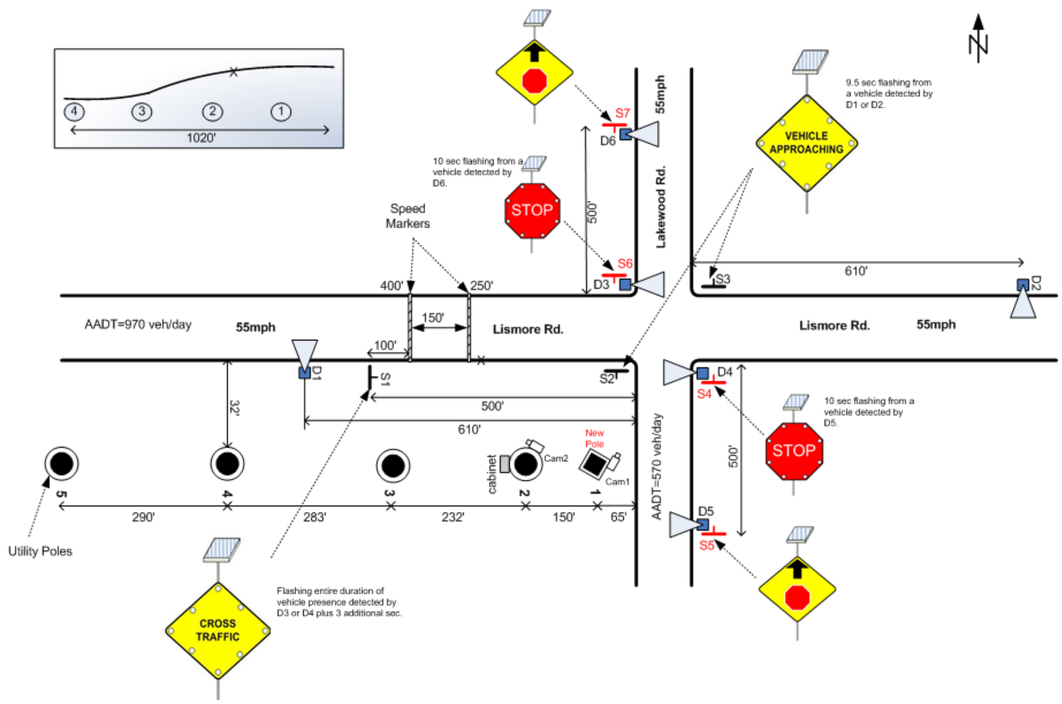


Figure 4: Intersection layout after installation of ALERT-2.

The warning system consists of six vehicle detectors and five blinker signs and works as follows.

- Two Doppler radar detectors are located on Lismore Road; one of them (D1) is located west of the intersection and detects vehicles traveling eastbound, the other (D2) is located east of the intersection and detects vehicles traveling westbound. When a vehicle is detected by either Doppler detector, a wireless signal is transmitted to both blinker warning signs at the intersection, S2 and S3, with the legend "VEHICLE APPROACHING", and they flash for a fixed duration of 9.5 seconds. The flash time was calculated as the expected time for an eastbound vehicle traveling at the posted speed limit to arrive at the intersection, as this was considered the critical movement. If another vehicle is detected inside the 9.5 second blinking, a new fresh 9.5 second blinking time is started from the time of detection.
- Two Frequency Modulated Continues-Wave (FMCW) radar detectors (D3 and D4) are installed on the top of the two STOP signs located on the northwest and southeast quadrants of the intersection; these detectors detect vehicles stopped at the STOP signs. When a vehicle is detected at either STOP sign, a wireless signal is transmitted to the main approach blinker warning sign, S1, with the legend "CROSS TRAFFIC", and LEDs flash for the entire duration while the vehicle is present inside the STOP sign detection zone.
- Two Doppler radar detectors are located on Lakewood Road (D5 and D6), installed on top of the "STOP Ahead" signs, and detect vehicles approaching the intersection from both north and south legs (minor road). As a vehicle passes through the "STOP Ahead" sign, an actuation signal is wirelessly transmitted to the respective Blinker STOP sign, which then flashes for a fixed duration of 10 seconds. This time corresponds to an estimated time for a vehicle to decelerate from the STOP Ahead sign to the stop bar.

The locations of the major road detectors and blinker signs were calculated based on the following information: the posted speed limit of the major road (V_{major} which is 55 mph), the minimum advanced placement distance for major road warning sign (which is 320 ft) [12], and passenger vehicle time gap (t_g) for case B1-left turn from minor road (which is 7.5 sec) [13]. The computed Intersection Sight Distance (ISD) [14] is then:

$$ISD = 1.47*V_{major}*t_g = 1.47 * 55 * 7.5 = 606 \text{ ft} \approx 610 \text{ ft}$$

Tables 1-3 provide further details of the ALERT-2 signs, detectors, and their relations. Table 1 describes the Blinker signs; Table 2 describes the radar detectors; and Table 3 describes the communication messages used in the system.

Table 1: Blinker Signs Used in ALERT-2

Sign	Description	Dimensions
S1	"CROSS TRAFFIC" warning sign located on Lismore Road (major road) 500 ft west of the intersection	48 in (121.9 cm)
S2, S3	"VEHICLE APPROACHING" warning sign located on the northeast and southwest quadrants of the intersection	36 in (91.4 cm)
S4, S5	"STOP" sign located on the northwest and southeast quadrants of the intersection	36 in (91.4 cm)

Table 2: Radar Detectors Used in ALERT-2

Detector	Type	Description
D1, D2	24 GHz Microwave Doppler Radar	Located 610 ft on both east and west legs of Lismore Road and detect vehicles traveling toward the intersection
D3, D4	Frequency modulated continuous-wave (FMCW) Radar	Installed on top of the two STOP signs, located on the northwest and southeast quadrants of the intersection, and detect vehicles inside the STOP sign detection zone.
D5, D6	24 GHz Microwave Doppler Radar	Installed on top of the "STOP Ahead" signs, located on both north and south leg of Lakewood Road, and detect vehicles approaching the intersection from the minor road.

Table 3: Communication Relations Between Detectors and Signs in ALERT-2

Source	Destination	Message	Action
D1	S2, S3	A vehicle is approaching the intersection from the west side of the major road.	S2 and S3 flash for a duration of 9.5 seconds.
D2	S2, S3	A vehicle is approaching the intersection from the east side of the major road.	S2 and S3 flash for a duration of 9.5 seconds.
D3	S1	A vehicle is approaching or stopped at the STOP sign (S6) on the north leg of Lakewood Road.	S1 flashes for the entire duration of vehicle presence at the STOP sign plus three additional seconds.
D4	S1	A vehicle is approaching or stopped at the STOP sign (S5) on the south leg of Lakewood Road.	S1 flashes for the entire duration of vehicle presence at the STOP sign plus three additional seconds.
D5	S4	A vehicle passes the "STOP Ahead" sign and is approaching the intersection from the south side of Lakewood Road.	S4 flashes for a duration of 10 seconds.
D6	S6	A vehicle passes the "STOP Ahead" sign and is approaching the intersection from the north side of Lakewood Road.	S6 flashes for a duration of 10 seconds

2.3 Power Demand Estimates

The next step in the design process is to calculate the expected power demand of each unit in the system. Table 4 summarizes power consumption of the key components of the ALERT-2 system.

Table 4: Power Consumption of ALERT-2 Components

Component	Current Draw	Power Consumption
FMCW Radar Detector	100mA@12V	1.2 W
Doppler Radar	Standby: 70mA@12V	0.84 W
	Active: 115mA@12V	1.38 W
Blinker STOP Sign	Idle: 16 mA@2.4V	38.4 mW
	Active: 1A@2.4V	2.4 W
Blinker Warning Sign	Idle: 16 mA@2.5V	40 mW
	Active: 1A@2.5V	2.5 W
Charge Controller	8mA@12V	96 mW
Wireless Module: XBee Pro	Transmit: 215mA@3.3V	709.5 mW
	Receive: 55mA@3.3V	181.5 mW

The active state is when the component is detecting (Doppler Radar), transmitting/receiving (Wireless Module), or blinking (Blinker Sign).

2.3.1 Units with FMCW Radar (D3, and D4)

There are two units with FMCW stationary radar in the ALERT-2 system, located at either STOP sign on Lakewood Road. Each unit consists of a FMCW radar sensor for detecting vehicle presence, a Blinker STOP sign, a wireless module, and a charge controller. Figure 5 shows a diagram of the FMCW radar unit. Using the power consumption values in Table 4, the estimated power consumption of a FMCW radar unit is given by:

$$P_{S.R.} = 1.2\text{ W} + 38.4\text{ mW} + 96\text{ mW} + 181.5\text{ mW} = 1515.9\text{ mW} \approx 1.516\text{ W}$$

To calculate the average daily watt hours (Wh) usage, the total watts must be multiplied by 24 hours. The estimated daily energy consumption of the FMCW radar unit is then:

1.516 W x 24 hours = 36.384 Wh per day.

In this calculation, the idle power consumption (38.4 mW) of a blinker sign was used. To more accurately calculate the expected energy consumption, we consider power consumption under signal activation. It is assumed that the blinker sign will flash for an average of 10 seconds when a vehicle is detected, and half of this time will be On-time and half will be Off-time, i.e.,

570 AADT x 5 sec = 0.033 days, and:
2.4 W x 0.033 = 0.08 Wh per day for blinker STOP sign

Also, to calculate power consumption of the wireless module, expected transmission time at the 9600 bits per second (baud rate) is computed:

12Byte x 8 / 9600 = 10 ms, and thus:
570 AADT x 0.01 sec = 0.00007 day

Considering sending of "Alive" signal every 5 minutes adds up to:

12 x 24 x 0.01 sec = 0.00003 day, therefore:
709.5 mW x 0.00003 = 0.021 mWh per day

Considering average of two retries each transmit: 0.021 mWh x 2 = 0.042 mWh per day

Therefore, the total daily power consumption of the FMCW radar unit is:

36.384 Wh + 0.08 Wh + 0.042 mWh = 36.5 Wh per day

Calculating double storage to prevent battery damage: 36.5 Wh x 2 = 73 Wh

Considering a temperature adjustment factor, which is 1.59, then: 73 Wh x 1.59 = 116.1 Wh

For 23 days of power storage without charging, the final battery capacity required is:

116.1 Wh x 23 days = 2670 Wh

Solar panel consideration:
If 4 hrs of sun per day (Annual average),
36.47 Wh x 1.24 (batteries non-idealities)/4 hrs = 11.31 Watts of energy capture.
If 2 hrs of sun per day (Nov-Dec),
36.47 Wh x 1.24 (batteries non-idealities)/2 hrs = 22.62 Watts of energy capture.
The final battery and solar panel sizes that selected based on the above requirements for the FMCW unit are summarized in Table 5.

Table 5: Battery and Solar Panel Sizes Selected for the FMCW Radar Unit

Component	Qty	Part No.	Parameters
Battery	2	PVX-2240T	2x6Vx224Ah= 2688 Wh
Solar panel	1	SX 320J	20 W

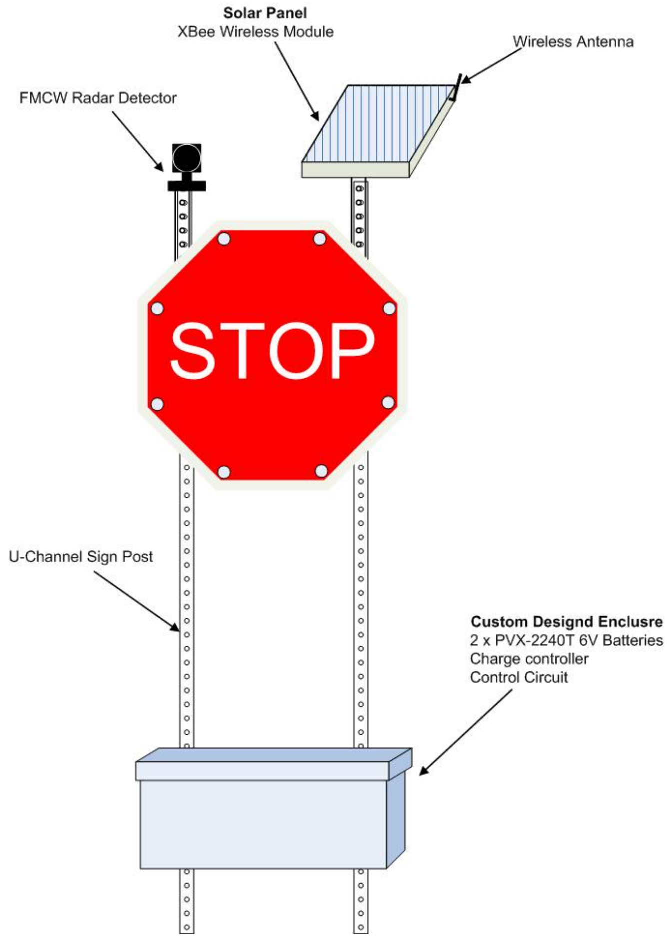


Figure 5: FMCW radar unit.

2.3.2 Units with Doppler radar: (D1, D2, D5, and D6)

There are four Doppler radar units in the ALERT-2 system, two are located on east and west legs of the intersection (Lismore Road), and the other two are installed on top of the "STOP Ahead" signs, located on north and south leg of the intersection (Lakewood Road). Each unit consists of a Doppler radar sensor for detecting approaching vehicles, a wireless transceiver module, and a charge controller. Figure 6 shows diagrams for each type of the two Doppler radar units. Using the power consumption values in Table 4, the estimated daily power consumption of the Doppler radar unit for standby state is:

$P_{D.R.}$= 0.84 W + 96 mW + 181.5 mW = 1117.52 mW ≈ 1.12 W

The average daily watt hours (Wh) is then: 1.12 W x 24 hours = 26.88 Wh per day

To more accurately calculate the expected power consumption, we assume the detection time of 1 second for each detection and compute the additional energy needed in activated state using AADT:

970 AADT x 1 seconds = 0.01123 days, and:
1.38 W x 0.01123 = 0.0155 Wh per day

The total transmission time considering 9600 bit per second baud rate is:

TxTime = 12Byte x 8 / 9600 = 10 ms, Therefore:
970 AADT x 0.01 sec = 0.00012 day

Considering sending an "Alive" signal every 5 minutes with two retries, the additional energy need is 0.042 mWh as computed in Section 2.3.1.

Therefore, the daily power consumption of the Doppler radar unit is:

26.88 Wh + 0.0155 Wh + 0.043 mWh ≈ 26.9 Wh per day

Calculating double storage to prevent battery damage gives: 26.9 Wh x 2 = 53.8 Wh

Considering the temperature adjustment (factor=1.59) gives: 53.8 Wh x 1.59 = 85.55Wh

Sizing the battery for 30 days of storage without charging gives: 85.55 Wh x 31 days = 2652 Wh

Solar panel:

If 4 hrs of sun per day (Annual average),

26.88 Wh x 1.24 (batteries non-idealities)/4 hrs = 8.34 Watts of energy capture.

If 2 hrs of sun per day (Nov-Dec),

26.88 Wh x 1.24 (batteries non-idealities)/2 hrs = 16.67 Watts of energy capture.

The final battery and solar panel sizes selected for the Doppler radar unit is summarized in Table 6.

Table 6: Battery and Solar Panel Sizes Selected for a Doppler Radar Unit

Component	Qty	Part No.	Parameters
Battery	2	PVX-2240T	2x6Vx224Ah= 2688 Wh
Solar panel	1	SX 320J	20 W

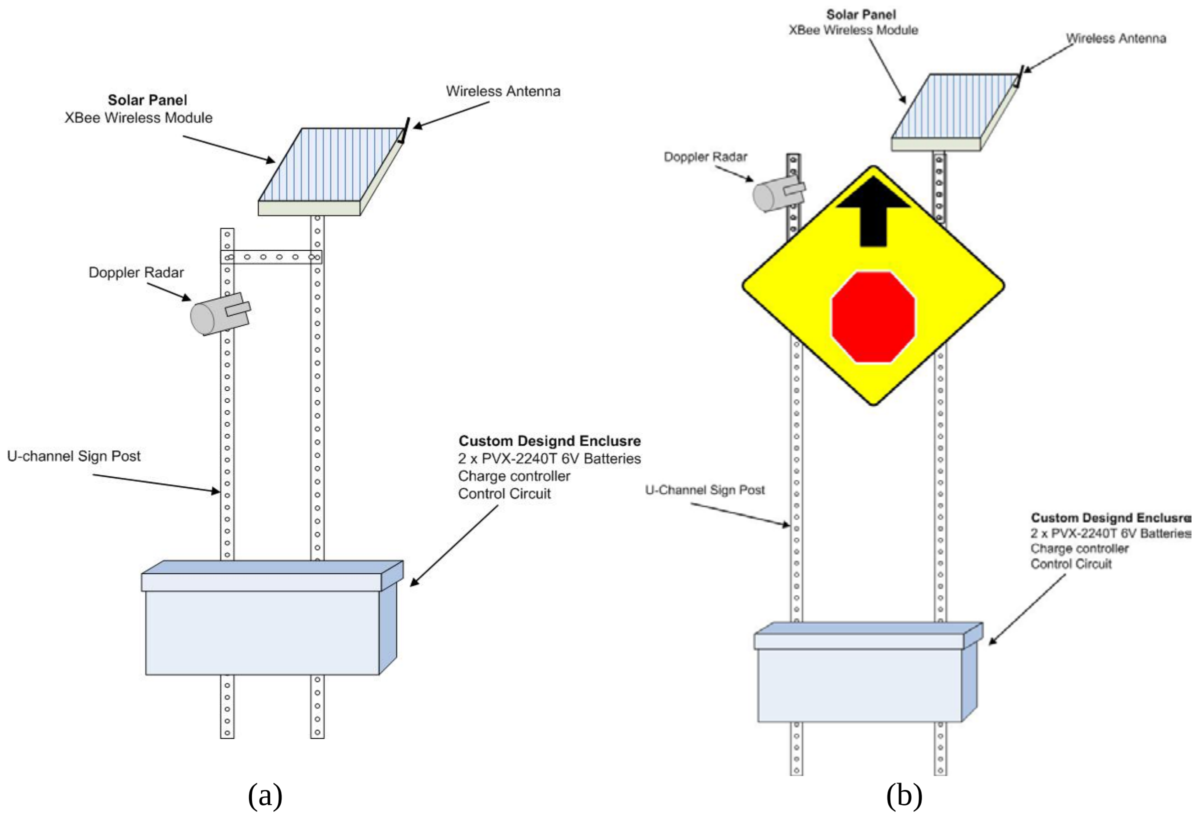


Figure 6: Doppler radar units: (a) located on the major road, (b) located on the minor road.

2.3.3 Units with Stand-alone Blinker Sign: (S1, S2, and S3)

There are three stand-alone Blinker warning signs in the ALERT-2 system. Two blinker signs are located at the NE and SW corners of the intersection of Lismore Road and Lakewood Road. The third blinker sign is located west of the intersection on the south side of Lismore Road. These signs were manufactured by Tapco Traffic and Power Control Co. and come with preinstalled eight high-power LEDs spread around the perimeter of the sign. Figure 7 shows a diagram of a stand-alone warning blinker sign unit. Using the power consumption values in Table 4, the estimated power consumption and daily power consumption of a unit with a stand-alone blinker sign at an idel state is given by:

P_B= 40 mW + 96 mW + + 181.5 mW = 317 mW
317 mW x 24 hours =7608 mWh ≈ 7.61 Wh per day.

For more accurate computation, we need to add power consumptions during active states. Assume that the blinker sign will flash for an average of 10 seconds when a vehicle detected, half of this time will be On-time and half will be Off-time:

970 AADT x 5 seconds = 0.056 days, and:
2.5 x 0.056 = 0.140 Wh per day

The total transmission time considering 9600 bit per second baud rate is:

Txtime = 12Byte x 8 / 9600 = 0.01 = 10 ms, therefore:
970 AADT x 0.01 sec = 9.7 s = 0.00012 day, and:
709.5 x 0.00012 = 0.08 mWh per day

Considering sending an “Alive” signal every 5 minutes with two retries, the additional energy need is 0.042 mWh as computed in Section 2.3.1.

Therefore, the daily power consumption is:

7.61 Wh + 0.140 Wh + 0.122 mWh = 7.75 Wh per day

Calculating double storage to prevent battery damage gives: 7.76 Wh x 2 = 15.52Wh

Considering the temperature adjustment (factor=1.59) factor gives: 15.52 Wh x 1.59 = 24.7 Wh

Considering 50 days of storage without charging: 24.7 Wh x 50 days = 1,235 Wh

Solar panel:
For 4 hrs of sun per day (Annual average):
7.76 Wh x 1.24 (batteries non-idealities)/4 hrs = 2.4 Watts of energy capture.
For 2 hrs of sun per day (Nov-Dec):
7.76 Wh x 1.24 (batteries non-idealities)/2 hrs = 4.8 Watts of energy capture.

The final value selected for this unit is summarized in Table 7.

Table 7: Battery and Solar Panel Selection for Blinker Sign Unit

Component	Qty	Part No.	Parameters
Battery	1	PVX-1040T	12Vx104Ah= 1,248 Wh
Solar panel	1	SX 320J	20W

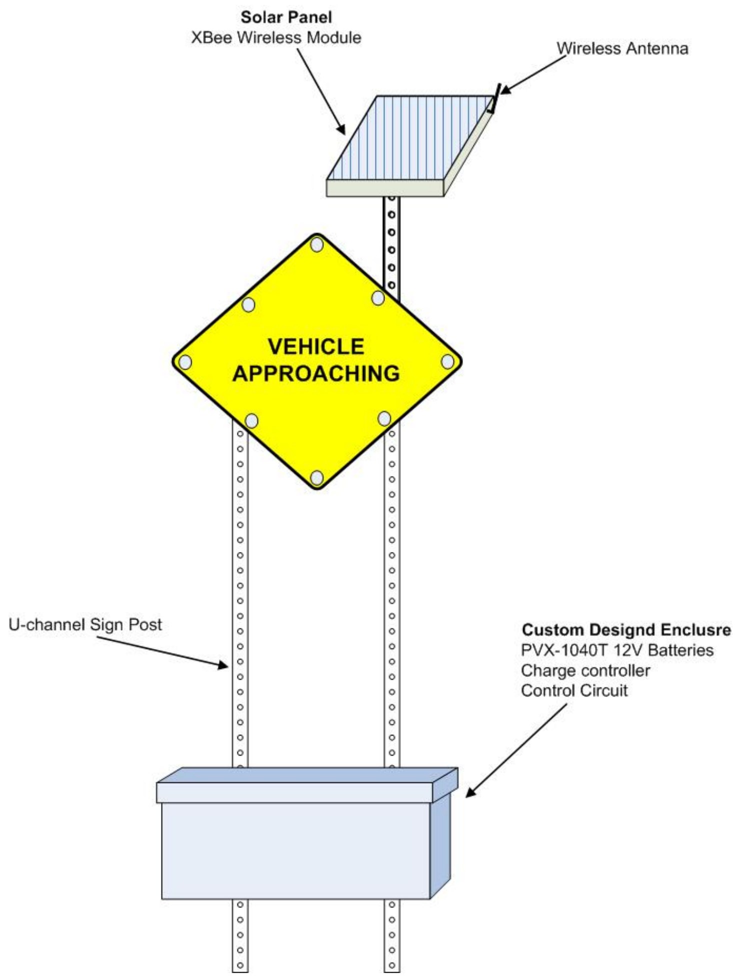


Figure 7: Blinker sign unit.

The results of Eq. 1, 2, and 3 are estimates of the daily power consumption for all three units of the ALERT-2 system. These estimates are used to size the batteries and the solar panels. Table 8 summarizes the power consumption, storage requirements, and battery selection for each unit of the ALERT-2 system:

Table 8: Power Consumption and Storage Requirement of the ALERT-2 System

Unit	Energy Consumption	Battery Selection	Solar Panel
D3&S6, D4&S4	116.1 Wh @ 23 days = 2670 Wh	PVX-2240T@2 (2x6Vx224Ah=2,688Wh)	SX 320J (20 W)
D1, D2, D5,D6	85.55 Wh @ 31 days = 2652Wh	PVX-2240T@2 (2x6Vx224Ah=2,688Wh)	SX 320J (20 W)
S1, S2,S3	24.7 Wh @ 50 days = 1,235 Wh	PVX-1040T@1 (12Vx104Ah=1,248 Wh)	SX 320J (20 W)

2.4 Battery Sizing and Charge Controller Selection

In the ALERT-1 system, lithium-ion (Li-ion) batteries were used and mounted below the solar panel. During the project, it was learned that Li-ion batteries' capacity is drastically reduced under a cold temperature. In the ALERT-2 system, the research team decided to use a deep-cycle Absorbed Glass Matts (AGM) batteries since this type of batteries have been successfully used in cold temperatures.

<u>2.4.1 FMCW Radar Unit</u>

For the FMCW radar unit, 23-days of continuous power supply is used as the battery storage requirement, which amounts to 2,668 Wh. This design choice is made based on availability of batteries and a reasonable size of the enclosure. The battery selected for this unit was the Sun Xtender PVX-2240T which is 6 Volt VRLA-AGM Deep Cycle battery with Nominal Capacity Ampere Hours of 224 Ah (Figure 8). Two batteries are connected in series to produce 12V. This battery was purchased from a local Batteries Plus store for $274. The dimensions of this battery are 10.28" x 9.92" x 7.06" and it weighs about 67 lbs. It should be noted that 23 days can only drain 50% of the battery by design, and, if we allow discharge of deep cycle, it should last up to 42 days without charging.

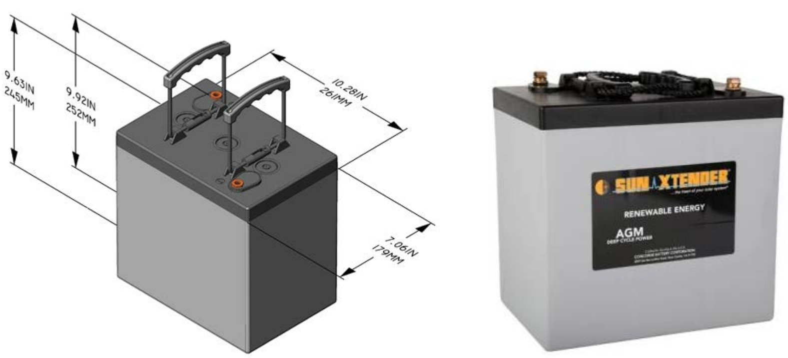


Figure 8: Sun Xtender PVX-2240T 6 V, 224 Ah (1344 Wh) VRLA-AGM battery.

<u>2.4.2 Doppler Radar Unit</u>

A Doppler radar unit consumes 85.55 Wh per day. Using the same battery pack as an FMCW radar unit would support 31 days for 50% drain and 62 days for 100% drain of the battery pack.

<u>2.4.3 Blinker Sign Unit</u>

A stand-alone blinker sign unit consumes only 24.7 Wh per day. Using the same battery pack as the Doppler radar unit would be able to support 109 days for 50% drain and 218 days for

100% drain without charging. This is an over design and would increase the cost unnecessarily. Therefore, the selected battery is 12V VRLA-AGM Deep Cycle Battery, Sun Xtender PVX-1040T, with Nominal Capacity of 1,248 Wh (Figure 9). This battery can support a blinker sign unit up to 50 days for 50% drain and 100 days for 100 % drain.   This battery was purchased from a local Batteries Plus store for $ 268.5. The dimensions of this battery are 12” x 8.93” x 6.60” and it weighs 63 lbs.

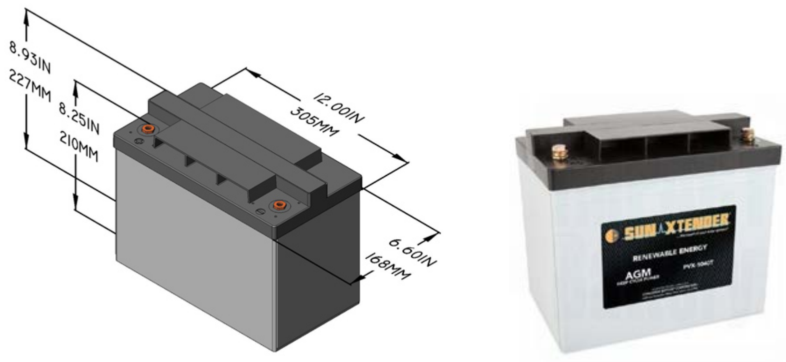


Figure 9: Sun Xtender PVX-1040T 12 V, 104 Ah (1,248 Wh) VRLA-AGM battery.

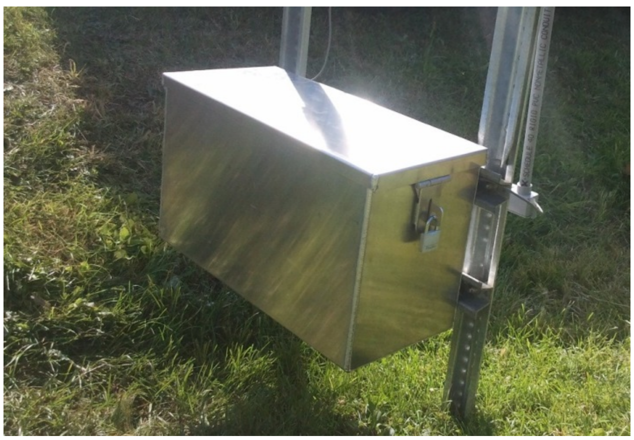
2.4.4 Charge Controller

The charge controller used in this project is Morningstar SunSaver SS-6-12V (Figure 10). This charge controller is used for charging AGM batteries. The SunSaver-6 is rated for 12 V systems and uses an advanced series Pulse Width Modulation (PWM) charge control for constant voltage battery charging. The maximum solar array open circuit voltage is 30 V. The operating power consumption is 8 mA. Use of cooper wires between 10 AWG and 14 AWG are recommended. Therefore, 12-AWG wires are used to connect the charge controller with the solar panel and battery.

Figure 10: Morningstar SunSaver-6 solar charge controller.

2.5 Custom Designed Cabinet

For easy access of electronic circuits and batteries for operational tests and maintenance, the controller circuit, the batteries, and the charge controller are placed inside a custom designed cabinet. The cabinet is mounted on the U-channel sign post, one to two feet from the ground elevation. To insulate the batteries from cold temperatures, a 1” foam insulation layer is added at the inner sides of the cabinet. An image of the cabinet and its design specification is shown in figure 11.



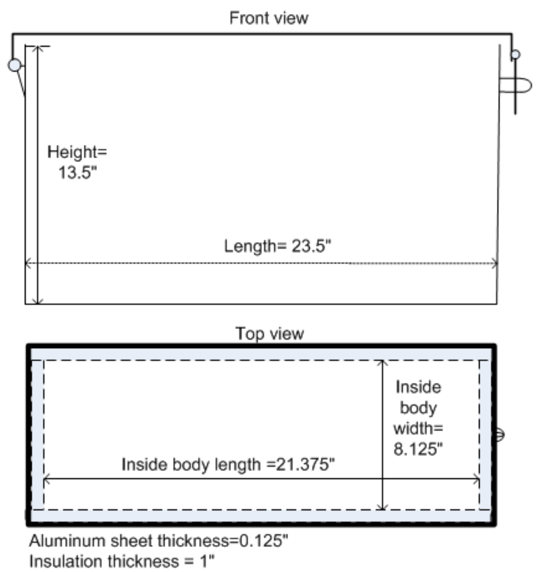


Figure 11: A custom design cabinet houses the controller circuit, charge controller, and batteries.

Since the batteries and all control circuits are housed in the cabinet less than 2 ft from the ground, it allowed maintenance and operational tests to be done without climbing the sign post with a ladder, which was the case in the ALERT-1 system. The top of the cabinet was mounted at approximately 20 inches, and was fixed onto the ground riser post. The purpose of this design was to ensure the cabinet was located at or below a typical vehicle bumper height and that the cabinet would not fly over the hood of a vehicle if the sign structure was impacted. Although this design has not been formally crash tested, the design parameters were such as to meet the general principles of the AASHTO Roadside Design Guide. This design change was one of the improvements done in the ALERT-2 system after learning maintenance difficulties from the ALERT-1 study.

2.6 ALERT-1 and ALERT-2 Power Consumption Comparison

First, the batteries used in the ALERT-2 system are AGM batteries, versus Li-ion batteries used in the ALERT-1 system. AGM batteries offer a low internal resistance and rapid migration of the acid into the glass matt plate, allowing deliver and absorb higher rates of amperage and quicker charging and discharging operates in low temperature environments. In contrast, Li-ion battery capacity start to quickly shrink at low temperatures. It has been reported that the capacity of Li-ion cells at -40ºC is 12% of the room temperature value [24]. In addition, consumer graded Li-ion batteries cannot be charged below 0 ºC. Second, the capacity of battery was increased from 106 Wh in ALERT-1 to 2,688 Wh in the ALERT-2 system, allowing more energy storage, especially during the winter months in Minnesota where temperatures regularly deep below 0°F. Third, only 20W solar panels are used in the ALERT-2 system. Table 9 summarizes the differences between the ALERT-1 and ALERT-2 systems on power demand, battery capacity, and solar panels.

Table 9: Power Demand, Battery Capacity, and Solar Panel Comparison

	Radar Detector Units		**Blinker Sign Units**	
	ALERT-1	**ALERT-2**	**ALERT-1**	**ALERT-2**
Average Daily Power Demand	26 Wh	36.5 Wh	8 Wh	7.8 Wh
Battery Capacity	106 Wh	2,688 Wh	67 Wh	1248 Wh
Days of Storage Without Charge	7 days	23 days	7 days	50 days
Solar Panel	20 W	20 W	14 W	20 W

2.7 Solar Energy Estimate and Solar Panel Selection

The availability of solar and wind energy in terms of potential convertible energy is highly dependent on location, and studying the expected annual availability is extremely important for system design. The National Renewable Energy Lab (NREL) provides an excellent resource for this study. For the solar radiation energy, NREL provides monthly breakdowns which should be used as an expected availability of solar energy source. The map in Figure 12 shows the national solar radiation for flat plate, solar panels facing south. According to this map, Duluth, MN provides 4.33 $kWh/m^2/day$. These numbers are used in the system design to estimate the amount of energy that could be generated by solar radiation.

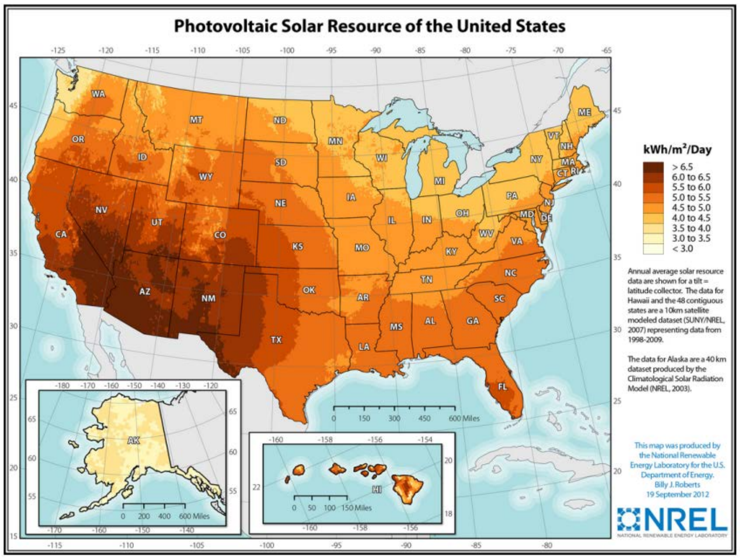


Figure 12: National average PV solar radiation energy map [15].

According to NREL data, 3.0-3.5 kWh/m^2/day of solar radiation is available in Duluth, MN in October, which represents fall. During January, which represents winter, 2.5-3.0 kWh/m^2/day is available. During April, which represents spring, the location provides 5.0-5.5 kWh/m^2/day. Finally, in July, which represents summer, the location provides 5.5-6.0 kWh/m^2/day. These numbers are used in the system design to estimate the amount of energy that could be generated by solar radiation.

The solar panel selected for ALERT-2 is the bp Solar SX 420J. Its specifications are summarized in Table 10.

Table 10: bp Solar SX 420J Solar Panel [16]

Model	Power	Open Circuit Voltage	Short Circuit Current	Peak Voltage	Peak Current	Weight	Dimensions
SX 420J	20 W	21.0 V	1.29 A	16.8 V	1.19 A	6 lbs	16.7 in x 19.8 in x 2 in

The unit kWh/m2/day is essentially equivalent to "hours of full noontime sun per day". To calculate an estimate of the expected Average Daily Producible Power (ADPP) of a solar panel, the following equation is used:

$$\text{ADDP (Wh)} = \text{solar panel power (kW)} \times \text{kWh/m}^2\text{/day} \times \text{efficiency factor} \times 1000$$

The efficiency factor is used to allow for unavoidable system inefficiencies. In Minnesota, the maximum convertible power of the 20.0 W PV is about 15.0 W under the full sun, which is 75 percent. Using an efficiency factor of 75 percent, the expected ADPP of the BP Solar SX 420J solar panel for each season is estimated as:

0.02 kW x 5.25 kWh/m^2/day x 0.75 = 78.8 Wh for spring
0.02 kW x 5.75 kWh/m^2/day x 0.75 = 86.3 Wh for summer
0.02 kW x 3.25 kWh/m^2/day x 0.75 = 48.8 Wh for fall
0.02 kW x 2.75 kWh/m^2/day x 0.75 = 41.3 Wh for winter

Since the stationary detector requires around 36.47 Wh per day, the selected solar panel is sufficient to supply enough power for the unit year round.

Chapter 3: Controller Design

The controller circuit, located in the custom designed cabinet, contains a PIC18F2455 microcontroller and communicates serially with a wireless module (XBee Pro) that is mounted inside the solar panel housing. This chapter describes the programming aspects of the microcontroller and configuration of the wireless module.

3.1 Microcontroller

The microcontroller used in each unit is the Microchip PIC18F2455, which is a 28-pin, High-Performance, Enhanced Flash, and USB V2.0 compliant microcontroller with Nano Watt technology. The PIC18F2455 microcontroller has a wide operating voltage range (2.0V to 5.5V), with sleep mode current of 0.1μA and idle mode current of 5.8μA. Table 11 summarizes some of the key characteristics of this microcontroller.

Table 11: PIC18F2455 Characteristics [17]

Device	Program Memory		Data Memory		I/O	10-Bit A/D (ch)	CCP/ECCP (PWM)	SPP	MSSP		EAUSART	Comparators	Timers 8/16-Bit
	Flash (bytes)	# Single-Word Instructions	SRAM (bytes)	EEPROM (bytes)					SPI	Master I^2C™			
PIC18F2455	24K	12288	2048	256	24	10	2/0	No	Y	Y	1	2	1/3

3.2 Configuration of Wireless Modules

The wireless module used in the ALERT-2 system is the IEEE 802.15.4 XBee-PRO RF Module, manufactured by Digi International. It operates within the ISM (Industrial, Scientific & Medical) 2.4 GHz frequency band, with outdoor line-of-sight up to 1 mile (1600 m). The XBee-PRO transmits at data rate of 250,000 bps, with receiver sensitivity of -100 dBm.

A Digi embedded wireless development kit was used to configure the XBee-PRO wireless modules. This kit contains a USB development board, a RS-232 development board, a USB cable, a RS-232 cable, two XBee-PRO modules with attached whip antenna, software and an instruction guide. The XBee-PRO wireless module can be configured by one of the development boards using the provided X-CTU (configuration & test utility) software.

When the X-CTU software is launched, the default tab selected is the “PC Settings” tab. The PC settings tab allows the user to select the connected COM port and configure its settings when accessing the port. Some of these settings include the baud rate, flow control, data bits, parity, and stop bits. To test the selected COM port and PC settings, user can press the Test/Query button. If a successful connection is made, a message will pop up and display the module type, firmware version, and its MAC address. Figure 16 shows the default settings for a USB development board.

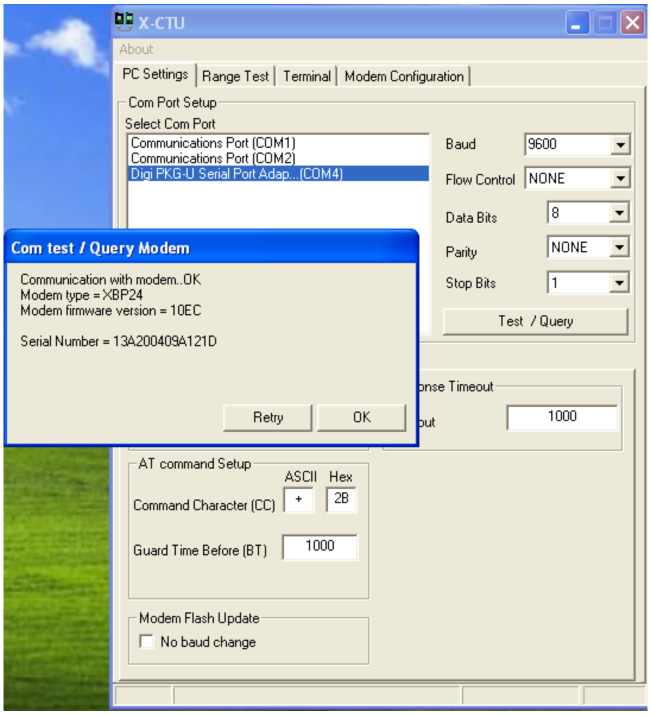


Figure 13: PC Setting tab in the X-CTU software.

After a successful connection, the Modem Configuration tab is used to configure the module. The Read button is used to display the current settings of the module. Once the module's firmware has been read, the configuration settings are displayed in three colors: black (not settable or read-only), green (default value), and blue (user-specified). To modify any of the user-settable parameters, the user must click on the associated command and select or type in a new value for that parameter. The following configurations must be applied to each module in the ALERT-2 system:

1. Set API Enable configuration to '1', to enable API Mode.
2. Assign a communication channel: there are 12 software selectable channels in the XBee-PRO module. Channel 'C', the default channel, is selected in the ALERT-2 system for all modules.
3. Select PAN ID: an RF data network that consists of one coordinator and one or more end devices forms a PAN (Personal Area Network). PAN ID must be unique to prevent miscommunication between PANs. In the ALERT-2 system, PAN ID selected is 'ABCD'.

Once all of the new values have been entered, the new configuration values are ready to be saved to the module's non-volatile memory, through the Write button located in the Modem Parameters and Firmware section. The Modem Configuration tab for XBee-PRO with the required configurations can be seen in Figure 17.

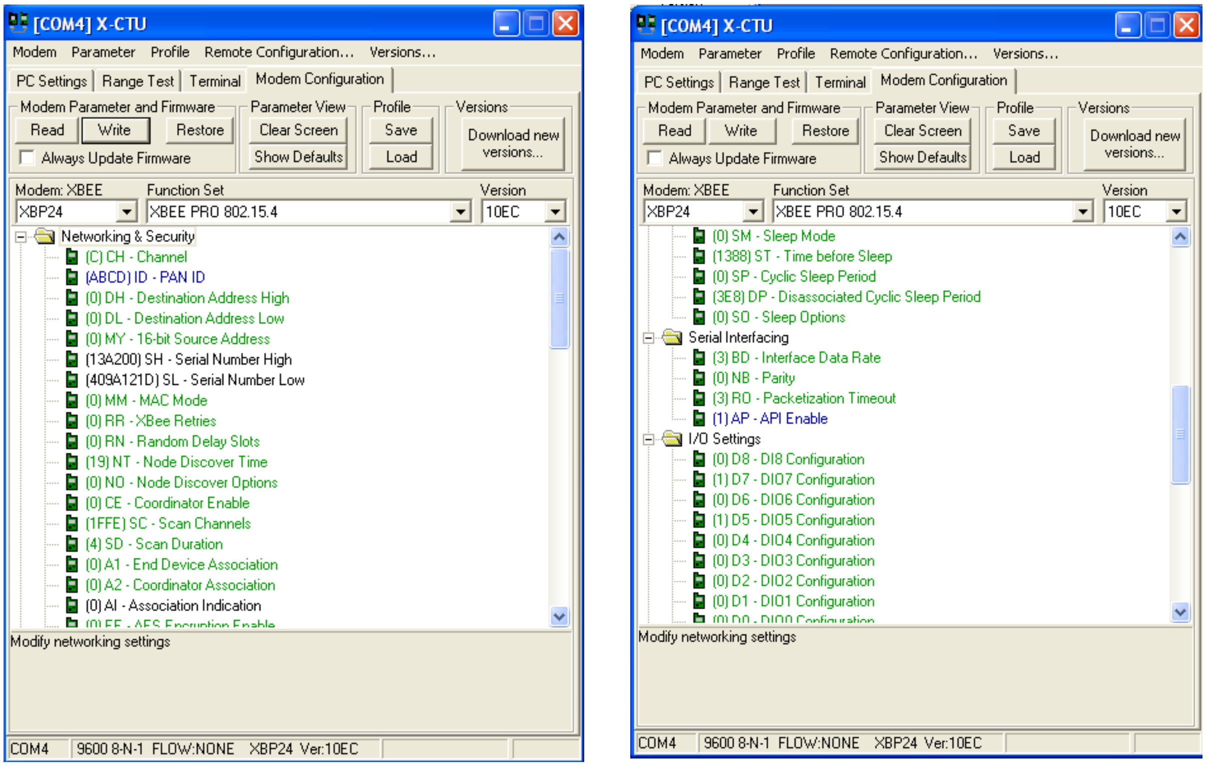


Figure 14: Modem configuration tab in the X-CTU software.

API (Application Programming Interface) operation is used to perform the communications between the modules based on their Media Access Control (MAC) addresses. The frame-based API extends the level to which a host application can interact with the networking capabilities of the module, where all data entering and leaving the module is contained in frames that define operations or events within the module. Table 12 summarizes the ALERT-2 system components and their MAC addresses.

Table 12: List of MAC Addresses of ALERT-2 Components

Symbol	Detector / Blinker Sign	MAC Address
P1	D1	00 13 A2 00 40 90 9D B5
P2	D2	00 13 A2 00 40 90 9D C2
P3	D3/S6	00 13 A2 00 40 90 9D 94
P8	D4/S4	00 13 A2 00 40 90 A0 C3
P7	D5	00 13 A2 00 40 90 A2 6E
P10	D6	00 13 A2 00 40 90 A2 3E
P11	S1	00 13 A2 00 40 90 A0 AE
P6	S2	00 13 A2 00 40 90 A2 4C
P5	S3	00 13 A2 00 40 90 9D 58

In API mode, the source module (transmitter) can send data frames to the destination module (receiver) which contains address and payload information, instead of using command mode to modify addresses. API operation requires that communication with the module be done through a structured serial interface (data is communicated in frames in a defined order). The API specifies how commands, command responses and module status messages are sent and received from the module using a UART Data Frame. The UART data frame structure and API-specific structure is defined as shown in Figure 18.

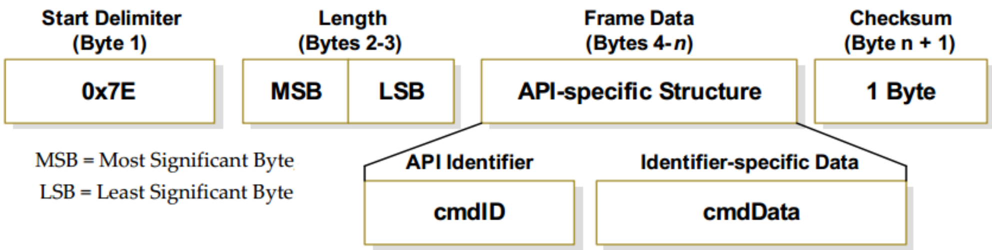


Figure 15: UART data frame structure and API-specific structure [18].

The Transmit Data Frames (received through the D_I pin (pin 3)) include the RF-transmit data frame, and the command frame. While the Receive Data Frames (sent out the D_O pin (pin 2)) include the RF-received data frame, and the command response.

In the detector module (transmitter), the 64-bit address transmit API packet frames are used. Transmit API packet is a powerful command that allows a module to send data to a single or multiple (broadcast) modules on a packet-by-packet basis. Figure 19 shows the 64-bit address TX Packet Frames.

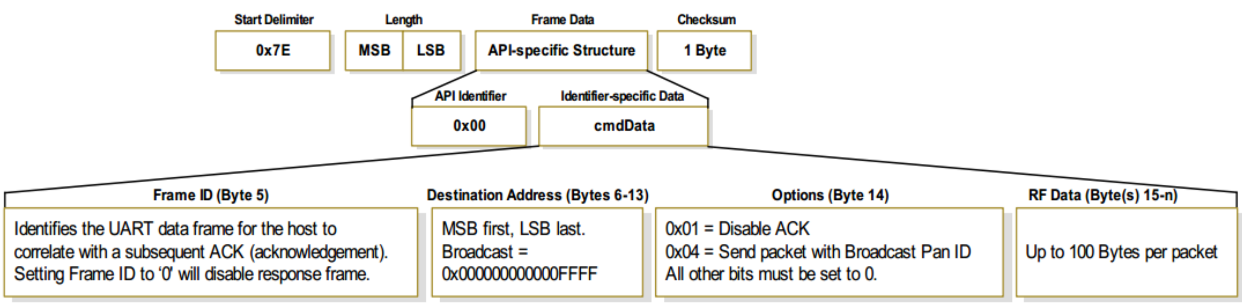


Figure 16: Format of the 64-bit address TX (transmit) API packet frames [18].

The detector modules send the transmit packet to the respective blinker module, which specified in the destination address. To increase the reliability, transmit retries are utilized. If the module receives the packet free of errors, it will return an acknowledgement within the same 50 millisecond hop. If a receive acknowledgement is not received, the transceiver uses a transmit retry to resend the packet. The transceiver continues to send the packets until either (1) an acknowledgement is received or (2) all transmit retries have been used. The received packet will only be sent to the host if and when it is received free of errors. The API TX (Transmit) Status Packet frames is used as the software acknowledgement indicator. The 6th byte of this packet indicates if the message was successfully delivered. Figure 20 shows the format of the API TX (Transmit) Status Packet frames.

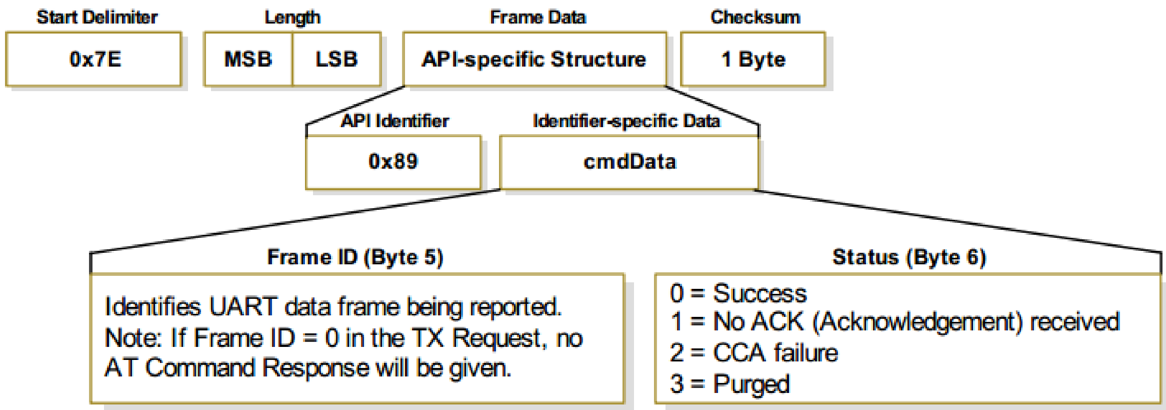


Figure 17: Format of the TX (Transmit) Status API Packet frames [18].

The blinker module receives the data packet through a 64-bit Address API Receive Packet. This packet indicate the source address, RSSI (received signal strength indicator), and the data message. Figure 21 shows the format of the API RX (Receive) Packet frames.

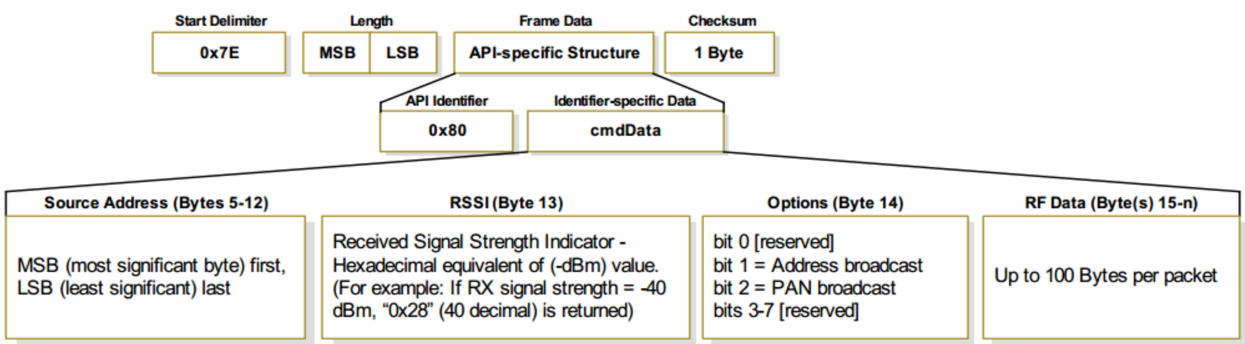


Figure 18: The format of the 64-bit address RX (Receive) API Packet frames [18].

3.3 Embedded Firmware

There are four separate embedded firmware pieces created for this project: a program for the Doppler radar detectors (D1, D2, D5, and D6), a program for the FMCW radar detectors (D3 and D4), a program for the major road blinker sign (S1), and a program for the intersection blinker signs (S2, S3, S4 and S6). This section will describe the software protocols and the algorithms used in the four programs.

3.3.1 Doppler Radar Unit Firmware

The Doppler radar program starts by defining variables and initializing Ports A, B, C, and the Timer 1 interrupt. Next, Timer 1 is started and the program enters a Finite State Machine (FSM) where the radar output is being checked. The radar outputs a digital signal which is connected to a digital I/O port on the PIC18F2455. The output of the radar is activated as long as objects within the field of view are moving. When movement stops, the output will be reset. The radar output level is determined through the Common Relay input (Yellow), which is supplied by a 3.3V output from the controller circuit, which is responsible for processing the output signal of the Doppler radar to determine if a vehicle has been detected.

Next, a Finite State Machine (FSM) is entered. If four consecutive samples are inside the detection range (state2), vehicle detection has occurred. A “BLINK” signal is sent to the associated blinker sign. If this message is sent successfully, the program returns to the FSM. If sending a “BLINK” signal fails, the same message will be retransmitted up to 5 times. If sending the “BLINK” signal fails after 5 retransmits, an error message is displayed and the program moves on. While in the FSM, an overflow counter is used to trigger the sending of an “ALIVE” signal. The “ALIVE” signal is sent every 2 minutes to the blinker sign. After the “ALIVE” signal is sent, the program returns to the FSM.

While each of the Doppler detectors D4 and D6 is associated with one blinker STOP sign, detectors D1 and D2 are associated with two blinker warning signs, S2 and S3. Figures 22 and 23 illustrate the firmware flow diagram of the Doppler radar program for the two cases.

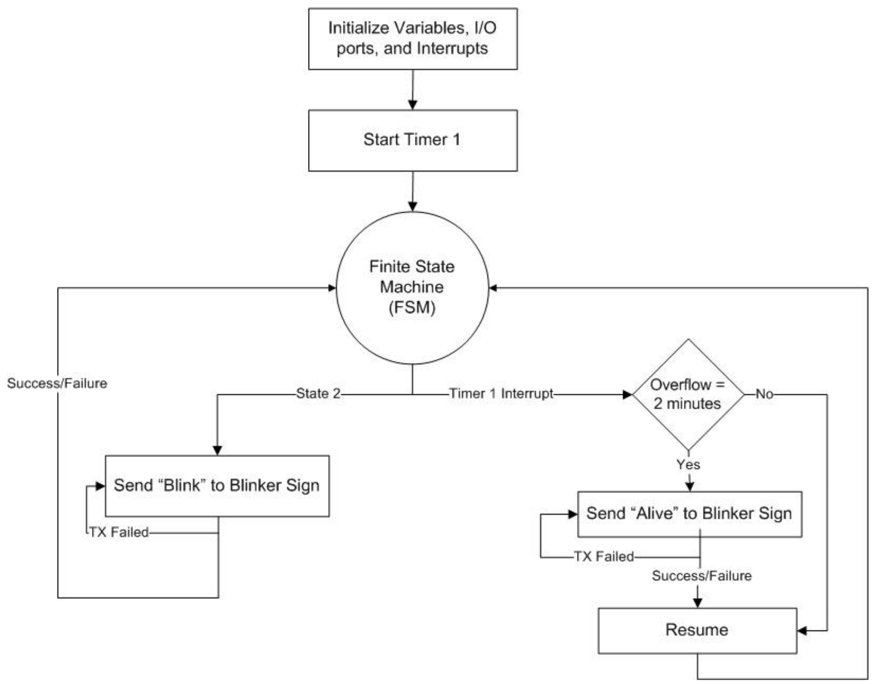


Figure 19: Firmware flow diagram of the Doppler radar units D4 and D6.

Figure 20: Firmware flow diagram of the Doppler radar units D1 and D2.

3.3.2 FMCW Radar Unit Firmware

The FMCW radar unit firmware starts by defining variables and initializing Ports A, B, C, and the Timer 1 interrupt. Next, Timer 1 is started and the program enters a FSM where the FMCW radar input is being checked. The FMCW radar outputs a 12V digital signal when detection occurred; this output is regulated to +3.3 V level in the controller circuit and connected to a digital I/O port on the PIC18F2455. Since a detection zone needs to be established at each radar detector, the program needs to send two signals: “START” and “END”. Once a vehicle has entered the detection zone, the Radar sensor output goes high and a “START” signal is sent to S1. When a vehicle leaves the detection zone, the radar output goes low. In the FSM, the output of the radar needs to be low for 2.5 consecutive seconds before the “END” signal is sent. This is to ensure that the vehicle has actually left the detection zone.

The FMCW radar detector software only has to send signals to one blinker sign, S1. If after 5 retransmits either signal did not successfully transmit, an error message will be displayed and the program will move on. The interrupt routine in the FMCW radar program is triggered by an overflow of Timer 1. The overflow happens every 2 minutes and triggers the Timer 1 interrupt service routine. In this routine, the “ALIVE” signal is sent to blinker sign S1. Figure 24 illustrates the firmware flow diagram of the Radar detector.

Figure 21: FMCW radar firmware flow diagram.

3.3.3 Blinker Sign S1 Firmware

Blinker sign S1 is responsible for processing the wireless signals received from both of the radar detectors (D3 and D4). A software flow diagram for blinker sign S1 is illustrated in Figure 25. First, the user will be asked to press "Enter" to enter the setup mode or wait for 2 seconds to start the main routine. Two parameters can be set by the user through the HyperTerminal interface: the blinking time and the LED illumination. After insertion of the required parameter, the main routine starts with defining variables and initializing Ports A, B, C, and the Timer 1 interrupt. Then, the program waits for incoming data. Three types of signals can be received from either of the FMCW radar detectors: The first signal is a "START" blinking signal. When this signal is received, a vehicle has entered either one of the detection zones at the intersection. Here, the overflow counter is reset and the blinking LEDs are turned on. The second signal is an "END" blinking signal. When this signal is received, a vehicle has exited either one of the detection zones at the intersection. Here, the overflow counter is reset and the LEDs are turned off. The third signal is an "ALIVE" signal. When this signal is received, the overflow counter is reset. If a "START", "END", or "ALIVE" signal is not received from a Radar detector for more than 12 minutes, the blinker sign will enter fail safe mode and the LEDs will blink continuously, until receiving any new signal.

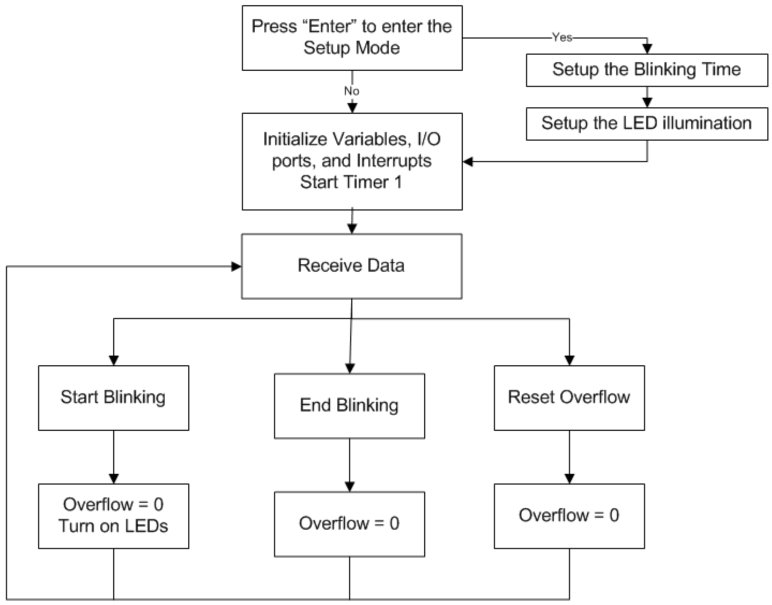


Figure 22: Blinker 1 firmware flow diagram.

3.3.4 Blinker Signs S2, S3, S4 and S6 Firmware

Blinker warning signs S2 and S3 are responsible for processing the wireless signals received from the Doppler radars D1 and D2, while the STOP Blinker signs S5 and S6 are responsible for processing the wireless signals received from the Doppler radars D5 and D6. The software flow diagram is illustrated in Figure 26. First, the user is asked to press "Enter" to enter the setup mode or wait for 2 seconds to automatically start the main routine. Two parameters can be set by the user through the HyperTerminal interface: the blinking time and the LED illumination. In the main routine, variables, Port A, Port B, Port C, and Timer 1 and its interrupt routine are initialized. Then, the program waits for incoming data from the Doppler detectors. Two types of signals can be received from a Doppler detector. The first signal is a "START" blinking signal. When this signal is received, it indicates that a vehicle has been detected. Here, the overflow counter is reset, the "BLINKTIME" variable is set to 9.5 seconds for S2 and S3, and 10 seconds for S4 and S6, and the blinking cycles of LEDs are turned on. The blinking LEDs are turned off when the "BLINKTIME" variable reaches zero. If another "START" signal has been received before the "BLINKTIME" variable reaches zero, the "BLINKTIME" variable is reset. The second signal is an "ALIVE" signal. When this signal is received, the overflow counter is reset. If either a "START" or "ALIVE" signal is not received from the Doppler detector for more than ten minutes, the blinker sign will enter the default mode, and the LEDs will blink continuously until a new signal is received.

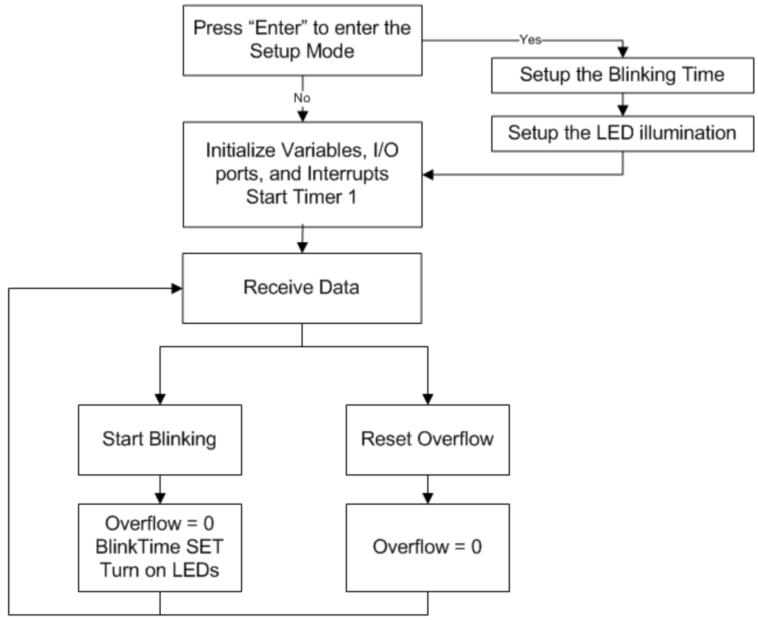


Figure 23: S2, S3, S4 and S6 firmware flow diagram.

3.3.5 Fail Safe Mode – ALIVE Signal

When a detector unit completely fails such as out of battery, it will be unable to send an “ALIVE” signal to its respective blinker sign. A fail-safe mode has been implemented into each blinker sign based on a timeout. If a blinker sign has not received any type of wireless signals for more than twelve minutes, it will enter into the fail safe mode and the LEDs will continuously blink until a new data is received. This assures that if a vehicle detector is not working but sign is working, the blinker sign is automatically switched into a traditional blinker sign which continuously blinks.

Chapter 4: Testing

Both lab and on-site tests were conducted before installation of the ALERT-2 system. It includes testing of the wireless modules, the controller PCB prototypes, the detectors, and the Blinker Sign LED driver circuits. Testing of wireless modules included selecting a low-cost, low-power module that had the capability of transmitting a sufficiently long distance (longer than required) between a detector and a blinker sign. Several versions of the PCBs that control each vehicle detector and blinker sign were designed and tested in the UMD lab.

4.1 Wireless Module Testing

The wireless module used in the ALERT-2 system is the IEEE 802.15.4 XBee-PRO RF Module manufactured by Digi International. The first test conducted in the UMD lab was to perform the serial connection between the module and the PIC18f2455 microcontroller. The PIC18F2455 sends an API frame, which includes the destination address and the data message, to D_I pin (pin 3) of the XBee-PRO module. When the XBee-Pro module receives the packet; it transmits the data message into the destination address. On the receiver side, when a packet is received, the module immediately passes the received frame into to the PIC18F2455 through D_O pin (pin 2) of the XBee-PRO module, and a proper action is taken depending on what type of message was received. These transactions were simulated on the lab to check reliability of the serial connection between the XBee module and the microcontroller.

A Digi embedded wireless development kit was used to configure the XBee-PRO wireless modules. The XBee-PRO module operates within the ISM (Industrial, Scientific & Medical) 2.4 GHz frequency band, with outdoor line-of-sight up to 1 mile (1600 m). In order to check a reliable range of the module, a range test circuit was designed and created to perform on-site tests. The range test circuit includes the PIC18F2455 microcontroller, XBee-PRO wireless module footage, and four LEDs to indicate a successful/failed transmission. One circuit acts as a transmitter, and another acts as the receiver. The on-site tests included all potential distances between detectors and blinker signs, with more focus on testing the distances between D1 detector and the intersection, which contains a vertical curve. The transmitter continuously sends data signal each two seconds, and waits for the acknowledgement signal from the receiver. While waiting, a yellow LED labeled “Wt” turns on to indicate the waiting. If an Acknowledgment is received, a yellow LED labeled “OK” blinks to indicate successful communication. If failed, a red LED labeled “F” blinks to indicate communication failure. The forth LED labeled “Lnk” was also used to insure the active state of the wireless module. This test system was powered by a 12 V battery. Figure 27 shows a picture of the range test circuit.

This range test was to ensure that the wireless signals reliably travel from the bottom of the vertical curve to the intersection where the warning blinker signs are located. In addition, wireless transmission was tested from each stop sign to the location of the blinker sign on the major road (Lismore Road). Several orientations of each module’s antenna were also tested. In all tests, XBee-Pro module worked reliably and there was not even a single case where the wireless communication failed. Since wireless communication was successful in every combinational tests conducted, the need for repeaters in this system was eliminated and we concluded that reliability of wireless communication is sufficient for this application.

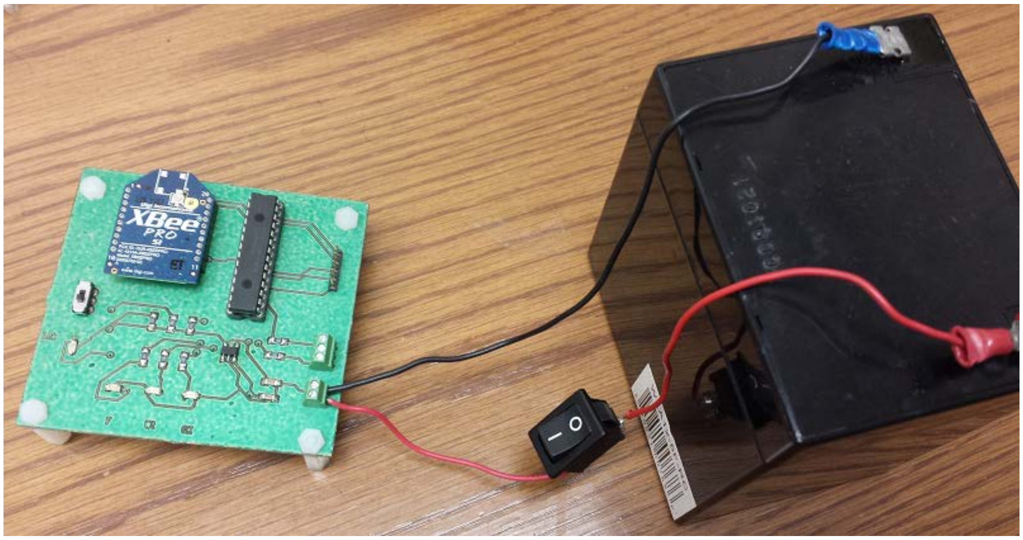


Figure 24: Testing the XBee-PRO range and the reliability of serial connection.

4.2 Detectors Testing

Vehicle detection in the ALERT-2 system occurs in two scenarios. The first scenario is at each stop sign on Lakewood Road where the FMCW detector is used to detect vehicles as they approach the intersection from the minor road (Lakewood Road) and as they are waiting at the intersection (D3 and D4). The second scenario is detecting vehicles traveling toward the intersection on the major or minor roads, where the Doppler radar is used to detect the vehicles traveling on one direction toward the intersection (D1, D2, D5, and D6). On-site tests were conducted for each scenario, and the detector outputs were recorded using a data-acquisition board.

4.2.1 FMCW Radar Testing

The FMCW Radar detector tested is the Banner R-Gage QT50RAF Sensor (Figure 28). This radar is the same radar used in the first phase, ALERT-1, with the same configuration. This radar sensor uses Frequency Modulated Continuous-Wave (FMCW) radar. It transmits a frequency sweep, often called a chirp which is reflected from distant targets and detected by the receiver. By measuring the frequency of the return signal, the time delay between transmission and reception can be measured, and thus the range is determined. Advantages of this sensor are that it can detect both moving and stationary objects. Also, using the R-Gage Radar sensor allows to set a detection zone near each stop sign. Vehicles are detected as they enter the detection zone and remain detected until they leave the detection zone. The sensor can be configured (via DIP switch) to sense objects up to a specific distance, ignoring objects beyond this distance. The detection zone is typically set between 3m – 15m from the sensor. Also, the sensitivity, output configuration, and response speed can be adjusted. Figure 29 describes the radar LED indicators. Figure 28 shows the Banner R-Gage Radar sensor.

Figure 25: Banner R-Gage QT50RAF radar [19].

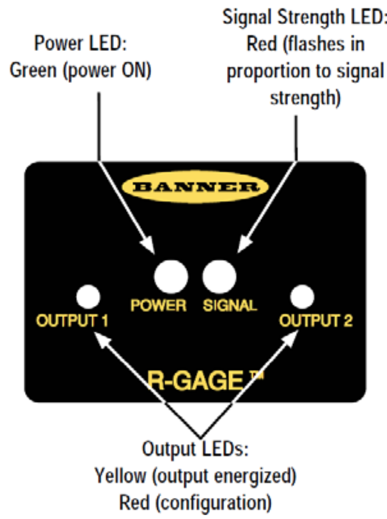


Figure 26: Banner R-Gage QT50RAF Radar DIP switch configurations [19].

The sensor was tested at the actual intersection by installing the sensor at one of the stop signs on Lakewood Road. The distance from the stop sign where each Radar sensor would be mounted to where a vehicle would typically come to a stop at the intersection is 24 ft (7.3 m). Naturally, the sensing distance was then set to 26.3 ft (8 m). The sensitivity of the sensor determines the width of the detection zone. The sensitivity was determined by actual testing at each stop sign and confirmed that the detection zone can be set according to our needs by adjusting the sensor angle. Figure 30 shows an example of the digitized FMCW radar output signal. Figure 31 shows an example of a typical beam pattern for different sensitivity levels of the R-Gage Radar sensor. As the sensitivity increases, the diameter of the detection zone increases.

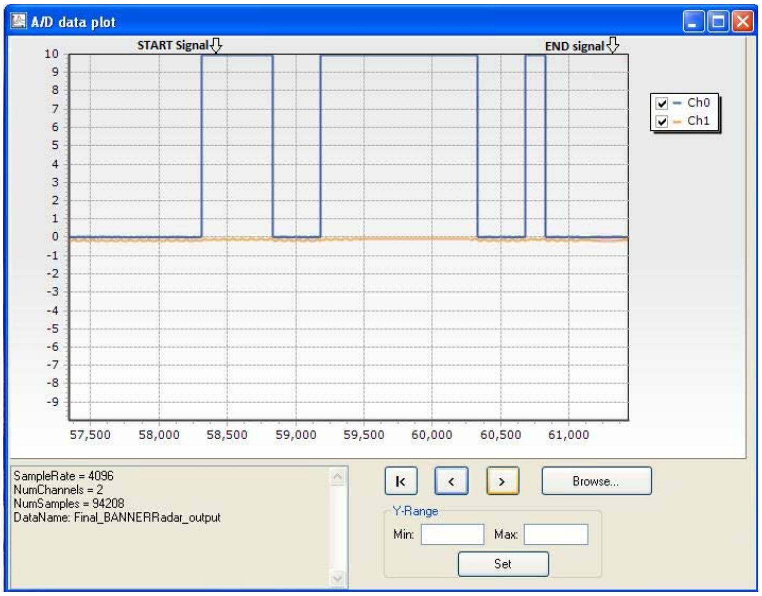


Figure 27: FMCW radar output signal.

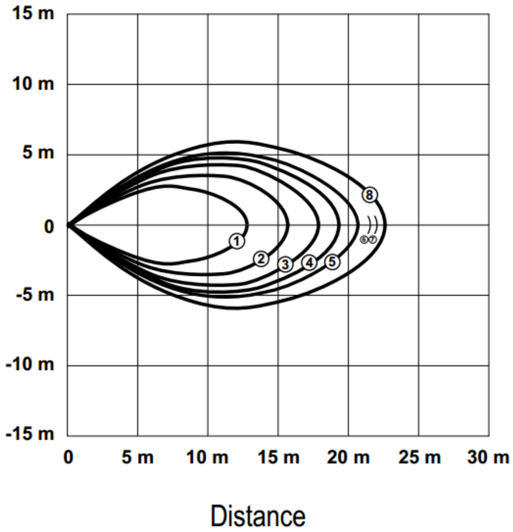


Figure 28: Typical beam pattern for different sensitivity levels of the R-Gage radar sensor [19].

The FMCW Radar sensor has three connections: 12 V, GND and 12 V digital output signal. This 12 V digital output signal is regulated down to 3.3 V in order to meet the input voltage specifications of an input/output (I/O) port on the PIC18F2455. Figure 32 shows the radar connection circuit.

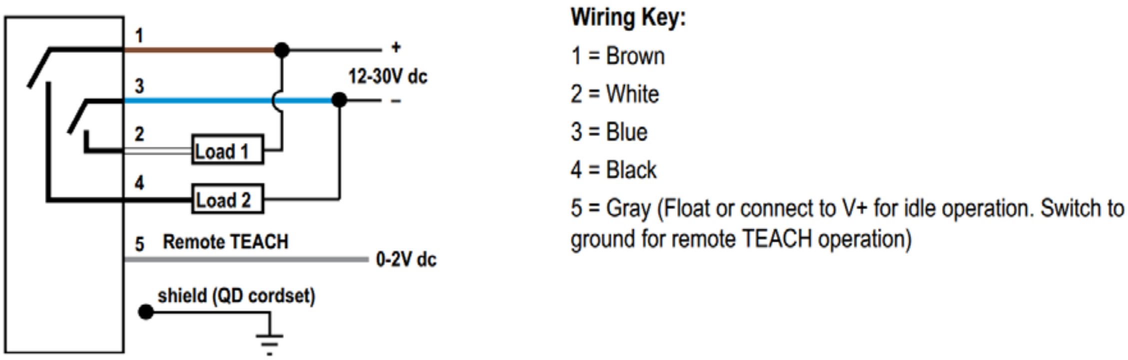


Figure 29: Banner R-Gage QT50RAF radar connections [19].

4.2.2 Doppler Radar Testing

The ASIM MW 334 Doppler Radar traffic detector is used to detect vehicles moving into or through their field of view in short to medium range. The digital output of the detector is activated as long as objects within the field of view are moving. When the movement stops the output will reset. It detects the approaching traffic moving faster than the low speed threshold of 4 km/h (2.5 mph). Standard mounting bracket is supplied with the radar to allow an easy and stable mounting. This radar has an operational temperature range of between -40°C to +70°C (-40°F to +158°F). Figure 33 shows the ASIM MW 334 Doppler radar.

The Doppler radar has four connections: 12 V, GND, Common Relay, and Normally Open relay. The common relay is connected to 3.3V output to set the output signal level to match with the microcontroller. Figure 34 shows the Doppler radar connection.

The Doppler radar can be configured via DIP switch to select the Direction discrimination, Minimum speed threshold, and timer function. Figure 35 shows an example of a Doppler radar output signal. In all tests, the ASIM MW 334 Doppler radar was found to be reliable in detecting directional moving vehicles. However, it was not able to detect stopped vehicles.

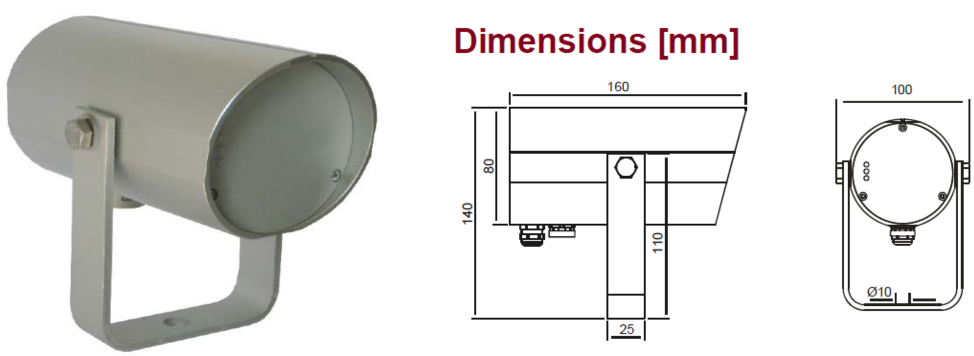
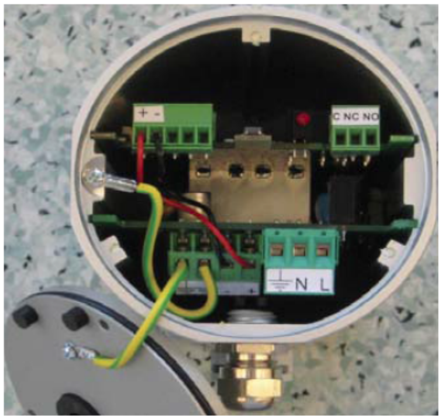


Figure 30: ASIM MW 334 Doppler radar (left) and radar dimensions (right) [20].



1	V+ Supply	Brown
2	V– Ground	White
3	res	
4	res	
5	res	

1	C Relay	Yellow
2	NC Relay	Green
3	NO Relay	Grey

Figure 31: Doppler radar connections [20].

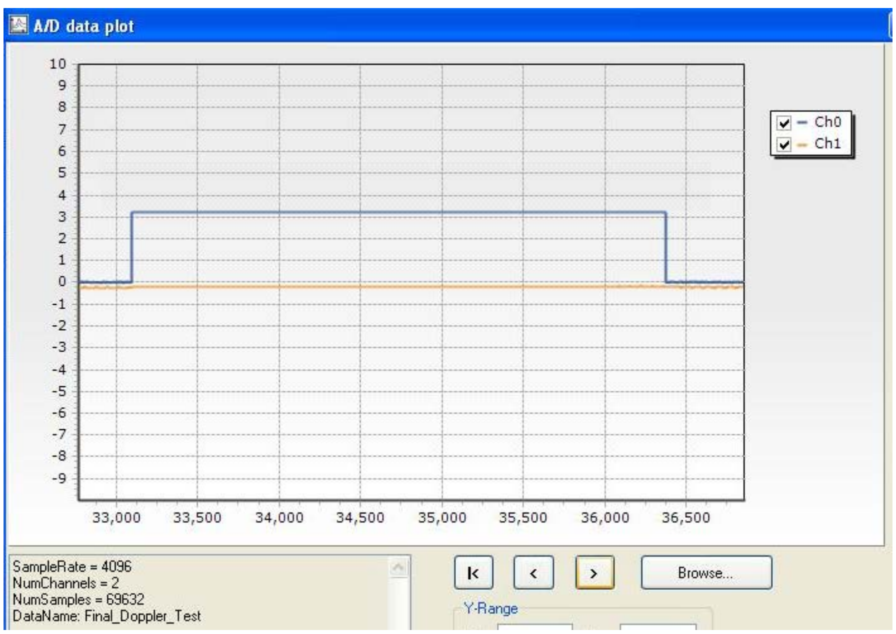


Figure 32: Doppler radar output signal.

4.3 PCB Design and Testing

4.3.1 Integrated PCB design

The ALERT-2 system requires 11 controller circuits: five for blinker signs, four for Doppler radar detectors, and two for FMCW Radar detectors. Each controller circuit controls vehicle detection, blinking LEDs, and wireless communication. PCBs that contain the electronics were designed and built using Mentor Graphics PADs software and a LPKF ProtoMat S62 Prototyping machine. Several versions of each PCB were built and tested. The final PCB version was created to combine both the Blinker sign and the radar detector circuits into one board, and the final design was used to produce factory-fabricated PCBs. The final version controller circuit contains the following components and its layout is shown in Figure 36:

- PIC18F2455 Microcontroller. (U1)
- LED Driver and associated components. (HV1, I2, C1, C3, C5, RCS, RT, D1, and I1)
- Voltage regulators: 12V to 3.3V (REG1, REG2)
- I/O connection terminals. (J1, J2, J3, R8, LED, B1, B2, B3 and B4)
- Test button. (SW1)
- Indicator LEDs. (D1Rx, D2OK, D3Tx, and D5)
- Jumpers (JMR1, JMR2, and JMR3)

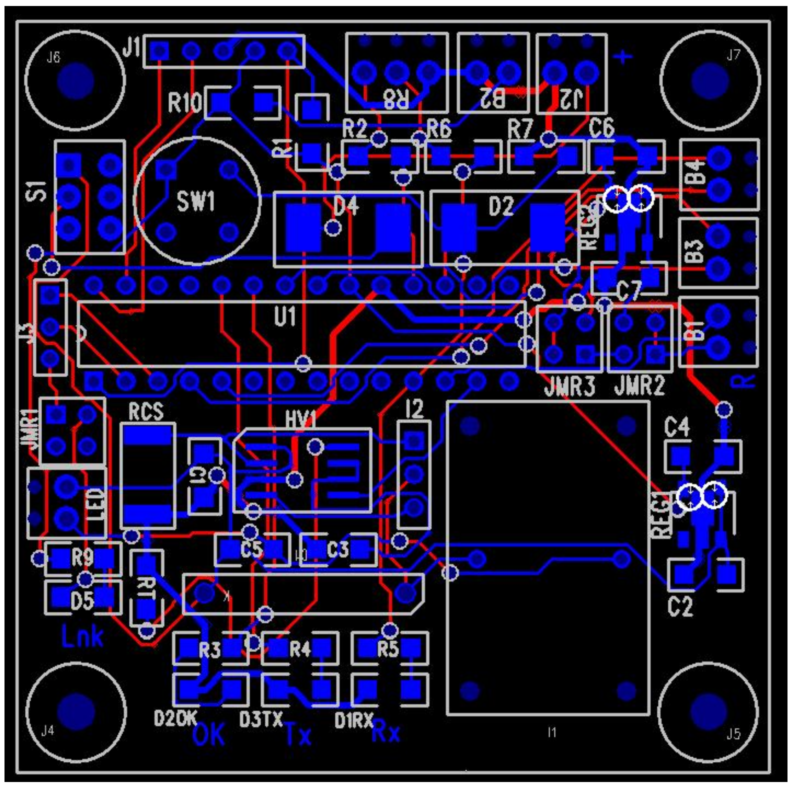


Figure 33: Controller circuit PCB layout.

J2 terminal is used to power the controller circuit with 12V. J1 is a 5-pin header used to program the PIC18F2455 using a laptop running MPLAB IDE and a Microchip MPLAB ICD 2 programmer. D1Rx, D2OK, D3Tx are LEDs used to indicate message sending and receiving status. D5 is used to indicate a successful connection between the wireless module and the controller circuit. This LED can be turned on or off using the jumper (JMR1). In the actual implementation, the jumper should be set to off to save on battery power. S1 is an on/off switch which controls power to the microcontroller. B1 is used to receive the Radar output signal and Event-logger actuation. B3 and B4 terminals are not used in the ALERT-2 system and reserved for future use. The detailed list of each component can be shown in Table 13. Figure 37 shows a picture of the final factory-fabricated PCB used in the project.

Table 13: List of All Controller Circuit Components

Designation	Description
REG1, REG2	LDO Regulator, 3.3V, 300mA, SOT-89
HV1	Current mode LED Driver, 8-Lead SOIC
C1, C3, C4, C5, C6	Ceramic Capacitor, 2.2µF, 16V, ±20%, 1206
C2, C7	Ceramic Capacitor, 0.1µF, 50V, ±10%, 1206
R1, R7, R10,	10K Ohm, 1/4W, 1%, 1206
R2	22K Ohm, 1/4W, 1%, 1206
R3, R4, R5, R6, R9	1K Ohm, 1/4W, 1%, 1206
I1	Inductor, 128uH, 4A, ±10%, Through Hole
Rsc	Current Sense Resistor, 80mΩ, 2W, 1 %, SMD
RT	1M Ohm, 1/4W, 1%, 1206
I2	N-Channel MOSFET, 14A @ 100 V,Through Hole
D2,D4	SCHOTTKY DIODE, 40V, 3A, SMC
	PIC Microcontroller, 28 DIP
U1	DIP SOCKET, 28PIN
D1RX, D5	RED LED,2V, 20mA, 635nm, 1206
D2OK, D3TX	YELLOW LED,2V, 20mA, 590nm, 1206
J1, J3	Right Angle Header, BRKWAY, 0.1"
S1	Vertical Slide Switch
SW1	Tactile Switch, SPST, 0.02A@15V
B1,B2,B3,B4, J2, LED	2.54mm Term Block, 2 Conn
R8	2.54mm Term Block, 3 Conn
JMR1, JMR2, JMR3	Double Row Header, BRKWAY, 0.1"

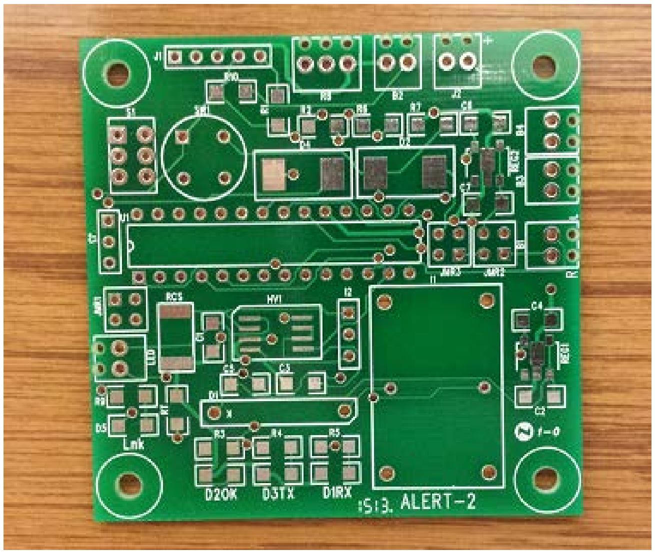


Figure 34: Factory-fabricated PCB.

The wireless module circuit is installed inside the solar panel enclosure so that the antenna can be directly mounted. A serial communication is used between the controller and the wireless transceiver. This strategy was used to eliminate the needs of antenna cable extension. Figure 38 shows the layout of the wireless module PCB design.

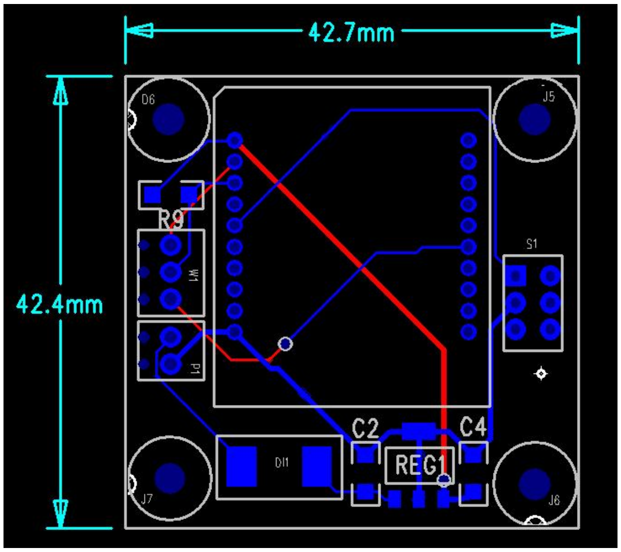


Figure 35: Wireless module PCB layout.

4.3.2 Controller circuit in the Blinker Signs

The blinker signs used in the ALERT-2 system have eight LEDs on the perimeter of the sign and had no control circuits. The blinker sign controller developed in this project drives the LEDs and controls blinking. A Blinker sign controller with all components soldered up is shown in Figure 39, and the corresponding components are summarized in Table 14.

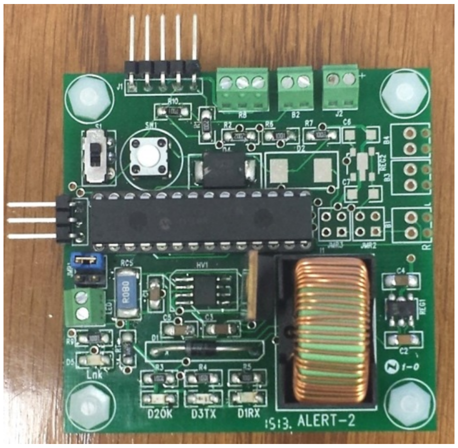


Figure 36: Blinker sign controller circuit.

Table 14: Blinker Sign Controller Circuit Components

Designation	Description
REG1, REG2	LDO Regulator, 3.3V, 300mA, SOT-89
HV1	Current mode LED Driver, 8-Lead SOIC
C1, C3, C4, C5, C6	Ceramic Capacitor, 2.2µF, 16V, ±20%, 1206
C2, C7	Ceramic Capacitor, 0.1µF, 50V, ±10%, 1206
R1, R7, R10,	10K Ohm, 1/4W, 1%, 1206
R2	22K Ohm, 1/4W, 1%, 1206
R3, R4, R5, R6, R9	1K Ohm, 1/4W, 1%, 1206
I1	Inductor, 128uH, 4A, ±10%, Through Hole
Rsc	Current Sense Resistor, 80mΩ, 2W, 1 %, SMD
RT	1M Ohm, 1/4W, 1%, 1206
I2	N-Channel MOSFET, 14A @ 100 V,Through Hole
D2	SCHOTTKY DIODE, 40V, 3A, SMC
U1	PIC Microcontroller, 28 DIP
	DIP SOCKET, 28PIN
D1RX, D5	RED LED,2V, 20mA, 635nm, 1206
D2OK, D3TX	YELLOW LED,2V, 20mA, 590nm, 1206
J1, J3	Right Angle Header, BRKWAY, 0.1"
S1	Vertical Slide Switch
B1, J2, LED	2.54mm Term Block, 2 Conn
R8	2.54mm Term Block, 3 Conn
JMR1	Double Row Header, BRKWAY, 0.1"

4.3.3 Controller circuits in the detectors

A single controller circuit can be used for the FMCW radar input and the Doppler radar input, and the jumpers (JMP1 and JMP2) are used to switch between them. Figure 40 shows a picture of the detector controller circuit, and the corresponding components are summarized in Table 15.

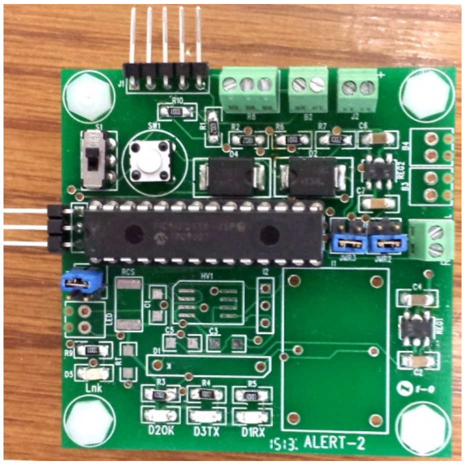


Figure 37: Detector controller circuit.

Table 15: Detector Controller Circuit Components

Designation	**Description**
REG1, REG2	LDO Regulator, 3.3V, 300mA, SOT-89
C4, C6	Ceramic Capacitor, 2.2µF, 16V, ±20%, 1206
C2, C7	Ceramic Capacitor, 0.1µF, 50V, ±10%, 1206
R1, R7, R10	10K Ohm, 1/4W, 1%, 1206
R2	22K Ohm, 1/4W, 1%, 1206
R3, R4, R5, R6, R9	1K Ohm, 1/4W, 1%, 1206
D2,D4	SCHOTTKY DIODE, 40V, 3A, SMC
	PIC Microcontroller, 28 DIP
U1	DIP SOCKET, 28PIN
D1RX, D5	RED LED,2V, 20mA, 635nm, 1206
D2OK, D3TX	YELLOW LED,2V, 20mA, 590nm, 1206
J1, J3	Right Angle Header, BRKWAY, 0.1"
S1	Vertical Slide Switch
SW1	Tactile Switch, SPST, 0.02A@15V
B1,B2 , J2	2.54mm Term Block, 2 Conn
R8	2.54mm Term Block, 3 Conn
JMR1, JMR2, JMR3	Double Row Header, BRKWAY, 0.1"

Chapter 5: Installation

On August 16, 2011, the actual installation of the ALERT-2 system took place. The on-site installation of the nine units took three days (not continuous but on and off) with help from the St. Louis County Sign Shop.

5.1 Solar Panels

The solar panel used in the ALERT-2 system is the bp Solar SX 420J. A custom designed enclosure was used to mount the solar panel. It allows the wireless module to be mounted inside the solar panel housing using four small attaching screws. The solar panel is attached to its enclosure via four self-tapping screws. Rubber weather strips along with the edges of the solar panel housing creates a seal when the two units are screwed together. This protects the wireless module inside from rain and snow. The antenna is mounted on the outside of the solar panel in either left or right upper corner and connected to the wireless module. All screw holes are sealed with white DAP Adhesive Caulk Seal. Each assembled solar panel and housing is attached to a solar panel mounting bracket. This bracket is designed to mount the solar panel to a u-channel sign post. It also allows the solar panel to be adjusted both horizontally and vertically. Figure 41 shows pictures of the solar panel housing and its mounting bracket. Each solar panel has seven connection wires, each wire with 12ft length to make the connection from the solar panel to the battery cabinet. Table 16 summarizes the solar panel wiring details.

Figure 38: Solar panel housing and its mounting bracket.

Table 16: Solar Panel Wires Connection

Connection Wire	Description	Wire Size
Solar panel connection	P+: to the charge controller	12 AWG
	P-: to the charge controller	
Wireless power connection	12 V: from the charge controller	20 AWG
	GND: from the charge controller	
Wireless communication connection	Tx: to receive the serial data from the controller	22 AWG
	Rx: to send the serial data to the controller	
	Lnk: to indicate the module connectivity	

After the solar panels are installed on the u-channel sign post, it must be adjusted in order to produce the most power of the available solar energy. Solar panels produce electricity most efficiently when they are pointed directly at the sun. The solar panel tilt angle is the angle measure between the solar panel and the ground, and it is adjusted. The best tilt angle for optimizing solar collection during winter can be calculated by multiplying the location's latitude by 0.875 and then adding 19.2 degrees [21]. According to Google Maps [11], the Latitude and Longitude of the project site are 46.94 ° N and 91.96 ° W, respectively. The selected tilt angle is thus:

$$\text{Tilt Angle} = \text{Latitude} \times 0.875 + 19.2° = 46.8° + 20° = 60.3°$$

5.2 Blinker Signs

Typical blinker signs commercially available contain electronic control circuits and battery on the back of the sign. The blinker signs purchased for this project contains no electronic circuits and batteries, except LEDs on the perimeter of the sign. A small junction box was attached on the back side of the blinker sign to connect wires from the control cabinet which contains battery and the control circuit. Figure 42 shows the back side of a blinker sign.

Figure 39: Back side of a blinker sign.

5.3 Controller Circuits

Control circuits consist of a battery charger and a controller for LED activation and communication. These controllers are designed as plug-and-play devices and thus do not require any settings. Only requirement is connecting the wires correctly. Since its size is small, it is simply placed inside a small plastic box of the battery enclosure as shown in Figure 43.

Figure 40: A clear plastic box is used to house controller circuits and placed inside the battery enclosure.

5.4 On-Site Installation

Installation of the ALERT-2 system at the site started on August 16, 2011, and it took three days. Physical installation of the signs was done by the St. Louis County Sign Shop crew, and installation of electronic circuits was done by a graduate research assistant of this project.

<u>5.4.1 Blinker Warning Signs Installation</u>

There are three blinker warning signs in the ALERT-2 system. Two “VEHICLE APPROACHING” warning signs located on the northeast and southwest quadrants of the intersection, and one “CROSS TRAFFIC” warning sign located on Lismore Road (major road)

500 ft west of the intersection. Figure 44 illustrate the components of the blinker sign unit, with connections between the components.

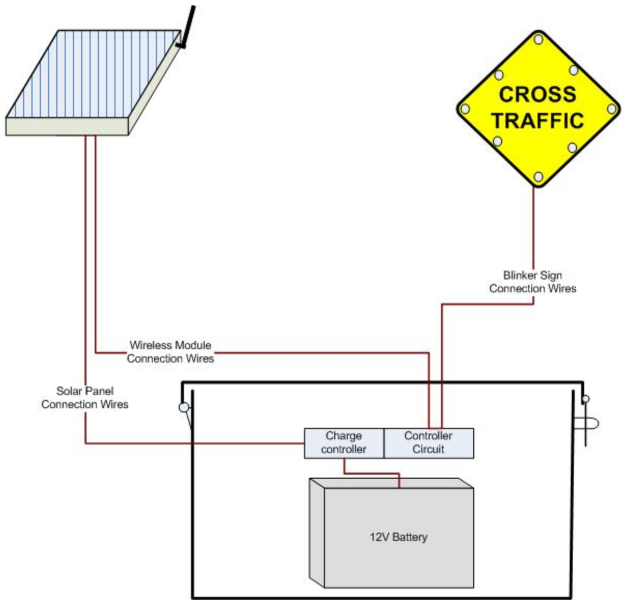


Figure 41: The components of a blinker sign unit.

The installation starts by attaching the pre-assembled solar panel housing on top of the u-channel sign post. Then, the warning sign is mounted between the two 8 ft (2.4 m) u-channel sign posts. These two posts are bolted to two 8 ft (2.4 m) u-channel sign posts buried 6 ft (1.8 m) in the ground. The battery cabinet is then attached to the two u-channel sign posts, using two perpendicularly crossing u-channel posts of a 28 inch (71.12 cm) length. To avoid vandalism, special fasteners were used in mounting the cabinet called "nylock" locking nuts. Figure 47 shows installed battery cabinet (left) and cabinet attachment dimensions (right).

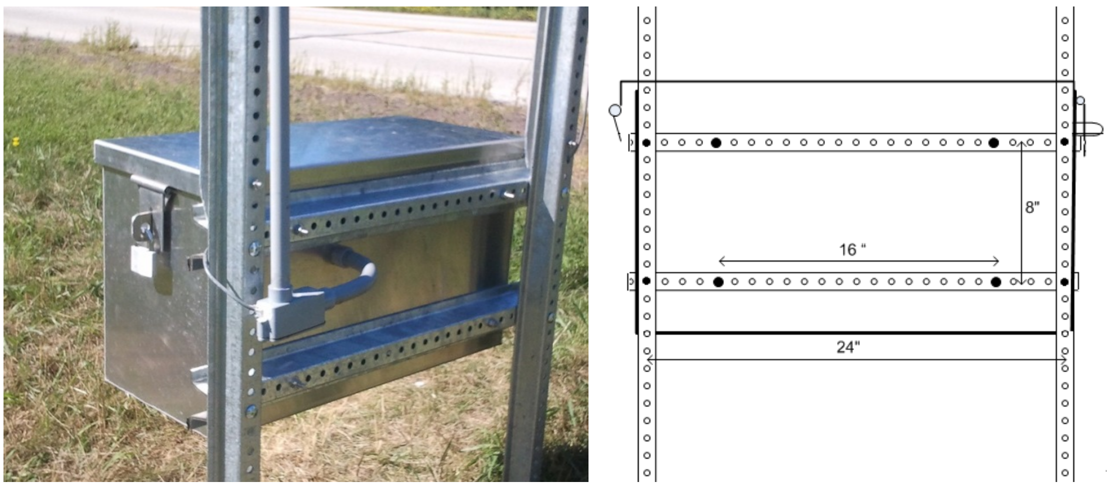


Figure 42: Battery cabinet installation.

The last step is to connect the wires through a 0.5 inch (1.27 cm) PVC conduit, which connects the solar panel housing to the battery cabinet. A hole with a diameter of 0.5 inch (1.27 cm) is made in the back side of the battery enclosure to allow the conduit to go through. In order to support the extra weight being added to the sign by the solar panel, another u-channel sign post is added as a brace in the back. Once the sign is in position, the solar panel needs to be adjusted to face south and tilted at an angle of 60.3 degree. Figure 46 shows the finished "VEHICLE APPROACHING" blinker sign.

Figure 43: Finished "VEHICLE APPROACHING" blinker sign.

5.4.2 FMCW Radar and Blinker STOP Sign Installation

There are two FMCW radar units in the ALERT-2 system and located in the southeast and northwest quadrants of the intersection. Figure 47 illustrates the components of a FMCW radar unit and connections between them. After mounting the solar panel on top of the outer u-channel sign post, the FMCW Radar bracket is bolted to the other u-channel sign post. Figure 48 shows the sign shop utility truck used in the installation. Finally, the pointing angle of the Radar sensor is adjusted. Figure 49 shows an image of the finished installation.

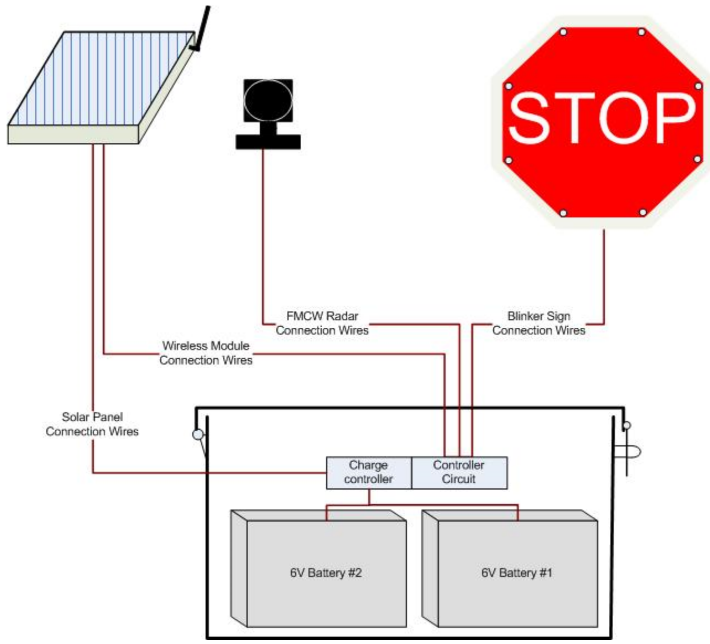


Figure 44: Main components of the FMCW radar unit.

Figure 45: Installing the STOP sign posts using the Sign Shop utility truck.

Figure 46: Finished FMCW radar unit.

5.4.3 Doppler Radar Unit Installation

There are four Doppler radar units in the ALERT-2 system. Two are located at 610 ft (186 m) on both east and west legs of the intersection (Lismore Road); the other two are installed at the “STOP Ahead” signs located on both north and south legs of the intersection. The connection diagram of a Doppler radar unit is shown Figure 50.

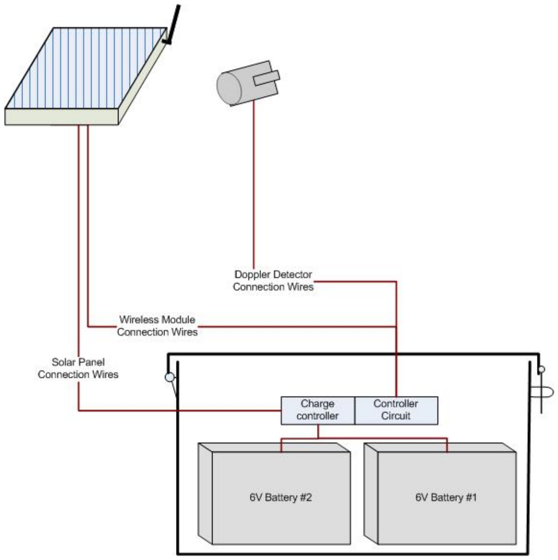


Figure 47: The main component of the Doppler radar unit.

For the Doppler detector D1 located on the east leg of the intersection, the two U-channel posts of existing road signs were used to mount the Doppler radar unit. The solar panel was mounted on the top the outer u-channel sign post, and a Doppler radar was mounted on the inner u-channel sign post. Another u-channel sign post was added as a brace and was attached at a 45° on the back of the sign and then to another post buried in the ground. Figure 51 shows a picture of the finished Doppler radar unit on the existing road signs of the major road.

Figure 48: Installed Doppler radar unit (D1) on the major road.

The second Doppler radar unit on the major road (D2) was not mounted on existing structure, because no signs were available in that side of the road. A new 8 ft (2.4 m) u-channel sign post was attached to another 8 ft (2.4 m) u-channel buried 6 ft (1.8 m) under the ground. The solar panel and the Doppler detector were attached to this single post. For the battery enclosure, another 8 ft (2.4 m) u-channel post was used to support the enclosure. Figure 52 shows an image of a finished stand-alone Doppler radar unit (D2).

The minor road Doppler detectors are mounted on the existing “STOP Ahead” signs as shown in Figure 53. A solar panel is mounted on the top the outer u-channel sign post, and a Doppler detector is mounted on the inner u-channel sign post.

Figure 49: Installed Doppler radar unit (D2) on the major road.

Figure 50: Installed Doppler radar unit (D5) on the minor road.

Chapter 6: Data Collection

6.1 Data Collection Setup

The on-site video recording system consists of two IP network cameras, two illuminators, a PoE (power over Ethernet) switch, and a PC video server. All video streams are digital and saved in the server hard disk through on-site Ethernet. Figure 54 shows a layout of the intersection and the installed on-site video monitoring system. The two shaded triangles represent camera viewing angles. The first camera is installed on a new custom pole near the intersection and captures the traffic behavior of the vehicles, approaching the intersection from the minor road. The second camera is installed on a utility pole located at 215 feet (65.5 m) west of the intersection and captures video streams of the through-traffic on the major road. Example images are shown in Figure 55.

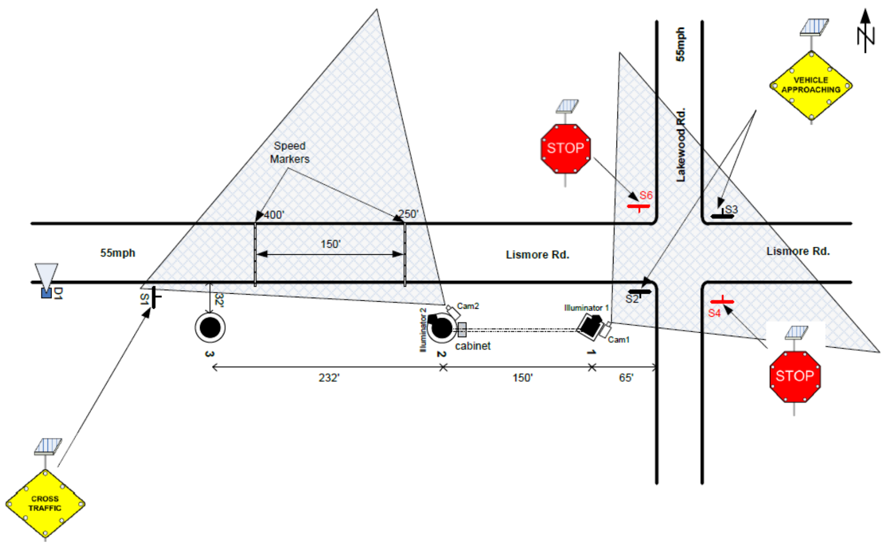


Figure 51: Video intersection layout.

Cam1: Records vehicles at the intersection

Cam2: Records vehicles at the major road

Figure 52: Network cameras and data samples.

In addition to video cameras, event-data loggers (USB-505, made by Measurement Computing) were used to record signal actuation events of both radar sensors and blinker signs. USB-505 is a standalone data logger for recording events (rising or falling edge triggered), state changes, and event counts. The logged data is download through a USB port of the data logger to PC for analysis. The data recorded by the event-data loggers are used to determine the activation status of the blinker signs and to test reliability of the system by matching the logger actuation event with the video data collected.

The duration of data collection was 13 months, and it was divided into two phases. Video data recorded before installation of the ALERT-2 system in that intersection is called the first phase data. This phase includes a total of 42 days of data with 15,893 vehicle movement records. Video data recorded after installation of the ALERT-2 system are called the second phase data. This phase includes a total of 258 days of data with 117,854 vehicle movement records.

Vehicle speeds were measured between two speed markers, which are 150 feet (45.7 m) apart. Two white bars were painted near the STOP signs at the intersection, which are used as a reference for measurements in the video analysis.

6.2 On-Site Video Recording System

The on-site video monitoring system was installed on June 8, 2011 by a local contractor (Laveau Electric Inc). The on-site video monitoring system consists of two AXIS P1346-E IP network cameras, two illuminators, a PoE (power over Ethernet) switch, and a PC video server. The AXIS P1346-E outdoor-ready network camera produces high-definition video streams (1920x1080) with P-Iris control for optimal image sharpness, and can operate in temperatures as low as -40 °C (-40 °F) [22].

The motion detection feature of the network camera allows storing video data only when a motion is detected on a specific detection zone, which would result in eliminating unnecessary data. When a motion is detected, the system was set to capture the vehicle movements for 5 seconds since the motion detection. The sensitivity of the motion detection, the size of the detected object, and the detection areas can be programmed by the user through the camera setup page. Figure 56 shows a screen shot of detection window setting and related configurations.

A custom designed cabinet is used to house a PC video server and a PoE (power over Ethernet) switch. This cabinet is mounted in front of the utility pole which Cam2 is attached to. This is because this utility pole had a pole-mount transformer, feeding 120 volt outlets. The cabinet has a front door that is lockable and it is the same cabinet used in the ALERT-1 project. Figure 57 shows pictures of this cabinet front and rear view.

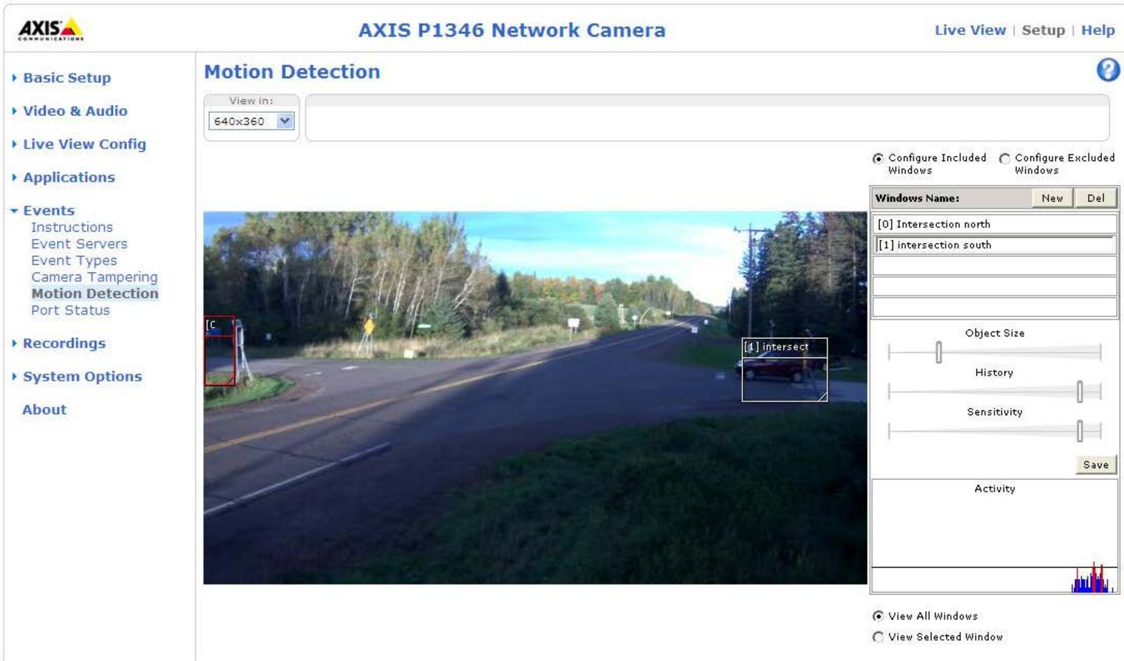


Figure 53: Network camera motion detection setup page.

Figure 54: Data collection cabinet front view (left) and back view (right).

6.3 Speed Markers

An important part of data analysis at the intersection is the speed of vehicles traveling eastbound towards the intersection on Lismore Road. Two transverse white lines, referred to as speed markers, and separated by a distance of 150 feet (45.7 m) were installed on the pavement surface on June 17, 2011. The first speed marker is located at 250 ft (76.2 m) east from the intersection. The second speed marker is located at 400 ft (121.92 m) east from the intersection. Speed markers are visible in the Cam2 image of Figure 55.

6.4 Event Logger

Event-data loggers were installed to record the activation times of the blinker signs and detection times of radar detectors. The data collected by the event loggers collectively provide information on whether the intersection was in a conflict or non-conflict case in the data analysis. It is also used to test whether a vehicle detection reliably resulted in activation of the corresponding blinker signs or not. Moreover, reliability of vehicle detections can be verified by matching the detection log data with the video data. The event-data logger used in the ALERT-2 system is the USB-505 model, manufactured by Measurement Computing. It is battery-powered, stores up to 32,510 readings, and accepts input voltages up to 24V [23]. Figure 58 shows a picture of the USB-505 data logger used.

Figure 55: USB-505 event-data logger [23].

Four event-data loggers were installed in the ALERT-2 system. Two loggers were installed in the blinker sign units S1 and S3, and the other two were installed in the detector units D1 and D3. The data were collected from the loggers monthly in a csv format and imported to Microsoft Excel. The logger’s configuration can be set through the Data Acquisition Software that came with the logger. Figure 59 shows a sample USB-505 file which came from for the logger installed in detector unit D3.

	A	B	C	D
1	USB-500 Log File			
2	Name: D3 Logger			
3	Model: USB-505			
4	Serial Number: 2193			
5	Index	Date/Time	Event(Rising Edge)	Input: 0 - 3 V
6	1	10/14/2012 8:01:03.8	1	
7	2	10/14/2012 8:07:52.5	1	
8	3	10/14/2012 8:09:04.2	1	
9	4	10/14/2012 8:09:24.4	1	
10	5	10/14/2012 8:10:20.1	1	
11	6	10/14/2012 8:11:17.3	1	
12	7	10/14/2012 8:17:55.3	1	
13	8	10/14/2012 8:21:35.5	1	
14	9	10/14/2012 8:21:40.5	1	
15	10	10/14/2012 8:49:55.2	1	
16	11	10/14/2012 8:59:56.2	1	
17	12	10/14/2012 9:04:16.9	1	
18	13	10/14/2012 9:16:24.1	1	

Figure 56: USB-505 log file sample.

6.5 Data Collection

Three external hard drives with one terabyte each were used to record the video stream data. Due to a huge data size, it was difficult to manage and navigate the video data. In order to cope with the data management problem, a software tool was developed to automatically move video data from the video server to the external hard drive, organizing them into hourly folders. The AXIS P1346-E camera supports video resolution up to 2048x1536 pixels. However, the image resolution was set to 640x480 pixels, which would result in the single image size to be around 30/35 KB. Based on these numbers, each hard drive was estimated to store data for 4 months and used at the site accordingly. The event-data logger stores up to 32,510 readings. A monthly data collection by manual downloading to PC was sufficient for collecting data from the event-data loggers.

6.5.1 Phase I Data: Before ALERT-2

This phase of data collection started on June 26, 2011. Video data was recorded until August 15, 2011. A total of 42 days with 15,893 vehicle movements were recorded in Phase I.

6.5.2 Phase II Data: After ALERT-2

Installation of the ALERT-2 system started on August 16, 2011, but the actual Phase II data collection was started on September 5, 2011 and ended on June 26, 2013. The data collection was purposely spaced to avoid collection of transitional period, by following the recommendation given by the technical liaison and advisory panel of this project. A total of 258 days of data with 117,854 vehicle movements were recorded.

Chapter 7: Data Analysis

Data analysis includes three key measurements on before-and-after installation of the ALERT-2 system: speed of the vehicles traveling eastbound on the major road, wait time of the vehicles stopped on the minor road before completing their turns, and the frequency of roll-throughs on the minor road. Crash data was not used in the analysis due to a short observation period and no actual crash data. Instead, these three driver behaviors were used as surrogates to assess the effectiveness of the system. The analysis also includes a mail-in survey of local residents.

Three main scenarios were considered in data analysis: before installation of the ALERT-2 system, after installation of the ALERT-2 system with conflict case, and after installation of the ALERT-2 system with non-conflict case. The conflict case is defined as the time when a vehicle is approaching the intersection on the major road, while another vehicle is stopping at the STOP sign on the minor road at the intersection. The data recorded by the event-data loggers are used to determine the activation status of the blinker signs (blinking/not blinking) at each event.

To further analyze the video data, three different categories were studied. The first category was the measurements during the peak traffic time and off-peak traffic time, where observing hourly traffic patterns determined the peak traffic hours. The second category was the measurements during the weekdays or weekends. The third category was the monthly average measurements. Holidays were excluded from all calculations.

7.1 Analysis Software

Two analysis software programs were developed to analyze the video data. The first one measures the speed of vehicles approaching the intersection on the major road (Lismore Road). The second one analyzes the movement of vehicles approaching the intersection from the minor road (Lakewood Road), calculates the wait times, and determines roll-through. The software tools used are Microsoft Visual Studio .NET C#, Aforge.net image processing library, and Microsoft SQL database.

7.2 Major Road Speed Measurement

To measure the speed of a vehicle traveling between the speed markers on the major road, the analysis software records the timestamps each vehicle crossing the speed markers extracted from the image file. Because the distance between the speed markers is known, 150 ft (45.7 m), the speed is calculated based on the following equation, where $t1$ is the recorded time of the vehicle crossing the first speed marker, and $t2$ is the recorded time of the same vehicle crossing the second speed marker.

$$\text{Speed (mph)} = \left(\frac{150\text{ feet}}{(t2 - t1)\text{ seconds}}\right)\left(\frac{1\text{ mile}}{5820\text{ feet}}\right)\left(\frac{3600\text{ seconds}}{1\text{ hour}}\right)$$

The calculated speed along with the vehicle image was stored into a vehicle database, where the images are later used for manual verification of vehicle detection and speed computation. The resolution of recorded timestamps is up to 1/100 second; this time was extracted from the image filename. Figure 60 shows a snapshot of the database in the speed measurement software.

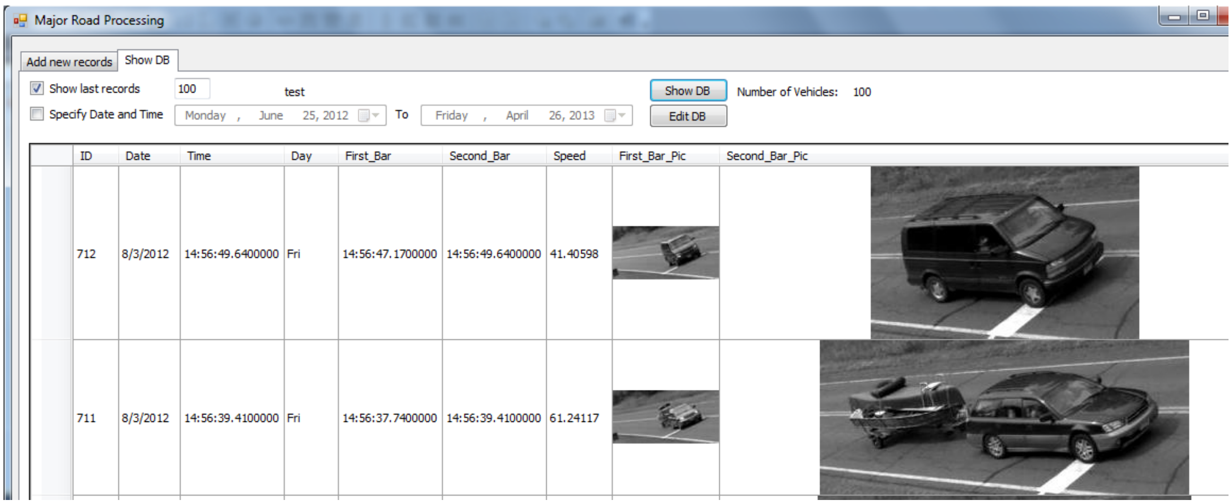


Figure 57: **SQL database created by the speed measurement software.**

At night, the network camera on the major road detected the vehicle headlights ahead of time, i.e., images were recorded before the actual vehicle reaches the detection zone and prematurely ended the recording. Therefore, we were unable to compute speeds at night.

During the period of 42 days before installation of the ALERT-2 system, a total 7,153 vehicles were processed. The average speed calculated for the before installation was 51.93 mph (83.57 km/h); the median was 53 mph (85.3 km/h); and the standard deviation was 7.81 mph (12.56 km/h). For the period of 258 days after installation of the ALERT-2 system, a total 47,443 vehicles were processed. The average speed calculated for the after installation was 50.97 mph (82.03 km/h); the median was 52.03 mph (83.73 km/h); and the standard deviation was 8.24 mph (13.26 km/h). Figure 61 shows the vehicle speed distribution before- and after-installation of the ALERT-2 system. Notice that speeds are slightly decreased after-installation of the ALERT-2 system.

Table 17 summarizes details of the average speeds on the major road before and after installation of the ALERT-2 system for three different categories: peak/off-peak time, weekend/weekday, and monthly average. In all cases, a simple average speed did not reveal much effects of the ALERT-2 system, producing only less than 1mph differences.

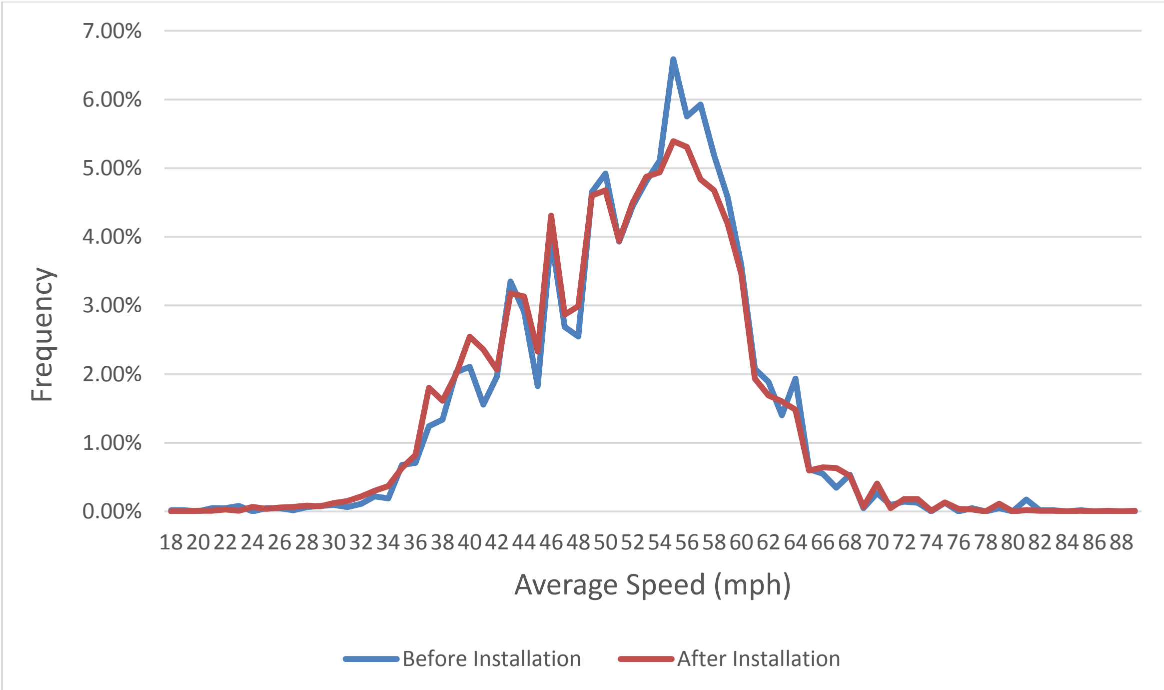


Figure 58: Vehicle speed distribution before and after installation of the ALERT-2 system.

Table 17: Comparison of Average Speeds on the Major Road Before-and-After ALERT-2 Installation

	Before Installation Average Speeds		After Installation Average Speeds	
Peak Time	51.95 mph		50.83 mph	
Off Peak Time	51.91 mph		51.02 mph	
Weekday	51.8 mph		50.94 mph	
Weekend	52.1 mph		51.31 mph	
Monthly Averages	July 2012	52.07 mph	September 2012	51.17 mph
	August 2012	51.77 mph	October 2012	51.29 mph
			November 2012	51.86 mph
			December 2012	49.93 mph
			January 2013	49.37 mph
			February 2013	50.71 mph
			March 2013	51.11 mph
			April 2013	50.34 mph
			May 2013	51.32 mph
			June 2013	51.48 mph

After installation of the ALERT-2 system, it was possible to distinguish conflict and no-conflict cases in the intersection. So the average vehicle speeds were divided into conflict and no-conflict cases. In the conflict cases, which are defined as the time when the "CROSS TRAFFIC" Blinker sign on the major road is blinking, the average speed was 47.91 mph (77.10 km/h), while in the non-conflict cases, which are defined as the time when the "CROSS TRAFFIC" Blinker sign on the major road is not blinking, the average speed was 51.8 mph (83.36 km/h). Therefore, the average speed decrease, when an intersection conflict exists, was 3.89 mph. This decrease translates into 0.93 seconds of difference in time from the moment the driver passes the blinking sign to entering the intersection, thus increasing the gap time. According to a z-test (Appendix C), this difference is statistically significant with a 99.5% confidence interval. This decrease also implies that the driver perceived and reacted to the information of the warning sign that a vehicle on the minor road is stopped at the intersection. Table 18 summarizes various speed measurements on conflict and no-conflict cases, categorized into the peak/off peak time, weekday/weekend, and monthly averages.

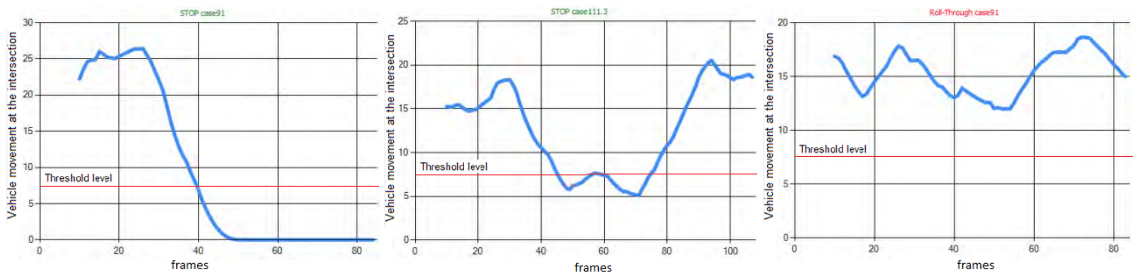
Table 18: Comparisons of Conflict and Non-Conflict Average Speeds after Installation

	No-Conflict	**Conflict**
Peak Time	51.63 mph	47.7 mph
Off Peak Time	51.88 mph	48.06 mph
Weekday	51.71 mph	47.89 mph
Weekend	51.97 mph	48.31 mph
September 2012	52.02 mph	49.10 mph
October 2012	51.54 mph	48.29 mph
November 2012	52.62 mph	47.93 mph
December 2012	51.12 mph	46.51 mph
January 2013	50.85 mph	46.62 mph
February 2013	51.53 mph	47.71 mph
March 2013	51.66 mph	48.1 mph
April 2013	51.06 mph	47.31 mph
May 2013	51.7 mph	48.19 mph
June 2013	52.29 mph	48.18 mph

7.3 Intersection Wait Time and Frequency of Roll-Throughs

The second analysis calculates and compares the wait time and the frequency of roll-throughs of the minor road traffic. Wait time is the length of time that a vehicle was stopped at a minor road stop sign before entering the intersection. A turn in an intersection is defined as a roll-through when a vehicle rolls through a stop sign without a complete stop. Image processing software developed measures the wait time and frequency of intersection roll-throughs.

The roll-through detection algorithm in the image processing works as follows. The software calculates relative velocity of an approaching vehicle in the minor road through frame-to-frame movement measurements with respect to vehicle's position in the image. This speed is not exactly mph speed but proportional to the speed with respect to the number of pixel widths the vehicle moved in the frame-to-frame images, which is the reason why we call it as a relative speed. When this relative speed drops to zero, it means that the vehicle made a full stop. If this value drops to close to zero but not zero, it means that the vehicle slowed down but did not make a complete stop. Therefore, a threshold on relative velocity is used to differentiate the roll-through cases from the stop cases. Figure 62 shows three different graph samples of relative speeds of actually observed vehicles entering the intersection. Case (a) is where the vehicle made a complete stop at the stop sign; Case (b) is where the vehicle slowed down significantly at the stop sign but did not make a complete stop; Case (c) is where the vehicle only momentarily slowed down. We only declare Case (c) as a roll-through because this is the only case in which the relative speed never dipped below the threshold line (red line).



(a) Complete STOP Case **(b) STOP Case** **(c) Roll-through Case**

Figure 59: Graph samples of vehicle movement at the intersection.

If the software determines a vehicle movement as a stop at the minor road STOP sign, the vehicle wait time is calculated by counting the number of frames where the relative speed is below the threshold level. Since the network camera uses a resolution of 30 frames per second, the wait time is calculated as the number of frames multiplied by 0.033. If the relative vehicle speed is never less than the threshold level, it is counted as a roll through.

Three roll-through types were identified: right-turn, through, and left-turn, which are illustrated in Figure 63. Here, only northbound traffic is drawn for clarity but the same classification is applied to the southbound traffic. The image processing software determines the roll-through types through the direction of the vehicle movements entering the conflict zone of the intersection. Each individual vehicle record of movements is stored in an SQL database for easy retrieval of analysis data, and the columns are shown in Figure 64.

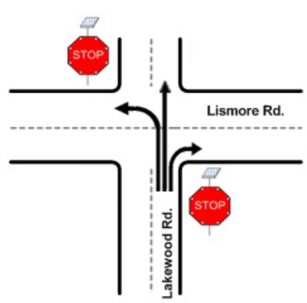


Figure 60: Three roll-through types from the minor road.

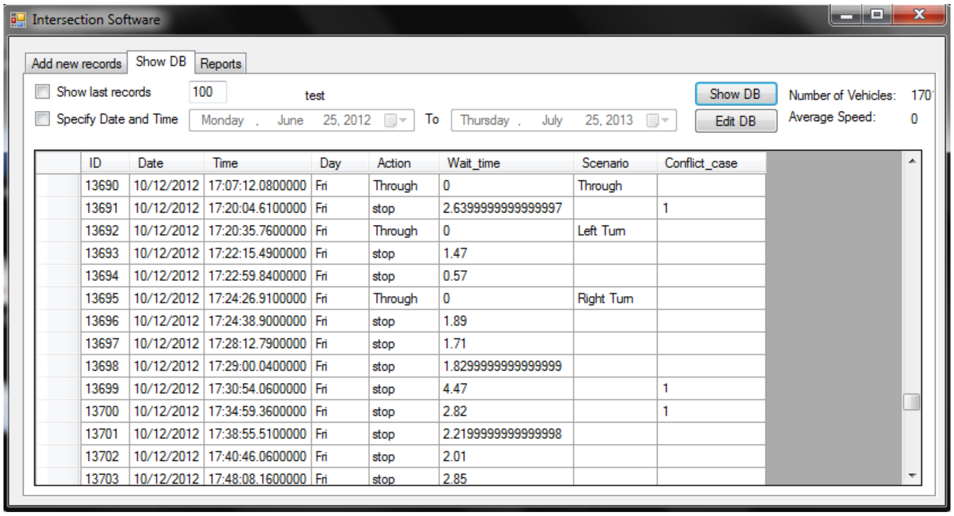


Figure 61: Database of vehicle records in the intersection.

Next, final results are summarized. Before installation of the ALERT-2 system, a total of 8,740 vehicle movements at the intersection were processed, and the average wait time for vehicles on the minor road was 1.96 seconds. The percentage of roll-throughs on all turns from the minor road was 28.15%. After installation of the ALERT-2 system, a total of 70,411 vehicle movements were processed, and the average wait time was 3.27 seconds. The percentage of roll-throughs on all turns combined after the ALERT-2 system installation was 14.27%. The percentage of roll-throughs on different turns is summarized in Table 19. In summary, the wait time at the minor road stop signs was increased by 1.31 seconds, while the intersection roll-through percent was decreased by 13.88% after installation of the ALERT-2 system. Note from Table 19 that most decrease of roll-throughs occurred on the through traffic, which indicates that the warning is more effective on through traffic than right or left turn traffic. Due to inclusion of before installation data, which does not have distinction between conflict and no-conflict cases, the data categorization of roll-rhoughs on intersection conflict/no-conflict is not available in the before/after data. Since intersection conflict or no-conflict cases are distinguishable after installation of the ALERT-2 system, such roll-through data is analyzed next.

Table 19: Roll-Through Percentage Before and After Installation of ALERT-2

	Before Installation Percent of Roll-throughs	**After Installation Percent of Roll-throughs**
Right-turn	16.45 %	9.93 %
Through	13.29 %	2.89 %
Left-turn	8.63 %	5.18 %
All turns combined	**28.15 %**	**14.27 %**

Intersection conflicts occur when one or more vehicles are approaching toward the intersection from the major road, and at the same time a vehicle is at one or both stop signs in the minor road and intends to enter the intersection. With installation of the ALERT-2 system, such conflict situations are easily identifiable and verifiable since the event-data logger records the activation time of the “VEHICLE APPROACHING” Blinker sign as well as the vehicle detection on the major road, and at the same time the video streams of the major and minor roads are recorded. Therefore, the percentage of roll-through vehicles was separately calculated for intersection conflict and no-conflict cases, and the results are summarized in Table 20. The length of wait time at the stop sign of the minor road is computed while the roll-through percentage is computed.

In no-conflict cases, the percentage of roll-throughs (on all turns combined) was 16.28 %, and the average wait time at the minor road stop sign was 2.51 seconds. In conflict cases, the percentage of roll-throughs (on all turns combined) was 1.16 %, and the average wait time was 3.91 seconds. These results are summarized in Tables 20-21. If the percentage of roll-throughs of before-installation (Table 19) is compared with the percentage of roll-throughs on no-conflict cases after-installation (Table 20), the percentage drops about 12%. With the ALERT-1 system, this percentage was actually increased by 11% and was a concern. In effect, the ALERT-2 system mitigated the concern by 22%. For intersection conflict cases, the ALERT-2 system virtually eliminated the roll-throughs, which means that it kept the advantage of ALERT-1. The wait time at the minor road stop signs was increased by 56% when an intersection conflict existed (Table 21). According to a z-test (Appendix C), the difference in wait time is statistically significant with a 99.5% confidence interval. A similar observation was made in the ALERT-1 study.

Table 20: Roll-through Percentage of Conflict and no-Conflict Cases After Installation of the ALERT-2 System

	Percent of Roll-Throughs Under No-Conflict	**Percent of Roll-Throughs Under Conflict**
Turning right	8.7 %	0.76 %
Going through	2.78 %	0.19 %
Turning left	4.74 %	0.21 %
All turns combined	**16.22%**	**1.16 %**

Table 21: Average Wait Time at Minor Road Stop Signs

	No-conflict	**Conflict**
Wait Time	2.51 sec	3.91 sec

Regarding the wait time computation in Table 21, a side note must be mentioned. When the network video camera was set up, the duration of recording after each motion detection was set to five seconds. For a roll-through or not determination, five seconds were sufficient, which was the reason that the recording time was set to 5 seconds. However, the wait time at the minor road stop sign in conflict cases required a longer recording time. Based on manual measurements, the actual wait-time of conflict cases in Table 21 was about 7 seconds, i.e., if video data were recorded for 10 seconds per event, the wait time should have been about 7 seconds. This problem was found out after completion of the data collection.

7.4 Mail-in Survey

A mail-in survey was conducted by sending out survey forms to local residents living within a 2-mile radius of the intersection. The survey includes a short explanation of the purpose of the mail-in survey, five short questions, and space for additional comments. A pre-stamped return envelope was included with the survey. This envelope was self-addressed to keep the survey anonymous and confidential. Figure 65 shows the mail-in survey letter sent out.

A total of 206 survey letters were sent out, and 119 (58%) surveys were completed and returned. The results of the mail-in survey are summarized in Table 22.

Survey:
LED Intersection Warning System

You likely have noticed signs with flashing LEDs and other equipment installed at the intersection of Lismore Road and Lakewood Road. These components are part of an experimental intersection conflict warning system. This project was sponsored by the Local Road Research Board, University of Minnesota-Duluth, Minnesota Department of Transportation, and St. Louis County. In addition to the data that has already been collected, we need your help. Please answer this short survey so that we can understand your opinion of this system. Once completed, please return the survey in this self-addressed and pre-stamped envelope. Your response is very important to us. You may contact the research assistant, Husam Ismail, at 218-591-9933 with questions. This survey is anonymous and confidential.

1. On average, how many times a day do you travel through the intersection of Lismore Road and Lakewood Road?

☐ 0 ☐ 1 ☐ 2 ☐ 3 or more

2. How much do you agree with the following statements?

2a. This warning system is easy to understand.

☐ Strongly Agree ☐ Agree ☐ Disagree ☐ Strongly Disagree

2b. This warning system improves safety at the intersection.

☐ Strongly Agree ☐ Agree ☐ Disagree ☐ Strongly Disagree

2c. The vehicle activated Blinker STOP signs obtain my attention.

☐ Strongly Agree ☐ Agree ☐ Disagree ☐ Strongly Disagree

2d. This warning system could be used at other intersections.

☐ Strongly Agree ☐ Agree ☐ Disagree ☐ Strongly Disagree

3. How would you rate the overall effectiveness of the warning system?

☐ Excellent ☐ Good ☐ Fair ☐ Poor

4. Additional Comments (use back if needed):

LED Intersection Research Team, UMD, 2013

Figure 62: Mail-in survey letter.

Table 22: Mail-in Survey Results

Question				
1. On average, how many times a day do you travel through the intersection of Lismore Road and Lakewood Road?	**0**	**1**	**2**	**3+**
	13 (11%)	24 (20%)	55 (46%)	27 (23%)
2. How much do you agree with the following statements:	**Strongly Agree**	**Agree**	**Disagree**	**Strongly Disagree**
2a) The warning system is easy to understand.	65 (55%)	46 (39%)	6 (5%)	2 (1%)
2b) The warning system improved the safety of the intersection.	67 (56%)	43 (36%)	1 (1%)	8 (7%)
2c) The vehicle activated Blinker STOP signs obtain my attention.	83 (70%)	34 (28%)	1(1%)	1(1%)
2d) The warning system could be used at other intersections.	63 (53%)	45 (38%)	6 (5%)	5 (4%)
3. How would you rate the overall effectiveness of the warning system?	**Excellent**	**Good**	**Fair**	**Poor**
	62 (52%)	42 (35%)	10 (9%)	5 (4%)

The majority of responses frequent the intersection at least two times a day (69%). One of the important results was that 92% of the responses were either strongly agree or agree that the system improved the safety of the intersection. Another important result obtained was that 98% of responses strongly agree or agree that the vehicle activated Blinker STOP signs obtained their attention. Overall, 87% of the responses rated the effectiveness of the system as excellent or good, 9% as fair, and 4% as poor.

From the received responses, 81 responders (68%) included additional comments about the system. The comments ranged between positive, suggestive, negative, and irrelevant. The positive comments on the survey were appreciating the idea and considering the system increases the safety of the intersection, while the suggestive comments mainly recommended some modifications to the system, and negative comments are either did not like the idea of the system, or concerned about the false sense of safety this system might provide. Below are samples of the received comments. After each comment, the frequency of traveling through the intersection per day by commenter is displayed in parentheses.

Positive Comments:

- With this system we may not have any problems there (2)
- What a great improvement – the intersection is much safer now. Hope it stays there (3+)
- I like the idea of using solar, nice having this option in the country (2)
- Wonderful idea, my worry is that people might rely on it too much (3+)
- Please leave the warning system in place, we are retired 65+ old, longtime Lakewood residents and appreciate the system at that corner. Thank you. (2)
- This is very dangerous intersection, stop sign is not enough, this new system is a step in the right direction. (2)

Suggestive Comments:

• To activate the sign from the west should be 100 ft earlier. At 55 mph, it is not enough time if you turn just before the lights come on. (2)
• Lights on the stop sign are unnecessary. At night, I can see them 3 miles away. The vehicle crossing sign is great. (2)
• Sometimes people don’t always look for oncoming traffic now. I feel they should not rely only on the lights because they do not always work. (2)
• From a cost-effective standpoint I wonder would it not have been much less expensive and more reliable to just make a potentially hazardous intersection a four-way stop, without any need of maintenance. (3+)
• Make it more understandable. (2)
• Could lower the speed maybe 5 mph (3+)

Negative Comments:

• We find the blinking lights are way of distraction. I worry that drivers would rely on the blinking lights versus looking for themselves for oncoming traffic. I would be relieved to see those signs removed. (2)
• Drive through it many times, it was waste of money. (3+)
• The yellow is crazy, first it says stop and then the yellow is saying proceed with caution if you don’t read it. The first time I went through it, it was very confusing. Keep the red, junk the yellow. (2)
• The system is dangerous, it gives false sense of safety when quite often it was not working. The stop signs are good idea (2)
• The flashing LED is very distracting and divert drivers attention from the road and traffic, they are a serious hazard.

Irrelevant Comments:

• 2-4 times a day on weekends, have never seen it (2)
• I am not in a position to be able to answer this. What does the data say? (1)

Chapter 8: Conclusions and Future Recommendations

8.1 Conclusions

This report documented the second phase of the ALERT project. The second phase objective was to improve all aspects of the ALERT-1 system and to create a next generation of the system, i.e., a better ALERT-2 system with respect to reliability, maintainability, and safety performance. The following summarizes the features improved in the ALERT-2 system.

- Higher battery capacity, supporting up to 23 days without charging (7 days in ALERT-1)
- Better charging performance in winter by using AGM batteries (Li-ion batteries in ALERT-1 had charging problems when the temperature was below 0 ºC)
- Use of a standard wireless protocol, IEEE 802.15.4 (a proprietary protocol was used in ALERT-1)
- Easy access to battery and controllers for maintenance (ALERT-1 required a ladder)
- IP networked video cameras for recording high quality digital video data (analog cameras were used in ALERT-1)
- Commercial grade PCBs fabricated from a factory were used for higher circuit reliability (lab fabricated PCBs were used in ALERT-1)
- Integrated a sign controller and a detector controller into one PCB board, requiring only one type PCBs (two different types of PCBs were used in ALERT-1)
- Improved, customized LED driver circuits were used for efficient LED controls (Tapco driver circuits were used in ALERT-1)
- Development of more sophisticated image processing algorithms for data analysis (image quality was poor in ALERT-1)
- Doppler radar detectors were used for directional vehicle detection in both major and minor roads (infrared motion detectors were used in the major road of the ALERT-1 system, and it was less reliable)
- Event data logger for capturing electrical signal events for monitoring sign/detector actuation sequences (no event logger instruments were used in ALERT-1)
- Inclusion of additional dynamic sign units to mitigate roll-throughs

In the first phase, the data showed that the ALERT-1 system reduced vehicle speeds on the main approach, increased the wait time on the minor approaches, and eliminated roll-throughs for vehicles on the minor approaches when a conflict exists in the intersection. However, when no conflict exists in the intersection, an increase in roll-throughs was observed [8, 9]. The ALERT-2 system was designed to mitigate this increase in roll-throughs by redesigning the minor approach sign system. In the new design, two STOP signs in the minor road were turned into LED blinker STOP signs. The LED blinking was activated by a vehicle at the corresponding STOP Ahead sign and terminated when the vehicle reaches the STOP sign.

The roll-through percentage measured after installation of the ALERT-2 system was 1.16% when an intersection conflict exists and 16.22% when no conflict exists. This data agrees with the findings of the ALERT-1 study in that most roll-throughs occur when no intersection conflict exists. A new finding in ALERT-2 is in the following data. The roll-through percentage of before ALERT-2 installation was 28.15%, and this number includes both conflict and no-conflict cases (it is not separable in the before data). After installation of the ALERT-2 system, this number was decreased to 17.38% which is the sum of 16.22% (no-conflict cases) and 1.16% (conflict cases). Consequently, the ALERT-2 system was able to decrease the roll-throughs by 10.8%. However, it should be noted that this is actually a 22% improvement over the roll-through percentage of the ALERT-1 system since it was increased by 11%.

The stop wait time at the minor approaches was 2.5 seconds for no-conflict cases and 3.91 seconds for conflict cases, resulting a 56% increase in conflict cases. The analysis of average vehicle speeds on the major road showed a decrease of 3.89 mph in the conflict case. These results agree with that of ALERT-1.

In the ALERT-2 mail-in survey, 92% of the responses were either “strongly agree” or “agree” that the system improved the safety of the intersection. In contrast, this number was 72% [9] in the ALERT-1 survey. An important result obtained from the ALERT-2 survey was that 98% of responses were “strongly agree” or “agree” that the vehicle activated blinker STOP signs obtained their attention. Since the main purpose of placing the dynamic blinker STOP signs was to obtain driver’s attention, this goal was well achieved in the ALERT-2 design.

In summary, data analysis of the ALERT-2 system showed that it kept or improved all of the benefits of the ALERT-1 system while mitigating the roll-through problem when no conflict exists. With respect to technological advances, the ALERT-2 system improved many aspects of the ALERT-1 technologies, providing higher system reliability, easier maintainability, and better self-sustainability.

The final question is did this system improve safety at rural, two-way stop intersections? Although this project was unable to directly answer this question, the analysis of the surrogate data suggests a safety benefit. In the NCHRP Report 500, Volume 5: A Guide for Addressing Unsignalized Intersection Crashes, it lists various safety strategies that could be implemented to improve intersection safety. Based upon the analysis of the surrogate data for this project, the ALERT-2 system appeared to accomplish the implementation of two general safety strategies in this NCHRP report. First, it improved gap recognition for drivers on the minor approach and second, it reduced the vehicle speeds on the major approach. Since gap recognition is such an important factor in the determination of whether there is a crash at an unsignalized intersection, the ALERT-2 system appears to have the potential to significantly improve safety at rural, two-way stop intersections.

8.2 Future Recommendations

The ALERT-2 system improved upon the ALERT-1 system in many aspects. However, if an ALERT-3 system is developed in the future, the research team would like to improve the following aspects.

- Consider use of a higher watt-rated solar panel in the FMCW stationary radar unit. Since these units consume most energy in the system, a higher watt-rated solar panel, such as 40W, would provide a better power-supply reliability in the winter.

- The FMCW radar alone was not as reliable as expected in detecting vehicle presence of a zone. For example, the radar sensitivity in the summer was set to 5, but it had be increased to 7 in the winter. A better and reliable solution would be use of a combination of a Doppler radar and the FMCW radar, making the Doppler radar detect the entrance time of the detection zone and the FMCW radar detect leaving time of the detection zone. However, adding a Doppler radar would require more energy and, consequently, a higher cost.
- In data collection:
    - The 5 second video stream after a motion detection was not sufficient to measure the minor-road STOP wait time in the intersection conflict cases. A recommended solution for this limitation is to increase the duration of the stream to 10 seconds. However, this would double the hard disk capacity requirement. We recommend the image resolution to be reduced so that the hard disk storage requirement does not increase.
    - Speed measurements on the major road using video cameras had severe limitations at night due to low visibility and in snowy road conditions due to snow-covered speed bars. It is an inherent problem of video-based speed measurements, and thus we do not recommend this method in the future. We recommend use of a Doppler radar-based speed measurement instrument.

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APPENDIX A - COMPLETED MAIL-IN SURVEY SAMPLES

Survey:

LED Intersection Warning System

UNIVERSITY OF MINNESOTA
Driven to Discover

LRRB

You likely have noticed signs with flashing LEDs and other equipment installed at the intersection of Lismore Road and Lakewood Road. These components are part of an experimental intersection conflict warning system. This project was sponsored by the Local Road Research Board, University of Minnesota-Duluth, Minnesota Department of Transportation, and St. Louis County. In addition to the data that has already been collected, we need your help. Please answer this short survey so that we can understand your opinion of this system. Once completed, please return the survey in this self-addressed and pre-stamped envelope. Your response is very important to us. You may contact the research assistant, Husam Ismail, at 218-591-9933 with questions. This survey is anonymous and confidential.

1. **On average, how many times a day do you travel through the intersection of Lismore Road and Lakewood Road?**

☐ 0 ☐ 1 ☐ 2 ☒ 3 or more

2. **How much do you agree with the following statements?**

2a. This warning system is easy to understand.

☐ Strongly Agree ☒ Agree ☐ Disagree ☐ Strongly Disagree

2b. This warning system improves safety at the intersection.

☐ Strongly Agree ☒ Agree ☐ Disagree ☐ Strongly Disagree

2c. The vehicle activated Blinker STOP signs obtain my attention.

☐ Strongly Agree ☒ Agree ☐ Disagree ☐ Strongly Disagree

2d. This warning system could be used at other intersections.

☒ Strongly Agree ☐ Agree ☐ Disagree ☐ Strongly Disagree

3. **How would you rate the overall effectiveness of the warning system?**

☐ Excellent ☒ Good ☐ Fair ☐ Poor

4. **Additional Comments** (use back if needed):

It is very helpful on foggy days and at dusk. I still trust my own vision better, but it has helpful.

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2c. The vehicle activated Blinker STOP signs obtain my attention.

☑ Strongly Agree ☐ Agree ☐ Disagree ☐ Strongly Disagree

2d. This warning system could be used at other intersections.

☑ Strongly Agree ☐ Agree ☐ Disagree ☐ Strongly Disagree

3. **How would you rate the overall effectiveness of the warning system?**

☑ Excellent ☐ Good ☐ Fair ☐ Poor

4. **Additional Comments** (use back if needed):

I love it! I almost got hit by a car that I didn't see because of the blind dip east of the intersection. Several times now I've waited because of the flashing lights and on-coming vehicle warning and sure enough - they were coming, even though I couldn't see them. Helps in Foggy conditions too. Thank You!

LED Intersection Warning System Research Team, UMD, 2013

Survey:

LED Intersection Warning System

UNIVERSITY OF MINNESOTA
Driven to Discover
LRRB

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2c. The vehicle activated Blinker STOP signs obtain my attention.

☒ Strongly Agree ☐ Agree ☐ Disagree ☐ Strongly Disagree

2d. This warning system could be used at other intersections.

☒ Strongly Agree ☐ Agree ☐ Disagree ☐ Strongly Disagree

3. **How would you rate the overall effectiveness of the warning system?**

☐ Excellent ☒ Good ☐ Fair ☐ Poor

4. **Additional Comments** (use back if needed):

It was a great idea. With all the hills and high speed limits in the township I can easily see similar systems in other areas. My husband goes through that intersection more during the achedemic year. I choose not to go that way because of the danger - but your system has me doing it more often. I think there have been a few times this year when it hasn't seemed to work. Please keep up the good work ☺ Debbie Swenson

ps - re question 3, as would be normal, drivers may not always heed any signal system. The flashing stop sign is outstanding

APPENDIX B - ARTICLES AND VIDEOS ABOUT ALERT-2

- CTS Catalyst Article: “Warning system aims to alert drivers to potential crashes”
  http://www.cts.umn.edu/Publications/catalyst/2013/july/intersection/

- CTS Phase II research project page
  http://www.cts.umn.edu/Research/ProjectDetail.html?id=2012027

- Presentation slides from the CTS Research Conference
  http://www.cts.umn.edu/events/conference/2013/presentations/6_kwon_ismail.pdf

- WDIO TV video report about ALERT-2: “New Warning System May Make Rural Intersections Safer”
  http://www.wdio.com/article/stories/s3114404.shtml?cat=10335

- ALERT-2 photo album on Mn/DOT Research Facebook page:
  https://www.facebook.com/media/set/?set=a.10151552961873657.1073741831.329166533656

- ALERT System: Interview with Traffic Engineer Vic Lund
  http://www.youtube.com/watch?v=-Urnxa_8Bqs&feature=youtu.be

- ALERT-2 Project Overview:
  http://www.youtube.com/watch?v=9eOJ4qlBrQU&list=UUv7YzuOZPIXuRZH1DObtlrA&feature=c4-overview

- ALERT-2 in operation videos in YouTube:
  http://www.youtube.com/watch?v=o1PUZApW5f4
  http://www.youtube.com/watch?v=c003lciH18Y
  http://www.youtube.com/watch?v=Rk7oZWdps-s

APPENDIX C - Z-TEST CALCULATIONS

Vehicle Speeds in MPH, Before (μ_1) and After (μ_2) Installation

Period	Sample Size (n)	Mean $(\bar{X})$	Standard Deviation (σ^2)
Before Installation	7,153	51.93	7.81
After Installation	47,443	50.97	8.24

Hypothesis:

Null: No significant difference in speed
H_0: $\mu_2 - \mu_1 = 0 \rightarrow \mu_2 = \mu_1$

Alternate: Significant difference in speed
H_1: $\mu_2 - \mu_1 \neq 0 \rightarrow \mu_2 \neq \mu_1$

Test Statistic:

$$z = \frac{\bar{X}_2 - \bar{X}_1}{\sqrt{\frac{\sigma_2^2}{n_2} + \frac{\sigma_1^2}{n_1}}} = \frac{50.97 - 51.93}{\sqrt{\frac{8.24}{47443} + \frac{7.81}{7153}}} = -27$$

Decision Rule:

Confidence Level	Lower Critical Value	Upper Critical Value
99.5%	-2.81	2.81

Reject null hypothesis if $z \leq$ lower critical value or $z \geq$ upper critical value.

$z = -27 <$ lower critical value

REJECT null hypothesis. Therefore, there is a significant difference in speed.

The two-tailed P value is less than 0.0001 for z = -27. By conventional criteria, this difference is considered to be extremely statistically significant.

Vehicle Speeds in MPH, Conflict (μ_1) and No Conflict (μ_2) After Installation

Period	Sample Size (n)	Mean $(\bar{X})$	Standard Deviation (σ^2)
Conflict	10,150	47.91	8.04
No Conflict	37,283	51.8	9.13

Hypothesis:

Null: No significant difference in speed
H_0: $\mu_2 - \mu_1 = 0 \rightarrow \mu_2 = \mu_1$

Alternate: Significant difference in speed
H_1: $\mu_2 - \mu_1 \neq 0 \rightarrow \mu_2 \neq \mu_1$

Test Statistic:

$$z = \frac{\bar{X}_2 - \bar{X}_1}{\sqrt{\frac{\sigma_2^2}{n_2} + \frac{\sigma_1^2}{n_1}}} = \frac{51.8 - 47.91}{\sqrt{\frac{9.13}{37283} + \frac{8.04}{10150}}} = 120.8$$

Decision Rule:

Confidence Level	Lower Critical Value	Upper Critical Value
99.5%	-2.81	2.81

Reject null hypothesis if $z \leq$ lower critical value or $z \geq$ upper critical value.

$z = 120.8 >$ upper critical value

REJECT null hypothesis. Therefore, there is a significant difference in speed.

The two-tailed P value is ~0 for z = 120.8. By conventional criteria, this difference is considered to be extremely statistically significant.

Vehicle Wait Time in Sec, Before (μ_1) and After (μ_2) Installation

Period	**Sample Size** (n)	**Mean** $(\bar{X})$	**Standard Deviation** (σ^2)
Before	6,280	1.96	1.69
After	60,363	3.2	1.81

Hypothesis:

Null: No significant difference in wait time
H_0: $\mu_2 - \mu_1 = 0 \rightarrow \mu_2 = \mu_1$

Alternate: Significant difference in wait time
H_1: $\mu_2 - \mu_1 \neq 0 \rightarrow \mu_2 \neq \mu_1$

Test Statistic:

$$z = \frac{\bar{X}_2 - \bar{X}_1}{\sqrt{\frac{\sigma_2^2}{n_2} + \frac{\sigma_1^2}{n_1}}} = \frac{3.1 - 1.96}{\sqrt{\frac{1.81}{60363} + \frac{1.69}{6280}}} = 71.7$$

Decision Rule:

Confidence Level	**Lower Critical Value**	**Upper Critical Value**
99.5%	-2.81	2.81

Reject null hypothesis if $z \leq$ lower critical value or $z \geq$ upper critical value.

$z = 71.7 >>$ upper critical value

ACCEPT null hypothesis. Therefore, there is a significant difference in vehicle wait time.

The two-tailed P value is ~0 for z = 71.2. By conventional criteria, this difference is considered to be extremely statistically significant.

Vehicle Wait Time in Sec, Conflict (μ_1) and No Conflict (μ_2) After Installation

Period	**Sample Size** (n)	**Mean** $(\bar{X})$	**Standard Deviation** (σ^2)
Conflict	13,297	3.91	1.81
No Conflict	13,845	2.51	1.76

Hypothesis:

Null: No significant difference in wait time
H_0: $\mu_2 - \mu_1 = 0 \rightarrow \mu_2 = \mu_1$

Alternate: Significant difference in wait time
H_1: $\mu_2 - \mu_1 \neq 0 \rightarrow \mu_2 \neq \mu_1$

Test Statistic:

$$z = \frac{\bar{X}_2 - \bar{X}_1}{\sqrt{\frac{\sigma_2^2}{n_2} + \frac{\sigma_1^2}{n_1}}} = \frac{2.51 - 3.91}{\sqrt{\frac{1.76}{13845} + \frac{1.81}{13297}}} = -86$$

Decision Rule:

Confidence Level	**Lower Critical Value**	**Upper Critical Value**
99.5%	-2.81	2.81

Reject null hypothesis if $z \leq$ lower critical value or $z \geq$ upper critical value.

z = -86 << lower critical value

REJECT null hypothesis. Therefore, there is a significant difference in vehicle wait time.

The two-tailed P value is ~0 for z = -86. By conventional criteria, this difference is considered to be extremely statistically significant.