

UNIVERSITY OF OKLAHOMA
GRADUATE COLLEGE

THE DEVELOPMENT OF A SMART AND LOW POWER CONSUMPTION
VARIABLE SPEED LIMIT SIGN FOR THE OKLAHOMA DEPARTMENT OF
TRANSPORTATION

A THESIS
SUBMITTED TO THE GRADUATE FACULTY
in partial fulfillment of the requirements for the
Degree of
MASTER OF SCIENCE

By
MARCELO FRANZ MORENO MARIN
Norman, Oklahoma
2024

THE DEVELOPMENT OF A SMART AND LOW POWER CONSUMPTION
VARIABLE SPEED LIMIT SIGN FOR THE OKLAHOMA DEPARTMENT OF
TRANSPORTATION

A THESIS APPROVED FOR THE
SCHOOL OF ELECTRICAL AND COMPUTER ENGINEERING

BY THE COMMITTEE CONSISTING OF

Dr. Jorge L. Salazar-Cerreño, Chair

Dr. Jay W. McDaniel

Dr. Yan Zhang

Acknowledgments

First and foremost, I would like to express my gratitude and thanks to God for His blessings throughout my life, allowing me to reach this day when I am finalizing my Graduate Thesis Research. To my beloved wife, Mariela, who shared all the sacrifices involved during this stage of my life and has been an endless source of trust and support. To my advisor, Dr. Jorge L. Salazar, for supporting me throughout my graduate studies and giving me this great opportunity to be part of the ARRC. To Alan Stevenson and Basel Kilani, the sponsors of this research. I also owe my graduate achievements to my parents, Liliana and Walter, who have done their best and made many sacrifices to shape me into who I am today, without whom I would not have made it this far. I would also like to thank some of the friendships that have been instrumental to my success. Here in the USA, to my dear friends of the PAARD: Sergio, Burdi, Elizabeth, Mariel, Felipe, and Alexis, thank you for sharing your time and knowledge with me. I will never forget all those “study parties” we had while preparing for projects and examinations. Two important ARRC members, Dale and Johnny, have always been ready to help with any concerns that I have had. In Bolivia, I extend my gratitude to my brothers, Douglas and Mauricio, and my wife’s family, who are like a second family to me—Anny, Gastón, Veronica, Andrea, Cristhian, Daniel, and Blanca. Additionally, I am thankful to my professor, Victor Crispin, who pushed me beyond my limits to teach me the English language. Lastly, I want to acknowledge Rodrigo Collao, who perfectly embodies the meaning of the word “friend”. Simply put, thank you for being a part of my life.

Table of Contents

Acknowledgments	iv
List Of Tables	vii
List Of Figures	viii
List Of Acronyms	xv
Abstract	xix
1 Introduction	1
1.1 Motivation	1
1.2 Literature Review	2
1.3 Proposed System	12
1.4 Organization of the Thesis	15
2 System Requirements	17
2.1 Variable Speed Limit Sign	17
2.1.1 Size and Dimmensions	18
2.1.2 Visibility and Legibility	18
2.1.3 Power Consumption	20
2.1.4 Lifespan and Maintenance	21
2.1.5 Communications	22
2.2 Base Station	23
2.2.1 Size and Shape	23
2.2.2 Power Sources	23
2.2.3 Lifespan and Maintenance	24
2.2.4 Communications	25
2.3 Summary	25
3 Design Considerations and Tradeoffs	27
3.1 Topology of the system	27
3.2 Base Station	28
3.2.1 Installation Locations and Power Source Access	28
3.2.2 Network Access	30
3.2.3 Available Communication Protocols And Range	31
3.3 Variable Speed Limit Sign	32
3.3.1 Operating Environment And Weather Analysis	32
3.3.1.1 Snow and Freeze	33
3.3.1.2 Maximum Heat Levels	34
3.3.1.3 Rainfall and Wind Speed	34

3.3.1.4	Tornadoes and Severe Storms	34
3.3.2	Power Source Access	35
3.4	Summary	36
4	System Design	37
4.1	Variable Speed Limit Sign	37
4.1.1	E-Ink Displays	38
4.1.2	Communications Module - LoRa	41
4.1.3	GPS Module	44
4.1.4	Microcontroller	45
4.1.5	Battery, Solar Panel, And Enclosure	49
4.1.6	Front Light	53
4.1.7	Printed Circuit Board	54
4.1.8	Assembly and Mounting	55
4.1.9	Firmware	60
4.2	Base Station Design	63
4.2.1	CPU And Operative System	64
4.2.2	Comunications Module - LoRa	68
4.2.3	Auxiliar Outputs - Relays	68
4.2.4	Enclosure and PCB Shape	69
4.2.5	Printed Circuit Board	70
4.2.6	Software and API	72
4.3	Summary	76
5	Preliminary Results	79
5.1	Visibility Day And Night	79
5.2	Power Consumption And Battery Autonomy	83
5.3	Communications, Range, and Response Time	89
5.4	Summary	93
6	Conclusion	96
	Bibliography	98
	Appendix A Base station PCB schematics	104
	Appendix B Variable speed limit sign PCB schematics	106

List Of Tables

1.1	Representative VSL systems in the United States.	13
2.1	Available options of VSLS in the market.	21
4.1	Comparative list of available LoRa modules in the market.	43
4.2	Comparative list of different Espressif microcontrollers.	47
4.3	Theoretical power consumption analysis of the VSLS components (Active mode).	49
4.4	Theoretical power consumption analysis of the VSLS components (Standby mode).	50
4.5	Comparative list of available CPUs in the market.	65
5.1	List of the measured power of different VSLS components.	86
5.2	Power consumption analysis of the VSLS components using the mea- sured power values (Active Mode).	87
5.3	Power consumption analysis of the VSLS components using the mea- sured power values (Standby Mode).	88

List Of Figures

1.1	Different types of SLSs and their applications [13]. Statutory: The type of road determines baseline speed limits, even if there is no posted speed limit. Posted: Speed limit indicated by a posted sign along the road. School Zone: Modification of the speed limit during certain hours. Workzone: Modification of the regular speed limit due to works along an area. Variable: The speed limit is determined according to environmental conditions such as traffic, weather, or others. Advisory: Recommended speed limit due to a warning maneuver.	3
1.2	VSLs deployed in a highway construction zone during winter [15]. . .	4
1.3	One of the earliest implementations of a VSL system in the United States occurred on The Lodge Freeway in Michigan during the 1960s [17].	6
1.4	A picture of the 1960s Comiskey Park's Exploding Scoreboard of the Chicago White Sox illustrates the available technology at that time. a) An overall view of the complete scoreboard made out of incandescent bulbs and mechanical components [21]. b) A closer view of one of the top spinning wheels shows the incandescent bulbs installed on it [22].	7
1.5	A VMS and a VSLs installed on the New Jersey Turnpike in the late 1960s [16]. The picture clearly shows the use of neon lights for the VMS and mechanical parts for the VSLs, which were two of the most common technologies of that time.	8
1.6	Examples of the ATDM system corridors installed by WSDOT along Washington Highways [24]. a) Along Interstate 5 in Vancouver, the implementation of four DMS can be observed, with three of them displaying lane availability and the last one showing text information. b) On Highway 520 between Seattle and Bellevue, the implementation of four DMS can be observed, with three of them functioning as VSLs and the last one displaying text information.	10
1.7	Examples of VSLs installed by GDOT along I-285 Highway. a) A picture from Interstate 285 westbound at the tunnels across the south side of ATL Airport [27] shows two VSLs, with the one on the left appearing to use solar energy as the main source of power. b) A closer view of an I-285 VSL [28] reveals that the displays for the numbers are made out of an LED matrix.	11

1.8	Illustration of the Proposed System. 1. The VSLs: A visual device that informs drivers of the maximum allowed speed. It uses E-ink ultra-low power consumption technology to display the numbers and is configurable by the BS. 2. The BS: The interface between end users and the VSLs. It has the capacity to control up to 80 signs within a maximum range of 5 miles. Its small size and low power consumption allow for easy deployment and it is easily controlled by an API. 3. End users or web services: These are the entities that want to control or set a configuration in a VSL. To do so, they need to connect to the BS API. 4. Communication segment between the VSL and BS: LoRa modules handle communication in this segment. Characteristics such as low power consumption and long range make them suitable for this purpose. 5. Communication segment between the BS and the end user or web services: Internet connection is planned for this segment. The current coverage and stability of 4G and 5G networks provide the reliability needed for this purpose.	16
2.1	SLS manufacturing dimensions compliant with MUTCD standards in inches [29]. The mechanical drawing details all the crafting dimensions. Columns A and B correspond to the overall width and height, respectively. Once the overall size is selected, the other dimensions can be easily read from the Table. For the scope of this research, a size of 18x24 inches is required.	19
2.2	Siemens PLC, model Logo! [38]. The size, dimensions, shape, and mounting structure of this device are used as a reference for the form factor requirements of the BS.	24
3.1	Topologies of the IEEE 802.15.4 LR-WPAN [41]. After analysis, the star configuration was chosen as the topology for the system.	28
3.2	Map of the network of public devices controlled by ODOT. This information is available on the OK Traffic Map website [39], and this picture is used as a reference for possible locations to deploy a BS or a group of VSLs.	29
3.3	T-Mobile 4G & 5G Oklahoma coverage map [42]. This map shows that internet access is available in a large area of the state; therefore, internet access for the BS using a modem is a viable option.	30
3.4	Comparison of range and bandwidth of different wireless technologies [43].	32
4.1	The concept idea of the VSL involves a compact design, which will be less bulky than others in the market. It includes features such as E-ink technology, LoRa communications, and power harvesting capabilities, among others.	39

4.2	Numbers width comparison according to the speed posted in a SLS to select proper E-ink screen sizes. a) 15 miles per hour SLS example. Number height 8 inches, total width 10 inches. b) 45 miles per hour SLS example. Number height 8 inches, total width 14.3 inches.	40
4.3	Different sizes of E-ink displays available in the market. a) 7.8 inches. b) 9.7 inches. c) 10.3 inches. d) 13.3 inches.	42
4.4	LoRa modules available in the market. a) RYLR998 [51]. b) Ra-02 [52]. c) E32-900T30D [53].	42
4.5	Views of the Adafruit Ultimate GPS breakout V3 module. a) Top view. b) Bottom view next to a quarter coin.	46
4.6	Images of different development kits for the Espressif microcontrollers: a) DEVKITM ESP8266 [60]. b) DEVKITM ESP32 [61]. c) DEVKITM ESP32-S3 [62].	48
4.7	Different views of the RPDC12-9-15 outdoor power system [63]. a) Inside components. b) Solar panel complete kit.	52
4.8	Different views of VSLS lighting options. a) Inspired LED LLC presents a 12 V flexible LED strip equipped with 2835 diodes, boasting a power consumption of 21 W over a length of 84.5 inches [64]. b) From DFRobot, a 5 V rectangular COB LED offering 300 lumens, with dimensions measuring 12000.00 mm in length and 25.40 mm in width. Its power consumption is 3 W [65]. c) From Citizen, a 9.2 V rectangular COB LED delivering 760 lumens, with dimensions of 50.00 mm in length and 7.00 mm in width. This option consumes 6.5 W of power [66]. d) Lastly, the Hyper Tough 1200 lumen Rechargeable Work Light, features a lithium-ion battery and an LED bulb, providing bright light for up to 4 hours on a low setting and 2 hours on high. It comes with an integrated handle featuring a 180-degree swivel, allowing for flexible positioning [67].	55
4.9	VSLS PCB motherboard. 1. 12 V and 5 V power inputs. 2. Protection fuses. 3. Power supply test push buttons. 4. Solar panel signal feedback for auto-brightness functions. 5. LoRa module socket. 6. Microcontroller socket. 7. Power supplies status LED. 8. GPS voltage regulators. 9. GPS module socket. 10. Transistorized 12V PWM controlled outputs for frontlights. 11. E-ink drivers sockets. 12. Expansion I/O sockets with one GPIO each.	56

4.10	Exploded view of the layers for the front panel of the VSLS: 1. Black frame. It will cover the frontlight LED strips to prevent direct light towards the drivers and at the same time, is a characteristic determined by the MUTCD. 2. Frontlight frame conformed by LED strips. Will illuminate the sign, epoxy sealant will be poured along this whole layer, working as a waveguide to keep the light trapped. 3. Signage and pocket for displays. This layer will hold the display in position and cover the black frames of the E-ink displays 4. E-ink displays. this will show the desired speed through the numbers posted. 5. Spacing frame. This will give enough space for the E-ink display buses and circuitry 6. Back layer. It covers the back of the displays and will be attached to the solar panel enclosure, it is the fixture that holds the enclosure and the front panel.	57
4.11	Acrylic layers manufacturing process using a laser cutting machine: a) The layers from the 3D model design in 4.10 are exported as DXF files and configured for cutting and engraving. b) The laser machine cuts and engraves. c) Results of engraved pockets for E-ink displays. d) Results of letters cut for signage.	58
4.12	Front panel assembly using the acrylic layers includes: a) Bonding the bottom acrylic layer, frame for the frontlight, and letters with super glue and silicone caulking. b) A detailed view of the installed E-ink displays in the front panel. c) A detailed view of the installed LED strips in the front panel. d) Preparing and leveling the front panel for epoxy pouring to complete the manufacturing process. . . .	59
4.13	Modifications made to the solar panel system enclosure to accommodate electronics and the front panel. a) Holes drilled using an acrylic fixture that aligns with the bottom acrylic layer. b) Exterior view of the enclosure with the bottom acrylic layer attached. c) Internal view of the empty enclosure. d) Internal view of the enclosure with the mockup PCB.	61
4.14	Battery, solar regulator, and electronic components mounted inside the enclosure.	62
4.15	Results of the VSLS assembly: a) Comparison between the VSLS and a regular SLS, each mounted on an aluminum pole. b) Comparison between the VSLS and a regular SLS, both with the same speed limit. c) Close-up view of the VSLS front panel.	63
4.16	Generalized flow diagram of the VSLS firmware	64
4.17	Raspberry Pi latest released models. a) Raspberry Pi 4 model B [70]. b) Raspberry Pi 5 [71].	68
4.18	The AZ943, a 10 A miniature general-purpose PCB relay [72]	69
4.19	3D model of the base station enclosure designed using Sketchup software. a) Top-front corner view. b) Rear-front corner view	70
4.20	PCB mockup and enclosure 3D models designed using Sketchup software. a) Top-front corner view. b) Top-rear corner view. c) Transparent top-front corner view. d) Transparent top-rear corner view. . .	71

4.21	Base station printed circuit board functionalities. 1. General purpose inputs and outputs. 2. AC power input. 3. Raspberry Pi socket. 4. Dual 5 V power supply. 5. LoRa module socket. 6. General purpose buttons. 7. Status LEDs. 8. Fan socket. 9. 10 A Relays. 10. Relay terminal blocks	73
4.22	Base station manufacturing and assembly. a) Printed circuit board manufactured in the ARRC. b) Printed circuit board with electronic components. c) Printed circuit board inserted in the 3D printed enclosure. d) Base station completely assembled.	74
4.23	Tests of the BS API. The server was deployed using LoopBack 4, a highly extensible Node.js and TypeScript framework for building APIs and microservices.	76
5.1	Contrast issues arising from the combination of the retroreflective material and E-ink displays. a) A detailed view of the initial test reveals that the E-ink displays are completely obscured due to the reflection of surrounding material. b) As the car approaches and the light is not directly focused, it becomes easier to read the numbers, however, visibility is still insufficient for proper functionality. c) The use of high beams only exacerbates the problem.	80
5.2	Visibility tests setups. a) During the day, VSLS (1) and SLS (2) are deployed, and each test is conducted separately to avoid confusing the participants and producing biased data. b) During the night, three configurations are possible: VSLS with spotlight (1), VSLS with front light (2), and SLS (3). Similar to the daytime setup, each configuration is deployed individually to prevent confusion among participants. Due to street restrictions and sign sizes, three speeds were used: 15, 20, and 25 mph.	82

5.3	Visibility test results showing the measured legibility distance for a specific traveling speed. Tests were conducted during the day (Top figures) and at night (Bottom figures). In these tests, participants were asked to take time measurements using a stopwatch. They were placed in a car traveling at a constant speed. When they were able to read the number posted on the sign, they started the stopwatch. Then, when they were able to read the “Speed Limit” phrase, they marked a lap on the stopwatch. Finally, when they passed next to the sign, they stopped the timer. The total time divided by the traveling speed is the “Number” distance, and the last lap time divided by the traveling speed is the “Phrase” distance. The speeds used for this test were 15, 20, and 25 mph. The plots show the average distances for each speed. a) During the day the visibility of the number comparing the VSLS versus SLS is noticeable. The size of the displays does not cover the same width size as a regular SLS; therefore, this difference is entirely coherent. b) To corroborate that the display size was affecting the results in (a), the phrase “Speed Limit” is used as a point of reference because it is the same size in the SLS and the VSLS. In this case, as expected, the trend of the graphics are more similar. c) During the night, the two illuminations can be tested. Results show that the use of a spotlight has similar trends to a regular SLS. Unlike during the day in (a), this is determined by the fact that having a dark environment allows more focus on the well-illuminated sign. d) Similar to (b), the same size of the phrase allows for similar trends for the three different configurations.	84
5.4	Setup for power consumption measurements for individual components in the VSLS PCB. The Keithley 2401 SMU Low Voltage SourceMeter Instrument was used to measure the current at 5 V fixed. The main PCB was connected to the power supply and component by component where tested. For the LoRa transmitter a combination of microcontroller and module was needed to measure the transmitting power during a package sending.	85
5.5	Installation of the BS for range tests: 1. The ARRC facilities were used to mount the BS. 2. The BS was placed on a table on the top floor where ethernet connections and power outlets were available. 3. The antenna was mounted on the terrace, with fiberglass handles serving as the mounting structure.	90
5.6	Installation of the VSLS PCB in a truck for the range and response time tests: 1. An ARRC truck is prepared for the tests. 2. The VSLS PCB is placed on the dashboard in a way that the internal GPS antenna has a clear line of sight to the sky, and its serial output is connected to a computer to log the data. 3. The same antenna used for the final prototype is mounted on a structure in the bed of the truck.	91

5.7	Planning and results of the range and response time test using a map of Norman city from Google Maps. a) The theoretical range of 8 miles round is shown in a translucent blue circle, with the base station located at the center of the circle in the ARRC facilities. b) The planned tour in the truck is shown along the highways, covering the farthest possible points. c) The places where data was received by the VSLs PCB are marked as red points. d) The overlay of the three maps shows coherence between the captured data and the travel performed. Theoretical ranges were reached in certain locations. . . .	92
A.1	Base station electronics schematic diagram.	104
A.2	Base station printed circuit board diagram.	105
B.1	Variable speed limit sign electronics schematic diagram page 1.	106
B.2	Variable speed limit sign electronics schematic diagram page 2.	107
B.3	Variable speed limit sign electronics schematic diagram page 3.	108
B.4	Variable speed limit sign electronics schematic diagram page 4.	109
B.5	Variable speed limit sign electronics schematic diagram page 5.	110
B.6	Variable speed limit sign electronics schematic diagram page 6.	111
B.7	Variable speed limit sign electronics schematic diagram page 7.	112
B.8	Variable speed limit sign printed circuit board diagram.	113

List Of Acronyms

AC	Alternating Current
API	Application Programming Interface
ARRC	Advance Radar Research Center
ATDM	Active Traffic and Demand Management
ATSC	Automatic Traffic Surveillance and Control
BLE	Bluetooth Low Energy
BS	Base Station
CAD	Computer-Aided Design
COB	Chip On Board
CPU	Central Process unit
CSRS	Current Speed Radar Signs
CSS	Chirp Spread Spectrum
DMS	Dynamic Message Signs
DEC	Digital Equipment Corporation
DC	Direct Current
DXF	Drawing Exchange Format
EV	Electric Vehicle
FR4	Flame Retardant 4
GDOT	Georgia Department of Transportation
GPIO	General Purpose Input Output
GPS	Global Positioning System

HDMI High Definition Media Interface

HTML Hypertext Markup Language

I/O Input-Output

IEEE Institute of Electrical and Electronics Engineers

IDN Individual Identification Number

IoT Internet of Things

ISM Industrial, Scientific, and Medical

LAN Local Area Network

LED Light Emitting Diode

LPDDR Low Power Double Data Rate

LR-WPAN Low-Rate Wireless Personal Area Network

LoRa Long Range

LoRaWAN Long Range Wide Area Network

MUTCD Manual on Uniform Traffic Control Devices

MicroSD Micro Secure Digital

ODOT Oklahoma Department of Transportation

OS Operative System

OU University of Oklahoma

PCB Printed Circuit Board

PDF Portable Document Format

PLC Programmable Logic Computer

PoE Power Over Ethernet

PPS Pulse Per Second

PWM Pulse Width Modulation

RAM Random Access Memory

RF Radio Frequency

RTC Real-Time Clock

SATCD Standard Alphabets for Traffic Control Devices

SDK Software Development Kit

SDRAM Synchronous Dynamic Random Access Memory

SHSB Standard Highway Signs Book

SLS Speed Limit Sign

SMA SubMiniature version A

SoC System on a Chip

SPI Serial Peripheral Interface

SSD Solid State Drive

SATCD Standard Alphabets for Traffic Control Devices

SVG Scalable Vector Graphics

TSMC Taiwan Semiconductor Manufacturing Company

TTL Transistor Transistor Logic

UART Universal Asynchronous Receiver/Transmitter

ULP Ultra Low Power

USDOT United States Department of Transportation

USB Universal Serial Bus

VMS Variable Message Sign

VSL Variable Speed Limit

VSLS Variable Speed Limit Sign

VSLTS Variable Speed Limit Traffic System

WSDOT Washington State Department of Transportation

Abstract

Variable Speed Limit Signs (VSLs) play a crucial role in traffic management. Various studies have demonstrated that they can significantly reduce accidents and improve traffic flow, particularly on congested highways, during adverse weather conditions, in construction zones, and even during road accidents. However, existing technologies used to manufacture VSLs, such as Light Emitting Diode (LED) displays, mechanical rollers, and manually interchangeable cards, suffer from several drawbacks, including bulkiness, high cost, high power consumption, integration difficulties, and deployment complexity, thus impeding the implementation and expansion of such systems. This thesis addresses these challenges by proposing a novel approach using E-ink displays, which are well-known for their ultralow-power consumption and versatility. Since the development of E-ink technology, its applications have expanded rapidly and can now be found in various devices such as e-readers, smartwatches, shelf tags, license plates, and many others. Leveraging the benefits of E-ink, the proposed remotely managed Variable Speed Limit Traffic System (VSLTS) offers a more efficient and cost-effective solution for traffic management. By implementing E-ink displays in VSLs, we aim to reduce the size, weight, and power consumption of these devices while maintaining performance and visibility. This thesis outlines the design, development, and implementation of the proposed system, highlighting the advantages of E-ink technology in enhancing the functionality and usability of VSLs for traffic management applications.

Chapter 1

Introduction

1.1 Motivation

Speed Limit Signs (SLSs) are essential regulatory elements informing road users about maximum allowable speeds on various roadways [1]. With advancements in electronic technologies, regulatory signs have evolved, leading to the emergence of various types of variable signs [1]. Examples include Dynamic Message Signs (DMS), which display road numbers and travel times [2], Current Speed Radar Signs (CSRS), which indicate drivers' current speeds on LED displays [3], and VSLS, which can adjust speed limits based on factors like traffic conditions, weather, accidents, work zones, and crowded areas [4].

These variable regulatory signs utilize diverse technologies, including LED displays, flipping number displays, flipping dots, backlight letters, flashing strobes, and even manual interchangeable cards [5–9]. However, these options suffer from inherent drawbacks, including bulkiness, high power consumption, operational complexity, high costs, and integration challenges with web services.

Advancements in manufacturing make technologies more accessible, and E-ink is no exception. E-ink, with its ultra-low power consumption and legibility under

ambient light, resembles regular paper sheets [10, 11]. While widely used in e-readers, shelf tags, clocks, and logistics, E-ink’s potential in traffic signals has not been deeply explored.

In the transportation sector, E-ink has primarily been utilized in public transportation advertising, wayfinding displays, in-vehicle systems, and maps [12]. However, its application in VSLs could address the limitations of existing technologies. Implementing E-ink displays in VSLs could significantly reduce battery capacity, size, and cost compared to current solutions that use the technologies listed before and suffer from bulkiness, high costs, high power consumption, and deployment complexity. This thesis aims to explore the feasibility and benefits of integrating E-ink technology into VSLs, offering a more efficient and cost-effective solution for traffic management.

1.2 Literature Review

Over time SLSs have been one of the most common visual guidance on roadways. Although the speed limits can be a source of frustration and confusion because not all drivers like to travel at the same speed, some people may not understand why the speed limit changes on a particular road, or community residents often have concerns that traffic is moving too fast through their neighborhoods, properly set speed limits provide a safe, consistent, and reasonable speed to protect drivers, pedestrians, and bicyclists along the roadway [13].

According to [13], statutory speed limits are established by state legislatures for specific types of roads, such as interstates, rural highways, and urban streets, and can vary from state to state. They are enforceable by law and apply even if the speed limit sign is not posted. Examples of statutory speed limits include 25 mph in residential or school districts, 55 mph on rural highways, and 70 mph on rural interstate highways.

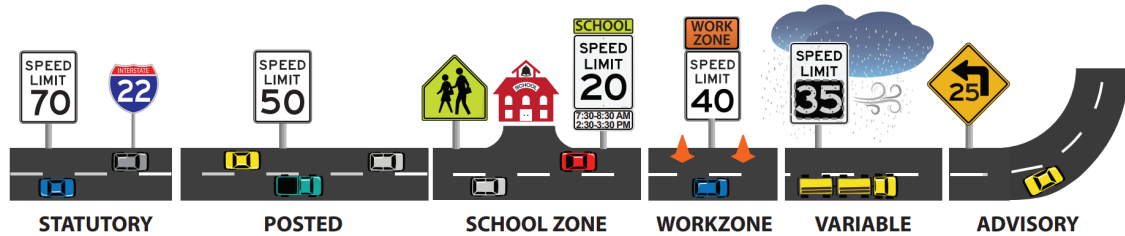


Figure 1.1: Different types of SLs and their applications [13]. Statutory: The type of road determines baseline speed limits, even if there is no posted speed limit. Posted: Speed limit indicated by a posted sign along the road. School Zone: Modification of the speed limit during certain hours. Workzone: Modification of the regular speed limit due to works along an area. Variable: The speed limit is determined according to environmental conditions such as traffic, weather, or others. Advisory: Recommended speed limit due to a warning maneuver.

To determine a specific speed limit for a road, state and local transportation agencies conduct engineering speed studies and adhere to the guidance outlined in the Manual on Uniform Traffic Control Devices (MUTCD) [1]. In some cases, they may also utilize a supporting web-based software tool called USLIMITS2 [14], which provides an objective second opinion and assists in making speed limit setting decisions [13].

In summary, the procedure is as follows: before constructing a new road, engineers select a design speed to inform their design decisions and prepare the plans.

Once the road is built, engineers evaluate the existing speeds by measuring the operating speed. This is often done by determining the speed at which 85 percent of drivers are traveling at or below, known as the 85th percentile speed. Widely used in the field of traffic engineering, the 85th percentile speed is based on the premise that the majority of drivers choose reasonable speeds given the road conditions and should be accommodated [13].

At times, environmental conditions may vary, and the calculated speed limit for a particular road could become hazardous. Examples of such conditions include fluctuating weather conditions, work zones, traffic congestion, traffic incidents, and even school zones. VSLs have proven to be effective tools in such scenarios.



Figure 1.2: VSLs deployed in a highway construction zone during winter [15].

The earliest reference to where the first VSLs had been installed can be found in [16]. This document points out that VSLs have been successfully implemented in European countries for several decades, and deployments in countries such as the

Netherlands and Germany have shown significant benefits. In Germany, VSL or speed harmonization systems have been deployed since the 1960s, with installations covering about 124 miles of highway. Germany's experiences show that VSL has the potential to decrease crash rates and increase road capacity by 5% to 10%. The Netherlands has implemented VSL since the 1970s to manage traffic speed, mitigate the effects of extreme weather, and improve safety. The United Kingdom has implemented VSL and hard shoulder running on the M-42 motorway. An evaluation over a 12-month period showed that the application of VSL and hard shoulder running resulted in a 7% increase in capacity, a 4% to 10% decrease in pollutants, and a 4% drop in fuel consumption.

In the United States, the earliest implementation of VSLs can be found in [17]. Figure 1.3 shows a picture of the Lodge Freeway in Michigan from the early 1960s. It features elements and strategies similar to modern-day active traffic management systems, such as VSLs, dynamic lane use control, and ramp metering. These solutions have evolved over time with the integration of newer technologies and data sources, and this trend is expected to continue into the future.

During this initial stage, the documentation of the results of using VSLs demonstrated improved safety on the roadways; however, the technology used is not clearly described. Taking into consideration that the invention of the transistor was in 1947 [18], the first integrated circuits were invented in 1958 [19], and the first visible LEDs were invented in 1962 [20], we can infer that the VSL shown in Figure 1.3 was made using mechanical components or bulb lights, which were more common technologies at that time. To make a comparison with other contemporary signages



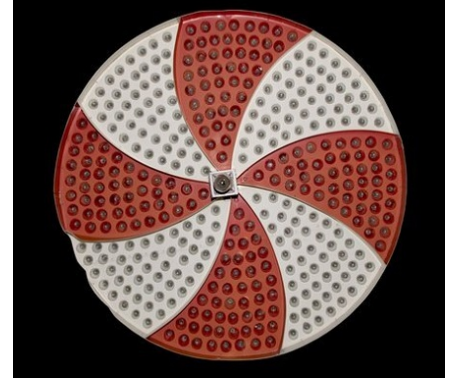
Figure 1.3: One of the earliest implementations of a VSL system in the United States occurred on The Lodge Freeway in Michigan during the 1960s [17].

that are significantly big and implemented to provide information in the same manner as VSLs, Figure 1.4a shows the 1960s Comiskey Park’s Exploding Scoreboard of the Chicago White Sox [21], and Figure 1.4b depicts one of the spinning wheels made out of incandescent bulbs [22], which was the state of the art for signages during that time.

The next state to implement VSLs was New Jersey in the late 1960s [16]. In addition to the VSL system, Variable Message Signs (VMSs) were also installed along the New Jersey Turnpike. All VSL signs are posted adjacent to a VMS that describes the reason for the speed change, as shown in Figure 1.5. The following word messages are used to warn drivers of conditions ahead. Both in Michigan and New Jersey, speed limits at these two pioneer VSL sites were adjusted manually according to traffic conditions observed by traffic operations staff.



(a)



(b)

Figure 1.4: A picture of the 1960s Comiskey Park's Exploding Scoreboard of the Chicago White Sox illustrates the available technology at that time. a) An overall view of the complete scoreboard made out of incandescent bulbs and mechanical components [21]. b) A closer view of one of the top spinning wheels shows the incandescent bulbs installed on it [22].

According to [23], the New Jersey Turnpike Authority's Automatic Traffic Surveillance and Control (ATSC) system was installed and made operational in January 1976. This system was originally conceived and developed prior to and during the widening of the northern 36 miles of the New Jersey Turnpike in the latter part of the 1960s. Its purpose is to completely automate traffic control on the 12-lane section of the New Jersey Turnpike that extends 36 miles from central New Jersey to the George Washington Bridge approaches.

The ATSC system provides traffic surveillance and control based on traffic data received from the field. Traffic parameters obtained from the computer include occupancy, average running speed, volume, unused capacity, and vehicle classification. These parameters are collected by means of 850 loop detectors embedded in the pavement of all roadway components of the 36-mile network. The collected traffic data are transmitted via buried cable to two front-end processors that process and

compress the raw data. Subsequently, the refined data is transmitted to a main computer for further analysis and action, if necessary.

The brand of this main operating computer is Digital Equipment Corporation (DEC), and the model is a PDP-11/40. Traffic control is implemented by this main computer through the use of traffic control strategies and accompanying algorithms programmed therein. These algorithms react to the collected data and, by remote control, operate various changeable message directional signs, variable message speed limit signs, and hazard warning signs installed at key locations throughout the 36-mile section.

Although there is a lot of information about the automation system, similar to Michigan, there is no clear information on the technology used for the visual signs. However, Figure 1.5 shows neon lights for the VMSs and mechanical moving parts for the VSLs.



Figure 1.5: A VMS and a VSLS installed on the New Jersey Turnpike in the late 1960s [16]. The picture clearly shows the use of neon lights for the VMS and mechanical parts for the VSLS, which were two of the most common technologies of that time.

Since 1990, there has been a significant increase in the use of Variable Speed Limits (VSLs) in the United States, driven by a renewed interest in expanding their functionality to achieve operational benefits. The complexity of VSL systems, including infrastructure, signage, real-time detection, and control algorithms, has also increased significantly [16].

On August 10, 2010, the Washington State Department of Transportation (WSDOT) launched an Active Traffic and Demand Management (ATDM) system, making it one of the first state transportation agencies in the United States to adopt this type of technology [24]. The ATDM utilizes overhead electronic signs to provide advance notice of changing traffic conditions. Messages provided by the system include:

- **Variable speed limits:** Speed limits can be reduced, sometimes lane by lane, to address congestion or backups and encourage drivers to slow down early, rather than making a sudden stop or braking maneuver.
- **Lane management symbols:** These symbols can be used to indicate a blocked lane or direct drivers to change lanes before they reach an incident site.
- **Traffic conditions ahead:** The larger signs can display messages warning of slowdowns, backups, or incidents ahead, including if the road is blocked in some way.

By providing real-time advanced notice of traffic conditions ahead, drivers are alerted earlier and can respond sooner, reducing the need for last second avoidance maneuvers or panic braking - both of which are primary factors that contribute to collisions.



Figure 1.6: Examples of the ATDM system corridors installed by WSDOT along Washington Highways [24]. a) Along Interstate 5 in Vancouver, the implementation of four DMS can be observed, with three of them displaying lane availability and the last one showing text information. b) On Highway 520 between Seattle and Bellevue, the implementation of four DMS can be observed, with three of them functioning as VSLs and the last one displaying text information.

The ATDM system deployed by WSDOT utilizes DMS composed of high-resolution LED matrices, as depicted in Figure 1.6. In this system, VSLs are just one feature among many. The installation of one display in each lane allows for greater flexibility in setting different speeds, opening or closing lanes, and simultaneously, a main, larger DMS can display the reason for the speed limit change. It's also evident that implementing a system of this magnitude requires substantial infrastructure. In Figure 1.6, the metallic frames installed from one shoulder to another along the highway are noticeable. Additionally, the provision of power sources and internet access appears to be necessary for the correct functioning of this system.

On October 5, 2014, under the slogan “Slow Down to Get There Faster,” the Georgia Department of Transportation (GDOT) initiated the operation of their VSL system on the I-285 Top End Highway [25,26]. The primary issue with this highway was car congestion during peak hours. Fixed speed limits compelled drivers to seek

faster lanes, resulting in frequent lane changes. Combined with adverse weather and high car density, this situation led to numerous accidents and crashes. The introduction of VSLs allowed for an increase in the speed limit to 65 mph in uncongested areas and 35 mph in congested ones, generating a more uniform and safer driving environment.

This system operates with a set of sensors for traffic volume. Based on this data, the VSLs can adjust the overall speed in increments of 10 mph. A total of 175 signs are distributed across 88 locations along the corridor. Each sign is placed at intervals of 0.5 to 1.5 miles, providing ample time for drivers to adjust their speed. Additionally, strategically placed VMSs offer information on the reasons for speed changes. Both the VSLs and VMSs utilize LED technology, and in some cases are energized by solar panels as depicted in Figure 1.7.



(a)



(b)

Figure 1.7: Examples of VSLs installed by GDOT along I-285 Highway. a) A picture from Interstate 285 westbound at the tunnels across the south side of ATL Airport [27] shows two VSLs, with the one on the left appearing to use solar energy as the main source of power. b) A closer view of an I-285 VSL [28] reveals that the displays for the numbers are made out of an LED matrix.

According to a synthesis report published by the United States Department of Transportation in 2017 [16], VSL systems have been widely implemented across many states for various functional purposes, some of which are summarized in Table 1.1. This Table lists active systems up to that year, excluding planned and removed systems.

The "Primary Functions" column may include any of the following descriptions:

- **Congestion:** addressing speed or incident management-related issues.
- **Weather:** addressing visibility or pavement condition-related issues.
- **Work zones.**

Note that some systems may consist solely of VSL, while others may incorporate additional traffic management techniques such as DMS, VMS, dynamic shoulder lanes, ramp metering, etc.

1.3 Proposed System

The literature review Section conducted a thorough analysis of implemented systems over time, highlighting several noticeable problems. These include system complexity, device bulkiness, deployment and expansion difficulties, the need for larger wirings to interconnect devices, complications in integrating the system with existing systems, high power consumption, and the requirement for larger solar system capacities, especially for LEDs matrix displays. To address these issues, the proposed system will consist of a low-power consumption network of wirelessly

Table 1.1: Representative VSL systems in the United States.

State	Location	System length (miles)	Status	Operation type	Primary functions
Florida	I-4	10.5	Active	Hybrid	Congestion
Florida	US 27	3	Active	Automated	Congestion
Georgia	I-285	36	Active	Hybrid	Congestion, Work Zones
Minnesota	I-35W	18	Temporarily Deactivated	Automated	Congestion
Minnesota	I-94	10	Temporarily Deactivated	Automated	Congestion
Nevada	US 395 Alternate	5	Active	Automated	Weather (wind)
New Jersey	NJ Trunpike	148	Active	Manual	Congestion, Weather
Oregon	OR 213	Single intersection	Active	Hybrid	Congestion
Oregon	OR 217		Active	Automated	Congestion, Weather
Tennessee	I-75	9	Active	Hybrid	Weather (fog)
Virginia	I-66	13	Active	Automated	Congestion, Work Zones
Virginia	I-95 Express Lanes	10	Active	Manual	Congestion
Washington	I-90 (near Snoqualmie Pass)	25	Active	Hybrid	Weather
Washington	US 2	23	Active	Hybrid	Weather
Washington	I-5	8	Active	Automated	Congestion
Washington	I-90 (Bellevue to Seattle)	10	Active	Automated	Congestion
Washington	SR 520	8	Active	Automated	Congestion

communicated devices illustrated in Figure 1.8. The system is composed by two principal elements: the VSLs and the Base Stations (BSs).

The VSLs serve as visual devices informing drivers of the maximum allowed speed. They receive configurations and data wirelessly from the BSs and display

the speed limit for the road segment where they are deployed. To improve power consumption, screens used for displaying numbers will employ E-ink technology, as detailed in Chapter 3. The main characteristic of “only current consumption during changes of displayed images” allows for considerable power handling improvement compared to other technologies. Simultaneously, this feature permits the reduction of other system components such as batteries and solar panels without compromising the working time.

The BSs act as interfaces between end users and the VSLs. These devices can communicate wirelessly with the VSLs, with a capacity to control up to 80 signs within a maximum range of 5 miles. Their small size and low power consumption enable deployment in areas where other systems already exist, such as cameras, DMSs, semaphores, and others. They are also capable of operating using solar energy. Additionally, they provide an Application Programming Interface (API) for remote control facilitating integration with other web services.

Communication between the elements can be divided into two segments: first, between the VSLs and the BS, and second, between the BSs and end users. For the first segment (VSL to BS), Long Range (LoRa) modules will be used. Their characteristics, such as ultra-low power consumption and long-range coverage, make them suitable for this segment. For the second segment (BS to end user), internet access is a requirement. The BS is equipped with an Ethernet port and Wi-Fi connectivity, enabling internet access in multiple ways.

Finally, the procedure for setting a speed on a specific VSL is as follows: Through internet connection and using the API, the end user sends a speed value

for a specific sign. The BS receives the message, searches its registered devices list for the sign ID, and, using the LoRa module, retransmits the message to the selected VSLS. Once the VSLS receives the message, if all configurations are correct, it sets the speed and replies with an acknowledgment message to the BS. The BS then retransmits the answer to the user through the internet connection.

1.4 Organization of the Thesis

The content of this thesis will follow a progressive approach. Chapter 2 will present the requirements according to regulatory and implementation characteristics. Considerations for size and weight, visibility, power consumption, maintenance, and communication systems will be detailed. Chapters 3 will discuss the design considerations and trade-offs for the topology of the system, deployment locations, power source access, network access, and environmental conditions. Chapter 4 will focus on the detailed explanation of the design of the VSLS and the BS. Technologies selected for system implementation, assembly details, and prototype sequence manufacture will be presented for both devices. Additionally, the software for online integration and firmware strategies for efficient power handling will be discussed. Finally, Chapter 5 will present the preliminary results of system characteristics such as visibility, power management, and range.

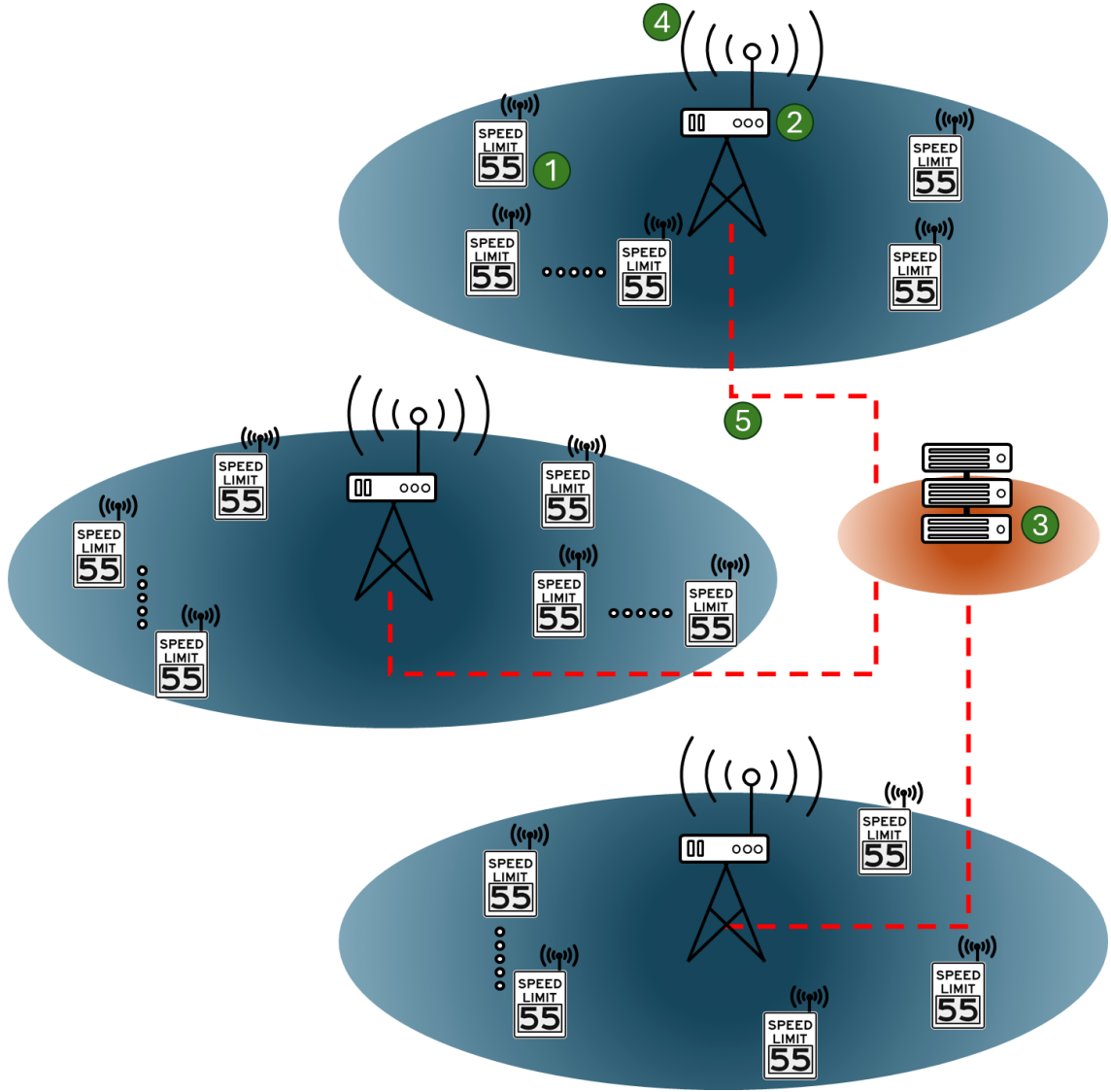


Figure 1.8: Illustration of the Proposed System. 1. The VSLs: A visual device that informs drivers of the maximum allowed speed. It uses E-ink ultra-low power consumption technology to display the numbers and is configurable by the BS. 2. The BS: The interface between end users and the VSLs. It has the capacity to control up to 80 signs within a maximum range of 5 miles. Its small size and low power consumption allow for easy deployment and it is easily controlled by an API. 3. End users or web services: These are the entities that want to control or set a configuration in a VSL. To do so, they need to connect to the BS API. 4. Communication segment between the VSLs and BS: LoRa modules handle communication in this segment. Characteristics such as low power consumption and long range make them suitable for this purpose. 5. Communication segment between the BS and the end user or web services: Internet connection is planned for this segment. The current coverage and stability of 4G and 5G networks provide the reliability needed for this purpose.

Chapter 2

System Requirements

This Chapter will present the requirements for the VSLs and the BS. For the VSLs, an analysis based on the MUTCD from the United States Department of Transportation (USDOT) will be conducted to comply with standard characteristics for a VSL. Furthermore, other requirements will be detailed, such as size, weight, visibility, power consumption, lifespan, maintenance, and communication systems. Regarding the BS, characteristics such as size, weight, mounting, lifespan, maintenance, and communication will be detailed according to Oklahoma Department of Transportation (ODOT) requirements, ensuring the best functionality for the device in each case.

2.1 Variable Speed Limit Sign

The VSL is the visual device for road users, enabling modifications to the overall speed on highways and serving as the final node in the system. This Section will describe requirements for size, dimension, visibility, legibility, power consumption, lifespan, maintenance, and communications.

2.1.1 Size and Dimensions

Different from LED displays, E-ink technology provides a high-resolution display that can replicate SLS typography so accurately that the presence of a display is indistinguishable from VLS with a regular SLS. Therefore, the requirement for size and dimensions is to comply with regular SLS standards. The MUTCD specifies parameters for size, colors, shapes, typography, hole positions, and several other aspects. Figure 2.1 displays a picture from the Standard Highway Signs Book (SHSB) [29], which is the companion document to the MUTCD and includes size specifications for all available traffic signs. In this figure, the manufacturing dimensions for an SLS in inches are depicted. Column A shows the total width of the sign, and column B shows the total height. Once the overall size is selected, the Table provides all the necessary measurements to manufacture the sign. The size for the prototype in the scope of this research will be 18 x 24 inches. This allows for the creation of a low-cost prototype for proof of concept and testing. However, the long-term application of this research will be on highways and various types of roads. Therefore, all sizes should be taken into consideration for future work.

2.1.2 Visibility and Legibility

In the preceding Section, it was established that using E-ink technology to display the numbers will allow the VLS to have the same typography, size, and dimensions as a regular SLS. Therefore, similar values for visibility and legibility are expected.



R2-1

SPEED LIMIT (ENGLISH)

A	B	C	D	E	F	G	H	J	K	L
18	24	.375	.625	3	3 E	2	8 E	7.188	5.5	1.5
24	30	.375	.625	4	4 E	2	10 E	9.563	7.313	1.5
36	48	.625	.875	6	6 E	5	14 E	14.375	11	2.25
48	60	.75	1.25	8	8 E	6	16 E	19.125	14.625	3

Figure 2.1: SLS manufacturing dimensions compliant with MUTCD standards in inches [29]. The mechanical drawing details all the crafting dimensions. Columns A and B correspond to the overall width and height, respectively. Once the overall size is selected, the other dimensions can be easily read from the Table. For the scope of this research, a size of 18x24 inches is required.

When the literature was reviewed, did not yield specific information regarding visibility or readability criteria for either SLS or VSLs. Nonetheless, two other

studies offer insights into how visibility can be assessed, laying the groundwork for designing a visibility test.

The first one is a report that analyzes the information as a source of distraction in DMS [30]. It analyzes when a DMS is more distracting for a driver on highways according to parameters such as the distance, colors, message, and size of the letter.

The second one analyzes the visibility of highway guide signs according to the shape and size of figures and typographies [31] and the results presented show the capability of legibility with respect to the distance.

Given that the VSLS and the SLS will have the same visible front shape, the requirement for visibility and legibility is that the VSLS has to be as visible and legible as a regular SLS. To corroborate this, a study must be conducted where both SLS and VSLS are tested individually, and the results should show similar parameters in either case.

2.1.3 Power Consumption

Given the focus of this research on enhancing energy management and improving information display in the VSLSs compared to conventional technologies like LED or mechanical drivers, it is important to ensure efficient power consumption. The aim is for the overall energy consumption of VSLS employing E-ink technology to be significantly lower than that of traditional technologies. This will directly impact the battery life, extending it considerably in case of using the same configuration. To establish a measurable benchmark for comparison, an analysis of current offerings of

similar VSLs on the market was conducted, and some relevant products are listed in Table 2.1.

Table 2.1: Available options of VSLs in the market.

Brand	Model	Display size	Source power	Typical power	Working time	Warranty
Swarco	McCain's VSLs [32]	25" x 38"	120 V AC	17 W	-	-
LED Lighting Solutions	SP550 [33]	15" x 8"	12 V DC	-	1-5 days	2 years
Carmanah	Speedcheck [34]	31" x 23 "	12 V DC	3.5 W	-	3 years
Hill and Smith Inc	VSL Trailer [35]	-	6 V DC	-	30 days	-

Based on this information, we can conclude that the best power consumption in the market is 3.5 watts for the Speedcheck VSLs; hence, even better power consumption is anticipated with the proposed system. The VSL Trailer is not considered due to a lack of information, the datasheet does not specify the number of batteries or power consumption. However, it is still included in Table 2.1 to represent it as an option in the market.

2.1.4 Lifespan and Maintenance

For the lifespan, a similar requirement analysis as in the last Section can be conducted. From Table 2.1, the available products in the market show that the longest warranty period is 3 years. We define warranty as the ability of a product to function continuously for a specified period without issues or failures under specified conditions. Therefore, we expect the VSLs to operate uninterrupted for at least 3

years. Additionally, considering factors such as remote installation zones and the high costs of personnel for repairs, long-term reliability of the design is crucial.

For optimal and convenient maintenance, high modularity is essential. Technicians should find it easy to replace display panels, enclosures, lights, harvesting modules, and communication modules.

During component selection, priority should be given to the newest devices to avoid premature obsolescence of any module in the sign.

2.1.5 Communications

The study procedure for determining the deployment locations of VSLS to reduce crash risks at freeway recurrent bottlenecks [36] concludes that the cost-benefit analyses showed that placing VSL signs in scenario C2, with a controlled section length of 11.7 miles and an average VSL density of 1.0 mile, had the best benefit/cost effect. Using 12 VSL signs, the collision risks were reduced by 69.16 %, and the total travel time increased slightly by 7.73 %. Additionally, the literature review from the implementation of the GDOT VSL system [26] shows that the distance used to implement their VSLS ranged between 0.5 and 1.5 miles.

Although specific installation points have not been determined yet, the information above indicates that a range of at least 1.5 miles is necessary. Therefore, the selected communication protocol should be able to cover that range while maintaining the low-power consumption characteristics needed.

2.2 Base Station

The BS is an interface device between end users and the VSLs. This Section will describe requirements for size, shape, power sources, lifespan, maintenance, and communications.

2.2.1 Size and Shape

The first requirement for the BS is its size, mounting, and shape. These characteristics should be similar to those of a Programmable Logic Computer (PLC) because the BS will be installed inside an electrical box with a DIN rail mounting.

The most common enclosure used for outdoor installations is the electrical box. Characteristics such as waterproofing and dust proofing make them ideal for outdoor use, and they are available in different sizes and shapes [37]. Additionally, the most common mounting method inside these enclosures is the Rail DIN type T.

As a reference for dimensions, the Siemens - Logo! PLC can be used. It has a width of 71.5 mm, a height of 90 mm, and a depth of 60 mm, with a mounting type of 35 mm DIN rail [38].

2.2.2 Power Sources

For the initial prototype, a 110 V AC input is required, however, 12 V DC or 24 V DC input should be considered as a possible future feature in case of deployment under solar panel implementation.

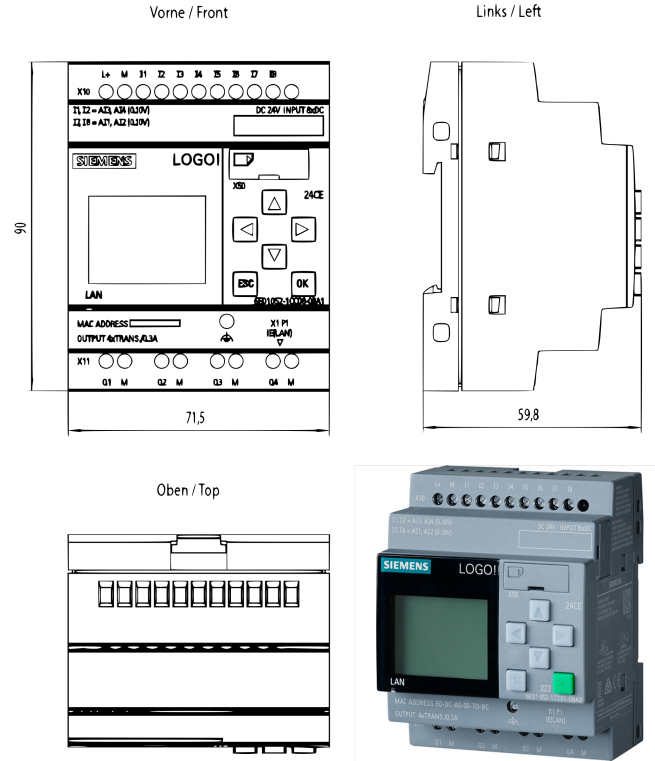


Figure 2.2: Siemens PLC, model Logo! [38]. The size, dimensions, shape, and mounting structure of this device are used as a reference for the form factor requirements of the BS.

2.2.3 Lifespan and Maintenance

The solicited lifespan of the device is ten years, considering maintenance and other repairs. An uninterrupted working period of at least three years is expected, based on the same considerations taken for the VSLs in Section 2.1.4. To improve the maintenance and reparability of the BS maximum modularity is desired for example interchangeable enclosures, PCBs, main controller, modems, and any other module. At the same time, is requested to look for novel components to avoid sooner obsolescence issues.

2.2.4 Communications

As the BS serves as an intermediate device, the required communications can be divided into two segments: the first one between the VSLs and the BS, and the second one between the BS and the end user or web services.

For the first segment, the BS must be capable of communicating with the VSLs, hence the same requirements outlined in Section 2.1.5 apply to the BS.

Regarding the second segment, internet access is necessary for the BS. This facilitates easy integration with other existing systems [39] deployed by the ODOT.

2.3 Summary

This Chapter outlines the requirements for the system, and both components, the VSLs and the BS, can be summarized independently.

Regarding the VSLs, the requirements are as follows:

- **Size and dimensions:** The prototype VSLs for this research must measure 18x24 inches and adhere to MUTCD guidelines.
- **Visibility and legibility:** Leveraging E-ink technology ensures the VSLs prototype maintains the same clarity and readability as conventional SLS. To validate this, the development of a specific study to obtain measurable values is required.
- **Power consumption:** The requirement is to reduce power consumption compared to existing signage solutions. In Section 2.1.3, different market available

options were shown, with a 3.5 W power consumption identified as the lowest among those options.

- **Lifespan and maintenance:** A minimum operational lifespan of three years was defined as a requirement for the VSLS prototype.
- **Communications:** Studies showed optimal results when VSLS are deployed within distance ranges between 0.5 to 1.5 miles. Therefore, a wireless protocol capable of covering those distances is required.

Regarding the BS, the requirements are as follows:

- **Size and shape:** The BS dimensions are defined by using industry-standard models like the Siemens - Logo! PLC as a reference. This will facilitate deployment into existing infrastructure.
- **Power sources:** Initially, the BS will operate on conventional power sources of 120 V AC. However, considerations for future integration with solar power options must also be made.
- **Lifespan and maintenance:** The BS must have a ten-year operational lifespan, with at least three years of uninterrupted operational service. The design should have modular components for ease of maintenance and repair.
- **Communications:** The BS has two segments of communications. The first one is between the BS and the VSLS, which must meet the requirements already mentioned for the VSLS. The second segment is between the BS and the end user or web service, where internet access is required.

Chapter 3

Design Considerations and Tradeoffs

In the last Chapter, the requirements for the system were discussed, however, other limitations could modify or interfere with them. In this Chapter, external factors will be analyzed, such as the optimal topology for the system, network coverage, power access, and weather conditions, among others.

3.1 Topology of the system

As mentioned in Chapter 2, the BS and the VLS need to be interconnected wirelessly and have low power consumption. Therefore, we will consider the topologies from Institute of Electrical and Electronics Engineers (IEEE) 802.15.4, which is a technical standard defining the operation of a Low-Rate Wireless Personal Area Network (LR-WPAN) [40]. The topologies are shown in Figure 3.1.

In the case of this research, the battery of each end device must be extended as much as possible therefore, a larger topology of more than one node implies repeating the signal more than one time, this will be more power-consuming and at the same time, the latency of sending-receiving a package will be increased. Thus the best option and the one that will be used is the star topology.

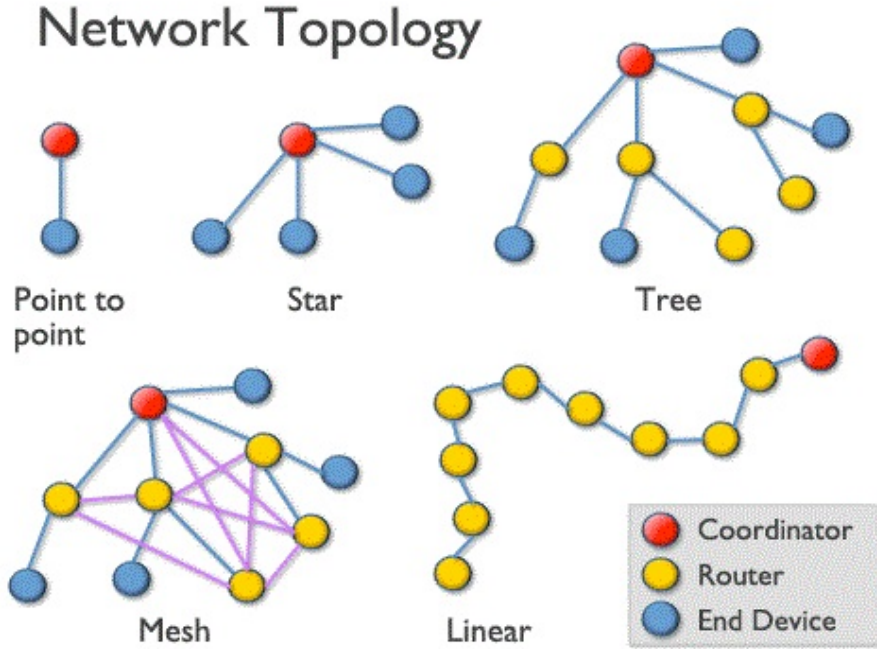


Figure 3.1: Topologies of the IEEE 802.15.4 LR-WPAN [41]. After analysis, the star configuration was chosen as the topology for the system.

3.2 Base Station

Although the requirements for the BS were already given before, other factors need to be considered such as power availability, installation locations, network access, communications, and coverage, along with the associated trade-offs.

3.2.1 Installation Locations and Power Source Access

Like other states, Oklahoma has a large network of public devices controlled by ODOT such as cameras, dynamic signage, meteorological stations, public luminaries, and Electric Vehicle (EV) charging stations along all the highways [39]. Figure 3.2 shows the location of all these devices and more information can be found in [39].

As the BS is the main controller for a group of signals, an uninterrupted and reliable

source of power is necessary, therefore the power supply for a BS could be easily taken from any point closer to any of the listed devices in [39]. At the same time, the structures that are already installed for device mounting could be also used to mount the electrical boxes and antennas for the BS.

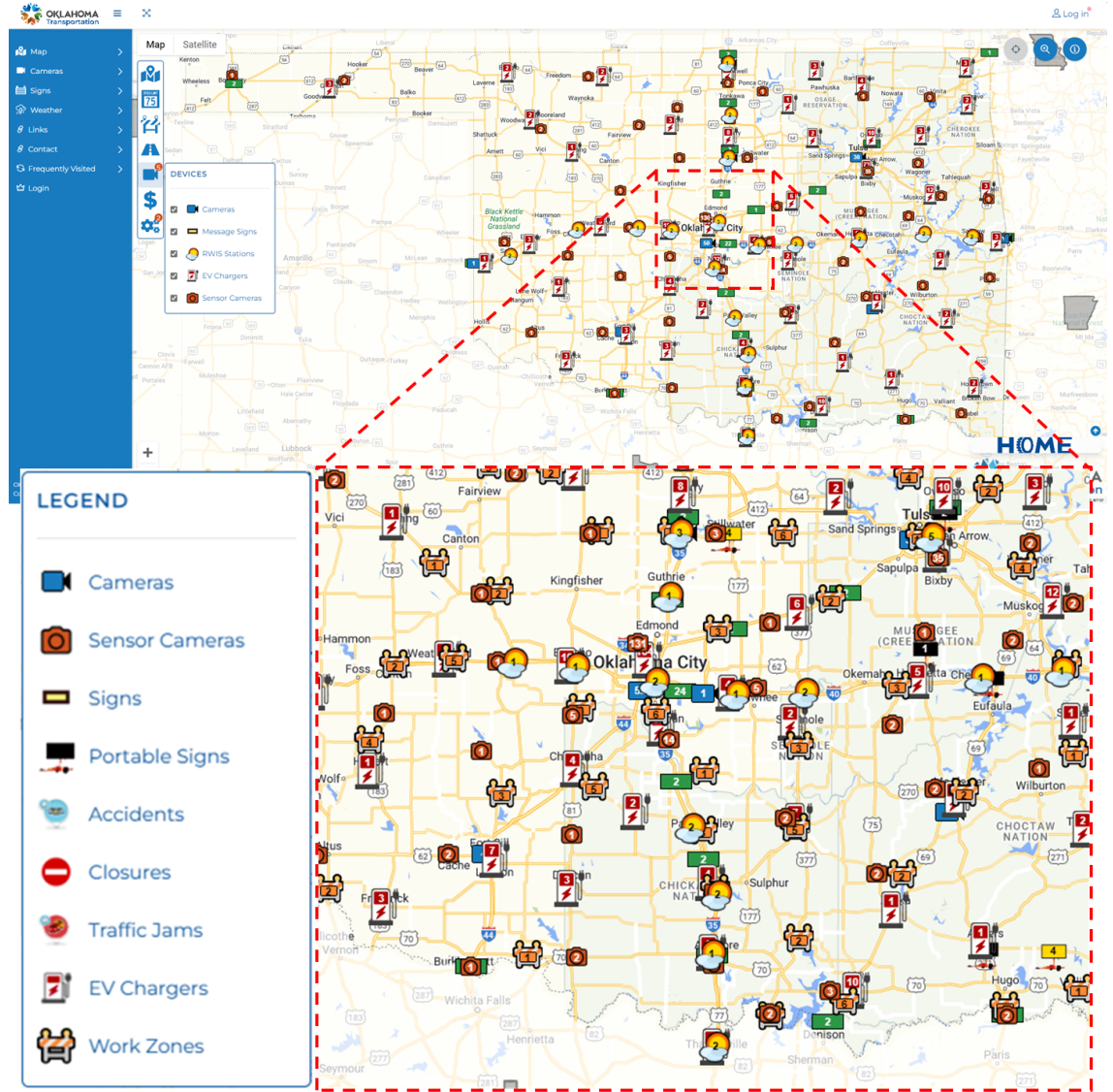


Figure 3.2: Map of the network of public devices controlled by ODOT. This information is available on the OK Traffic Map website [39], and this picture is used as a reference for possible locations to deploy a BS or a group of VSLs.

3.2.2 Network Access

As the system needs to be controlled remotely, Internet access is a priority for the Base Stations. A wired access is always preferred for the stability and reliability of the communication, however, not all areas of the state have the availability of wired service. On the other hand, the current coverage of mobile providers is widely reaching the whole state area. Figure 3.3 shows the coverage area provided by T-Mobile in Oklahoma state [42] which is largely spread. Currently, internet access using 4G and 5G modem technology is used to capture the stream of cameras from public sites in [39], thus, the use of the same mode as internet access is an acceptable option for the BS.

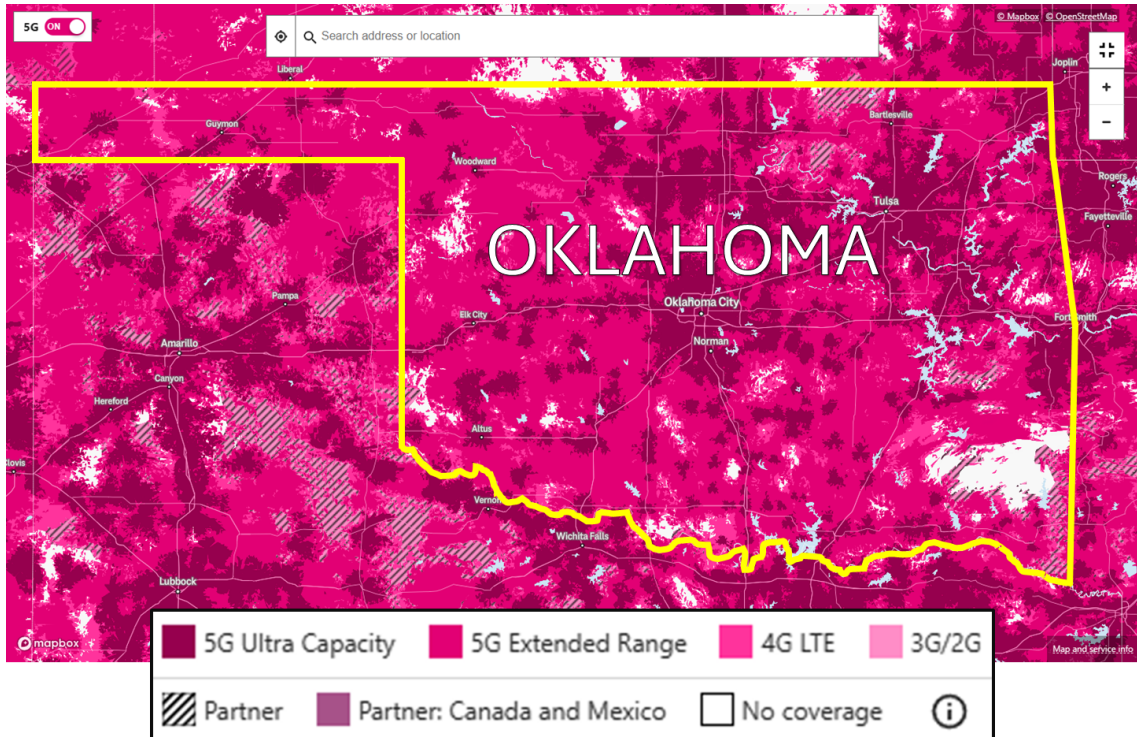


Figure 3.3: T-Mobile 4G & 5G Oklahoma coverage map [42]. This map shows that internet access is available in a large area of the state; therefore, internet access for the BS using a modem is a viable option.

3.2.3 Available Communication Protocols And Range

Has been already said in Section 3.2.2 that the BS needs constant internet access consequently the use of a modem or wired Ethernet is completely necessary. The use of one of these communication technologies to provide internet access for the BS will require a large amount of power compared to the specifications of ultra-low power consumption given for the VLSs, therefore is necessary to analyze a secondary communication standard to improve the power consumption of the end devices.

According to [43], LoRa has revolutionized the Internet of Things (IoT) by enabling data communication over a long range while using very little power. Networks with LoRa, such as those leveraging the Long Range Wide Area Network (LoRaWAN) standard, fill the technology gap of Cellular, Wi-Fi, and Bluetooth Low Energy (BLE) networks that require either high bandwidth or high power or have a limited range or inability to penetrate deep indoor environments. In effect, LoRa devices and the LoRaWAN standard are flexible for rural or indoor use cases in a wide range of industries including smart cities, homes and buildings, communities, agriculture, metering and utilities, healthcare, environment, and supply chain and logistics.

LoRa is a wireless modulation technique derived from Chirp Spread Spectrum (CSS) technology. CSS uses wideband linear frequency modulated chirp pulses to encode information. LoRa can operate on the following license-free sub-gigahertz Industrial, Scientific, and Medical (ISM) bands: 433 MHz, 868 MHz, and 915 MHz. ISM bands are internationally reserved for industrial, scientific and, medical uses.

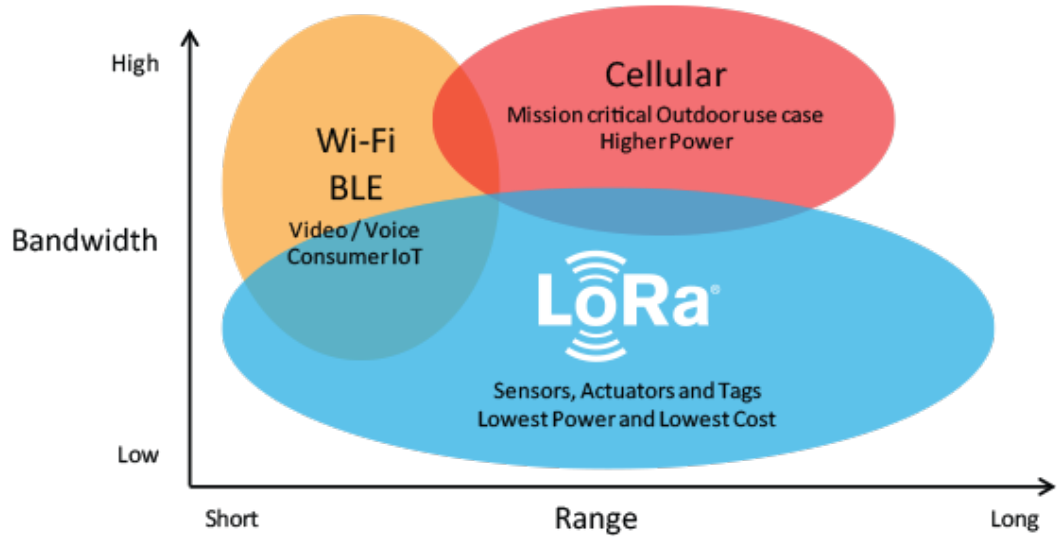


Figure 3.4: Comparison of range and bandwidth of different wireless technologies [43].

LoRa modulation technique was invented in 2010 by the French startup Cycleo; then, it was acquired in 2012 by Semtech [44].

3.3 Variable Speed Limit Sign

Although the requirements for the VSLs were already given before, other factors need to be considered such as the operating environment, weather analysis, power availability, installation locations, communications, and coverage, along with the associated trade-offs.

3.3.1 Operating Environment And Weather Analysis

Oklahoma offers a wide variety of climates. According to [45], the four seasons are distinct, but the impact of each varies by region. The climate is somewhat temperate in all regions and is controlled by the meandering of the mid-latitude jet stream and

the seasonal migration of a large, semi-permanent area of high pressure centered over the Atlantic Ocean near Bermuda.

Summers are generally hot. Daytime temperatures in the nineties are commonplace, and thermometer readings of 100 °F or more are frequent, especially in the southwest. Winters are cold in northern Oklahoma but quite mild in the south. Temperatures seldom fall below 10 °F, and rarely do they remain that low for long. Spring, the season of greatest precipitation, is noted for the severe thunderstorms that produce the most tornadoes (per unit area) of any place in the world. Autumn, while featuring some of the state's most pleasant weather, presents a secondary maximum of precipitation over most of Oklahoma.

3.3.1.1 Snow and Freeze

The lowest temperatures typically occur on clear, calm nights after a snowstorm. Thermometers have registered as low as -27 °F twice, at Vinita on February 13, 1905, and at Watts on January 18, 1930. Winter precipitation and cold are not well correlated, as Oklahoma's winter precipitation can be delivered as snow and ice or as rain. The cold-weather months are the driest everywhere in the state. Snowfall averages around thirty inches per year in the western Panhandle, declining to approximately ten inches in central parts of the state. Snowfall is rare in the southeast, but storms producing six inches or more occasionally occur. Freezing rain is a significant hazard during winter throughout the state. [45].

3.3.1.2 Maximum Heat Levels

Summer heat and drought are closely related. Oklahoma's hottest summers coincide with significant precipitation shortfalls. The state's highest recorded temperature of 120 °F has been reported six different times, most recently on June 27, 1994, at Tipton. Four of those record-high temperatures occurred during the brutal summer of 1936 [45].

3.3.1.3 Rainfall and Wind Speed

Annual precipitation, based on data collected between 1971 through 2000, averages approximately thirty-six inches across the state. Annual precipitation decreases both in frequency and amount from southeast to northwest, ranging from fifty-six inches in the extreme southeast to seventeen inches in the western Panhandle. Precipitation frequency declines westward from 115 days per year near the Arkansas border to forty-five days in parts of western Oklahoma [45].

3.3.1.4 Tornadoes and Severe Storms

Thunderstorm frequency (approximately fifty-five days per year) is highest over the Ouachita Mountains, the Ozark Plateau, and the extreme western Panhandle. Thunderstorms are least frequent over the southwestern corner of the state (fewer than forty-five days per year). Western and central Oklahoma are frequent breeding grounds for the severe thunderstorms that supply much of the state's spring and autumn precipitation and from which most of the state's tornadoes and other severe

weather events arise. Oklahoma experiences an average of fifty-four tornadoes per year. Most of them occur between April and June [45].

3.3.2 Power Source Access

The VSLs do have not a defined location at the moment of realizing this research, therefore, it is necessary to consider not only wired power supply but thus independent ways to harvest energy for the end devices. Two options considered for this purpose are the wind and sun as a power source.

Oklahoma is one state with significant wind resources. As of September 2022, it has 11,714 MW of wind capacity ranked the third state with the most larger capacity in the U.S. [46]. On the other hand, solar power is currently one of the most abundant energy resources available. The sun's energy can be harnessed through two primary methods, photovoltaics and concentrating solar power. Individuals and businesses across Oklahoma can harness the power of the sun through photovoltaics panels either through rooftops or ground mount installations [47].

Although a wind resource is an interesting option considering the environmental conditions and successfully installed farm projects in Oklahoma, implementing this technology in a VSLS can be bulky and complex. The installation flexibility offered by solar panels and the current availability and different offers regarding size, power, and technology make them more suitable for the prototype.

3.4 Summary

In this Chapter, external factors influencing the design and deployment of the system were explored. Beginning with the evaluation of system topology, the IEEE 802.15.4 LR-WPAN standard was utilized to assess different options, and a star configuration was ultimately chosen due to its efficacy in minimizing power consumption and latency. Regarding BS considerations, optimal installation locations were first identified by leveraging ODOT's public devices network, providing insight into where the BSs can be installed to enhance coverage for the VSLs and take advantage of the locations of existing systems. Subsequently, an analysis of T-Mobile's widespread coverage indicated that internet access is guaranteed in almost any location in Oklahoma for the BS. Additionally, through an analysis of available wireless protocols for communication between BSs and VSLs, LoRa technology was selected for its efficient communication range with low power consumption. As for the VSL, Oklahoma's diverse climate was analyzed to incorporate additional design considerations for robustness, and ultimately, solar power was selected as the preferred energy source due to its flexibility and larger market offer. Considering the topology, installation locations, weather patterns, network infrastructure, and power sources, more information was gathered to design a system capable of withstanding Oklahoma's varied environmental conditions.

Chapter 4

System Design

This Chapter will present a summary of the selection of devices and design of parts based on the requirements and analysis done in Chapters 2 and 3. For the VSLs, the selection criteria will be shown for parts such as the microcontroller, E-ink displays, LoRa module, Global Positioning System (GPS) module, battery, solar panel, enclosure, mounting parts, and the design process for the frontlight, firmware, and Printed Circuit Board (PCB). For the BS, the selection criteria will be shown for parts such as the Central Process unit (CPU), LoRa module, auxiliary outputs, and the design process for the PCB, enclosure, software, and API design.

4.1 Variable Speed Limit Sign

The VSL is the visual device that will be installed on highways and roads. It will set the speed limits for drivers and help improve driving conditions. The size selected for this prototype is 18 x 24 inches. Complete measurements for the design to meet MUTCD specifications can be seen in 2.1.2. The design consists of several components. First, an E-ink display will cover the area for displaying numbers. Since this is a specific-purpose device, only this part will change, and it does not make sense to use a display for the entire sign area. Second, a frontlight system will be implemented. The interaction between the retroreflective surface required

for traffic control devices [1], combined with the matte-tone surface of E-ink panels, creates undesired shadows and reduces visibility at night. Therefore, retroreflective surfaces will be removed and compensated with a frontlight system to achieve the same visibility at night. Third, communications will be handled by the LoRa module and a high-gain antenna. Fourth, a GPS module will be implemented to provide reliable time data for implementing security features in the communication between the VSLs and the BS. Finally, a set of batteries and solar panels will be used to provide power and location independence to the device.

4.1.1 E-Ink Displays

In Section 2.1.1, detailed measurements for manufacturing a regular speed limit sign are provided. When these measurements are analyzed for any sign, the first thing noticeable is that only the height of the numbers is provided. Initially, this might seem incomplete. However, the width of the numbers will vary according to the typography sizes and the number to be displayed. For example, the total width of ‘15’ is not going to be the same as ‘45’, as illustrated in Figure 4.2. According to the MUTCD, specific typography is designated for traffic control devices, as detailed in the Standard Alphabets for Traffic Control Devices (SATCD) [48]. This document outlines 6 series of alphabets. In 2.1.1, in Figure 2.1, we observe in column H (which corresponds to the number height) that there is a letter ‘E’ indicated next to the number. This indicates that Series-E typography should be used for that number. Given these conditions, using Computer-Aided Design (CAD) software and the Readgeek 2000 Series-E typography, as referenced in [48], the maximum

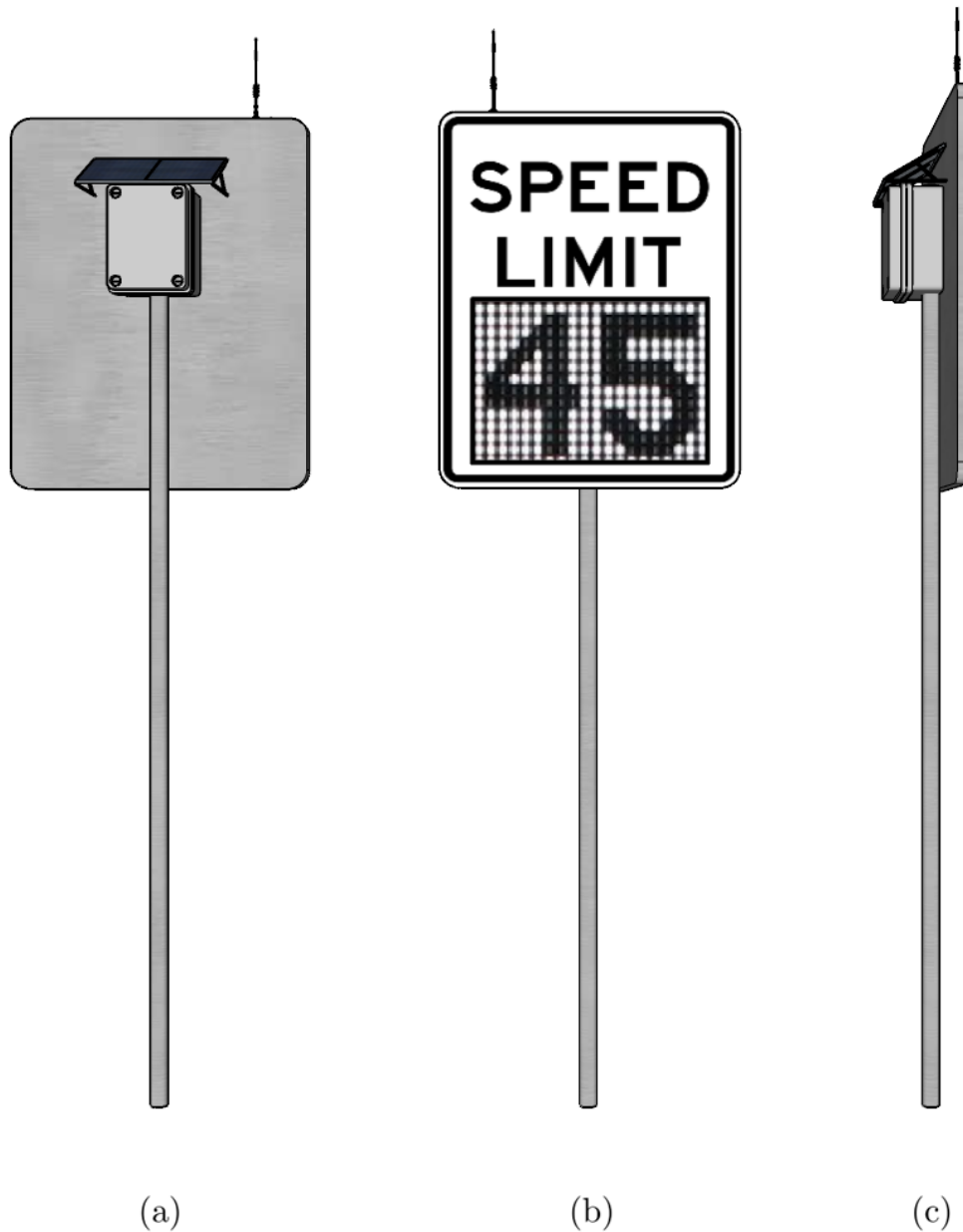


Figure 4.1: The concept idea of the VLS involves a compact design, which will be less bulky than others in the market. It includes features such as E-ink technology, LoRa communications, and power harvesting capabilities, among others.

width for two numbers is 14.3 inches and 6.3 inches for an individual number. The variation in size is determined by the space between the two numbers. In summary,

the dimensions will be 8 x 14.3 inches or 16.39 inches diagonal for two numbers, and 6.3 x 8 inches or 10.18 inches diagonal for one number. The providers analyzed were E-ink Shop [49] and Waveshare [50]. The available commercial measures were 7.8 inches, 9.7 inches, 10.3 inches, 12.48 inches, 13.3 inches, 25.3 inches, 31.2 inches, and 42 inches, some of them can be seen in Figure 4.3. Although 10.3-inch or 9.7-inch displays fit within the scope of this initial prototype, it is important to note that other display sizes are available and will meet the requirements for deploying future sizes.

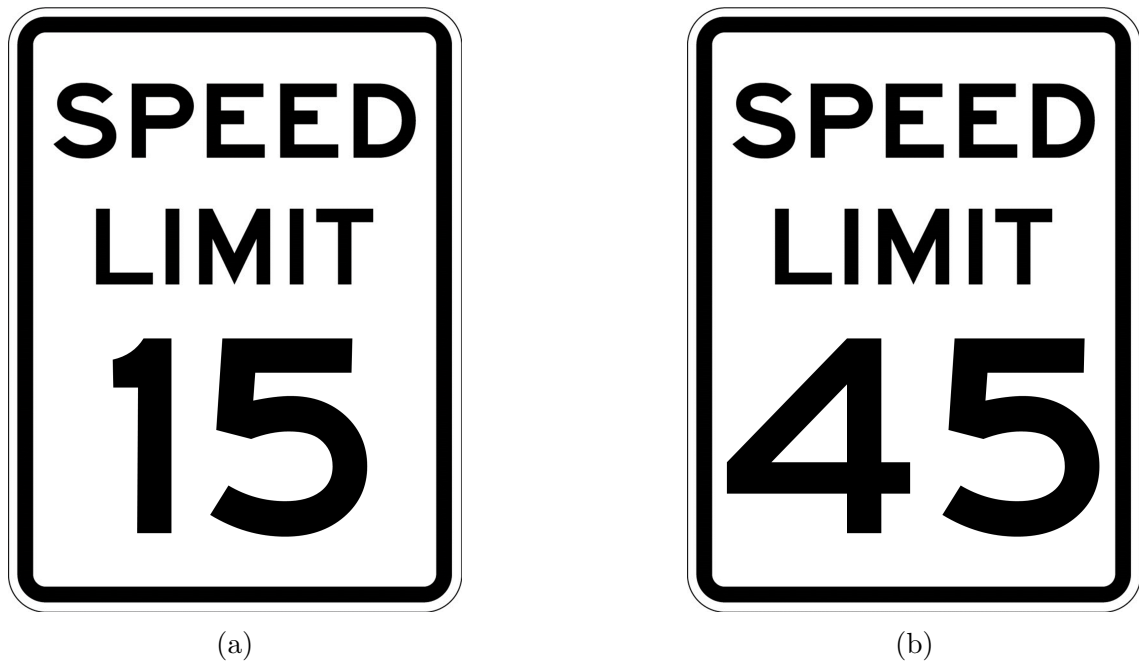


Figure 4.2: Numbers width comparison according to the speed posted in a SLS to select proper E-ink screen sizes. a) 15 miles per hour SLS example. Number height 8 inches, total width 10 inches. b) 45 miles per hour SLS example. Number height 8 inches, total width 14.3 inches.

Due to budget constraints and product availability at the time of the prototype building, the option selected for the initial design was the 9.7-inch display. Options ranging from 7.8 inches to 13.3 inches work with the same driver, so there will be no

difficulties in replacing it when possible. Some of the most remarkable characteristics of this display are:

- **Operating voltage:** 5 V
- **Communication Interface:** USB/SPI/I80
- **Resolution:** 1200×825
- **Display color:** black, white
- **Grayscale:** 2-16 (1-4 bit)
- **Full refresh time:** <1 s
- **Total refresh power:** 0.6 W
- **Total standby power:** 0.3 W
- **Viewing angle:** $>170^\circ$

4.1.2 Communications Module - LoRa

At 3.2.3 has been already discussed the use of LoRa as the communication protocol between the BS and VSLS, however, there are many different LoRa modules available for this purpose, three options were analyzed and compared, and can be seen in Table 4.1.

The RYLR998 transceiver module is designed and manufactured by Reyax Technology Corporation. Features the LoRa long-range modem SX1276 that provides ultra-long range spread spectrum communication and high interference immunity whilst minimizing current consumption [51]. According to SEMTECH's press release [54], throughout the 22 dBm transmitting power the module can reach distances of up to 20 kilometers in a good transmission environment and its small size

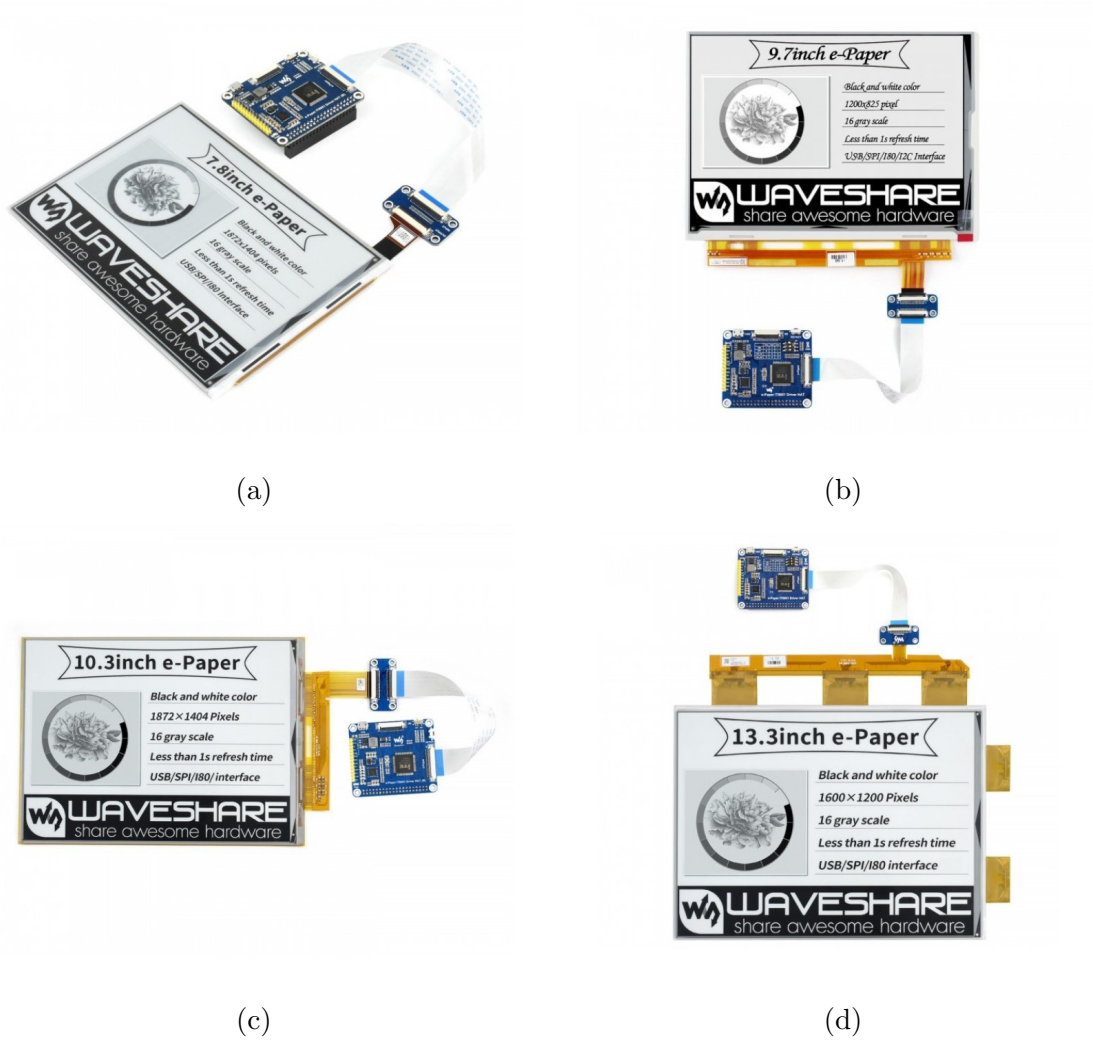


Figure 4.3: Different sizes of E-ink displays available in the market. a) 7.8 inches. b) 9.7 inches. c) 10.3 inches. d) 13.3 inches.

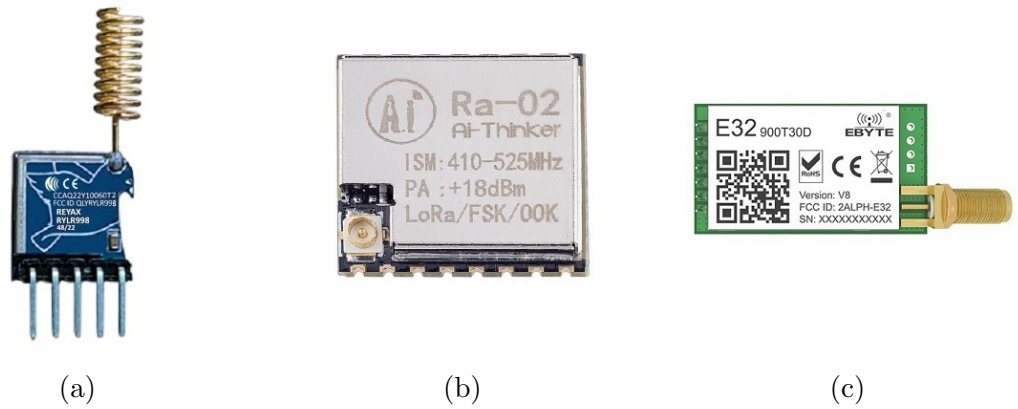


Figure 4.4: LoRa modules available in the market. a) RYL998 [51]. b) Ra-02 [52]. c) E32-900T30D [53].

Table 4.1: Comparative list of available LoRa modules in the market.

	Reyax RYLR9984	Ai-Thinker Ra-02	Ebyte E32-900T30D
IC	SX1276	SX1278	SX1276
Operating frequency	868 to 915 MHz	410 to 525 MHz	862 to 930 MHz
Sensitivity	-129 dBm	-140 dBm	-147 dBm
Transmitting power	22 dBm	20 dBm	30 dBm
Current on transmit mode	140 mA	105 mA	650 mA
Current on receive mode	17.5 mA	12.15 mA	25 mA
Current on sleep mode	10 uA	1.6 mA	5 uA
Operating temperatures	-40 to 176 °F	-4 to 257 °F	-40 to 185 °F
Communication interface	UART	SPI	UART
Price	12.60 USD	5.41 USD	8.63

of 32 x 14 x 2.2 mm makes it ideal for implementation in sensors and drivers with a smaller amount of space.

The Ra-02 Anxinke LoRa module is designed and developed by Anxinke Technology. The radio frequency chip of this series of modules is the SX1278 which uses a LoRa remote modem for ultra-long-distance spread spectrum communication, it has strong anti-interference and can minimize current consumption. With the help of SEMTECH's LoRa patented modulation technology, SX1278 has a high sensitivity of over -148 dBm, a power output of 20 dBm, a long transmission distance, and high reliability [55].

The E32-900T30D is a wireless LoRa module designed and produced by EByte. Uses the SX1276 SEMTECH's Radio Frequency (RF) chip, the same as the RYLR998 module. It has multiple transmission modes, LoRa spread spectrum technology, and Transistor Transistor Logic (TTL) output. The modules of 30 dBm transmitting power adopt industrial-grade crystal oscillators to ensure stability and consistency with an air data rate of 2.4 Kbps. It is widely applied in utility meters, IoT renovation, smart homes, etc. The modules feature data encryption and compression [53].

From the cited options in Table 4.1 the chosen one is the Ebyte E32-900T30D, although the current for the transmit and receive modes are the largest compared to the other options, this is compensated by a larger transmitting power and sensibility, in another words, larger distances can be covered. Taking into consideration that the transmission to set data towards the sign will not be continuous, the interval of the data set could be adjusted to achieve the same overall power consumption as the other two options. This module also has the smallest sleep mode current consumption which is an important parameter because this state will be most used. Price and market availability also make it a good option.

4.1.3 GPS Module

The GPS module was not an explicit requirement cited in Chapter 2, however, it is implemented to improve the overall security and reliability of the system. Currently, the data transmission between the BS and the VSLs is done by transparent packages spread over the air. Although the LoRa module can be set to transmit using a specific channel or frequency, any person with the correct hardware can sniff

these packages and replicate the information, posting unwanted data in the VLS and leading to accidents or undesired conditions. While GPS devices are primarily known for providing location data, the main purpose of this device in the scope of this research is to provide a Real-Time Clock (RTC) to the VLS. With this, a time-based security system could be implemented to protect the data packages transmitted between the BS and the VLS

The device selected for this purpose is the Adafruit Ultimate GPS breakout V3. 5 V compatibility, 20 mA current draw, hardware input for turning on/off, and external antenna compatibility make it a good option for the prototype. The breakout is built around the MTK3339 chipset, a no-nonsense, high-quality GPS module that can track up to 22 satellites on 66 channels [56]. Other characteristics of this GPS module are:

- -165 dBm sensitivity, 10 Hz updates, 66 channels
- 5 V friendly design and only 20 mA current draw
- RTC battery-compatible
- Built-in data logging
- PPS output on fix
- Internal patch antenna + u.FL connector for external active antenna
- Fix status LED

4.1.4 Microcontroller

The microcontroller serves as the main core of the sign, managing the displays, LoRa communication, GPS module, Micro Secure Digital (MicroSD) Cards, and

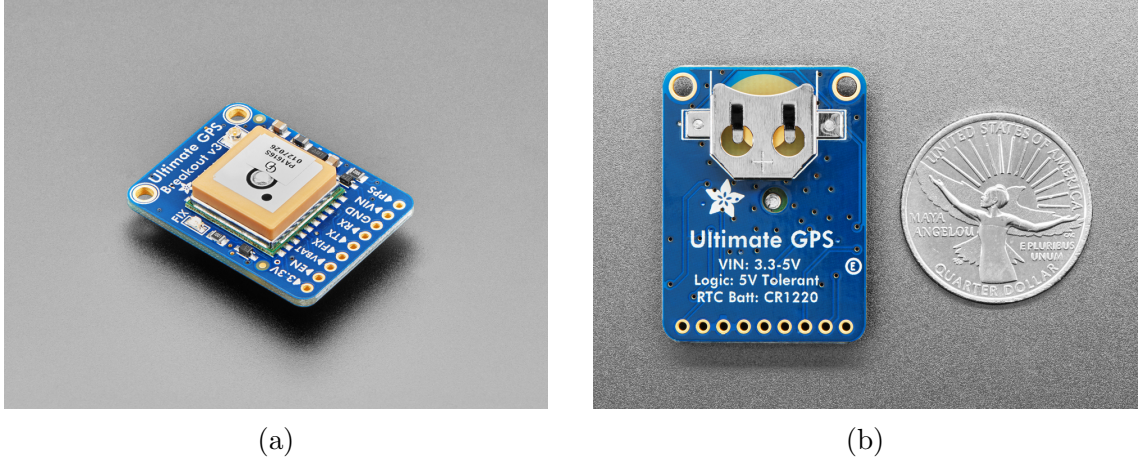


Figure 4.5: Views of the Adafruit Ultimate GPS breakout V3 module. a) Top view. b) Bottom view next to a quarter coin.

any other subsystem. Due to its integrated capabilities for Wi-Fi, Bluetooth, and Local Area Network (LAN) connectivity, the brand Espressif was selected for the main microcontroller. While these characteristics were not explicitly required, they offer scalability and ease of maintenance. For instance, if troubleshooting is needed, Wi-Fi or Bluetooth functionality could be enabled as a monitoring point, or they could even be used for firmware updates over the air. Table 4.2 presents three of the most commonly used integrated circuits from this brand.

ESP8266EX delivers a highly integrated Wi-Fi System on a Chip (SoC) solution to meet users' continuous demands for efficient power usage, compact design, and reliable performance in the IoT industry. Besides the Wi-Fi functionalities, ESP8266EX also integrates an enhanced version of Tensilica's L106 Diamond series 32-bit processor and on-chip SRAM. It can be interfaced with external sensors and other devices through the General Purpose Input Outputs (GPIOs). Software Development Kit (SDK) provides sample codes for various applications [57].

Table 4.2: Comparative list of different Espressif microcontrollers.

	ESP 8266	ESP 32	ESP32S3
Wi-Fi 802.11 b/g/n	Yes, HT20	Yes, HT40	Yes, HT40
Bluetooth	No	Yes, v4.2	Yes, LE v5.0
Frequency	80 MHz	up to 240 MHz	up to 240 MHz
SRAM	160 kBytes	512 kBytes	2 Mbytes
GPIO	17	36	45
SPI/I2C/I2S/UART	2/1/2/2	4/2/2/2	4/1/2/3
ULP processor	No	Yes	Yes
Current on modem sleep	15 mA	31 mA	25 mA
Current on deep sleep	20uA*	150 uA	150 uA
Price	8.00 USD	8.00 USD	15 USD

The ESP32 is a single 2.4 GHz Wi-Fi and Bluetooth combo chip designed using TSMC’s low-power 40 nm technology. It is engineered to achieve optimal power and RF performance, demonstrating robustness, versatility, and reliability across a wide range of applications and power scenarios. In addition to its RF capabilities, it integrates an Xtensa® single-/dual-core 32-bit LX6 microprocessor and an Ultra Low Power (ULP) coprocessor capable of operating in deep sleep mode with a current consumption of just 10 μ A, while still controlling the RTC and certain Input-Output (I/O) functions [58].

ESP32-S3 is a low-power MCU-based system on a chip SoC with integrated 2.4 GHz Wi-Fi and BLE. It consists of a high-performance dual-core microprocessor Xtensa® 32-bit LX7, a low-power coprocessor, a Wi-Fi baseband, a BLE baseband, an RF module, and numerous peripherals [59].

After analyzing the options, the device selected is the ESP32-S3, despite its higher cost. The advantage it offers is the large number of GPIOs and SRAM compared to the other options, which improves the scalability of the system in the long term.

Having more GPIOs allows for the incorporation of additional external devices if necessary. Additionally, this device allows for GPIO mapping for its peripherals, meaning that any GPIO can function as an ISP/PWM/I2C/UART or any other function, thanks to the internal multiplexing provided by the device.

The large memory capacity will allow for the storage of larger programs. Therefore, if new capabilities need to be implemented, the code size will also increase. If the SRAM capacity is sufficient, the images of the numbers can be stored there, eliminating the need for extra memory such as MicroSD cards or others.

Finally, for this prototype, a development kit will be used. The selected one is shown in Figure 4.6c. The ease of testing is the main reason for this selection.

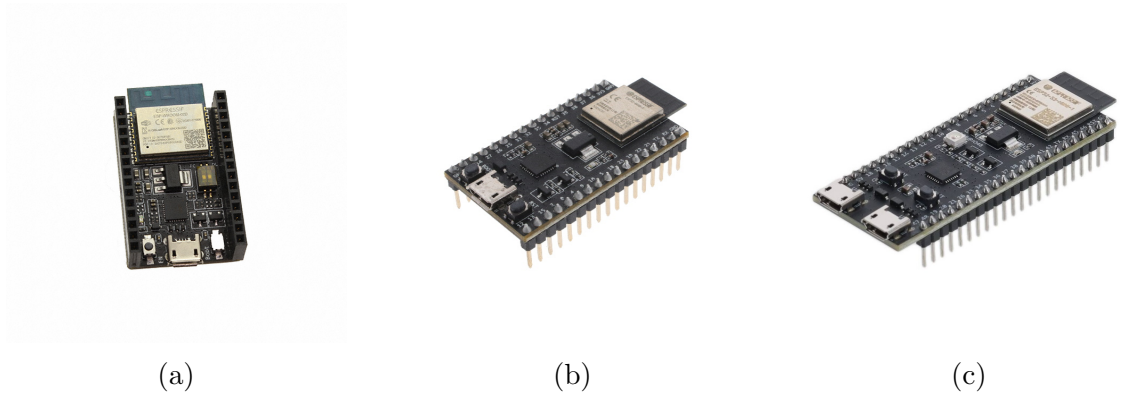


Figure 4.6: Images of different development kits for the Espressif microcontrollers: a) DEVKITM ESP8266 [60]. b) DEVKITM ESP32 [61]. c) DEVKITM ESP32-S3 [62].

4.1.5 Battery, Solar Panel, And Enclosure

Nowadays, complete solar systems that include solar panels, batteries, and charge regulators can be found on the market. For this initial prototype, an off-the-shelf solar system will be used. In future versions, the implementation of this power source system in the VSLs must be done. The inclusion of this in the manufacturing process will allow for better shaping of enclosures, avoiding additional costs from third parties, and providing overall control of the components used for this purpose.

In any case the first step is determine the capacity of the battery needed, we will base our calculations on the consumption of the components according to their datasheets, while also assuming usage times. The analysis will be separated into two parts: First, when the system is actively working, such as during display updating, LoRa transmitting, and/or GPS gathering data; and second, when the system is in standby mode. These analyses can be seen respectively in Tables 4.3 and 4.4.

Table 4.3: Theoretical power consumption analysis of the VSLs components (Active mode).

Item	Qty	Time per task (s)	Occur- ences per day	Total time (h/day)	Power con- sumption (W)	Consump- tion (Wh/day)
9.7 E-ink display and driver	2	2	24	0.013	0.6	0.2
LoRa module	1	14	24	0.093	3.25	0.30
GPS module	1	60	3	0.050	0.125	0.01
External GPS antenna	1	60	3	0.050	0.066	0.003
Microcontroller	1	60	24	0.400	0.0783	0.03
Total						0.36

Table 4.4: Theoretical power consumption analysis of the VLS components (Standby mode).

Item	Qty	Standby time (h)	Standby power (W)	Standby consumption (Wh/day)
9.7 E-ink display and driver	2	23.987	0.3	14.39
LoRa module	1	23.907	15×10^{-6}	3.59×10^{-3}
GPS module	1	23.971	26.85×10^{-6}	643×10^{-6}
External GPS antenna	1	23.971	0	0
Microcontroller	1	24.000	26.85×10^{-6}	643×10^{-6}
Total				14.40

The total power consumption per day will be given by the addition of the standby consumption plus the consumption when the elements are performing a task:

$$\text{Total power consumption} = \text{Active mode} + \text{standby mode}$$

$$\text{Total power consumption} = 0.36 \text{ Wh/day} + 14.4 \text{ Wh/day}$$

$$\text{Total power consumption} = 14.76 \text{ Wh/day}$$

This means that if we want to last one day without charging the system, the battery must have a capacity of at least 14.76 Wh.

Usually, batteries are rated by Ah, this is due to the voltage being different according to the size or the model. Supposing a battery of 12V:

$$\begin{aligned} \text{Ah} &= \frac{\text{Wh}}{\text{V}} \\ \text{Ah} &= \frac{14.76 \text{ Wh/day}}{12 \text{ V}} \\ \text{Ah} &= 1.23 \text{ Ah/day} \end{aligned}$$

According to requirements listed in Chapter 2, the VSLS without receiving any kind of charge should last at least one week. Therefore:

$$\begin{aligned} \text{Ah} &= 1.23 \text{ Ah/day} \times 7 \text{ days/week} \\ \text{Ah} &= 8.61 \text{ Ah/week} \end{aligned}$$

This means that the VSLS must use a 12V battery of at least 8.61 Ah.

After exploring various options in the market to meet the calculations, we selected the solutions offered by Tycom Systems. Alongside the complete solar power system, it also includes an enclosure capable of housing the design electronics and serving as the main support for the SLS, including the E-ink displays.

The product line is the RPDC RemotePro series, outdoor power systems designed to meet the requirements of applications that demand a primary off-grid power source for various electronic devices. Encased in die-cast aluminum enclosures, these systems are both hinged and gasket-sealed, providing versatile mounting options on poles or walls using the provided bracket system. Additionally, the

solar panels, boasting high quality and a 25-year power output guarantee, can be conveniently affixed to poles or walls using the accompanying bracket kit. Noteworthy features include an advanced battery charge controller, ensuring protection against over-charging or over-discharging of the valve-regulated sealed lead-acid batteries. Furthermore, the vented enclosures prevent the buildup of residual hydrogen gas. The batteries, of the Absorbed Glass Mat (AGM) type, exhibit commendable performance across all temperature ranges [63].

The selected model is the RPDC12-9-15, which includes the RemotePro 2.5 W continuous remote power system, a 15 W solar panel with mount, a 9Ah battery, a 12 V 20 A Pulse Width Modulation (PWM) solar controller, and a pole/wall mount outdoor die-cast aluminum enclosure. More details can be seen in Figure 4.7.

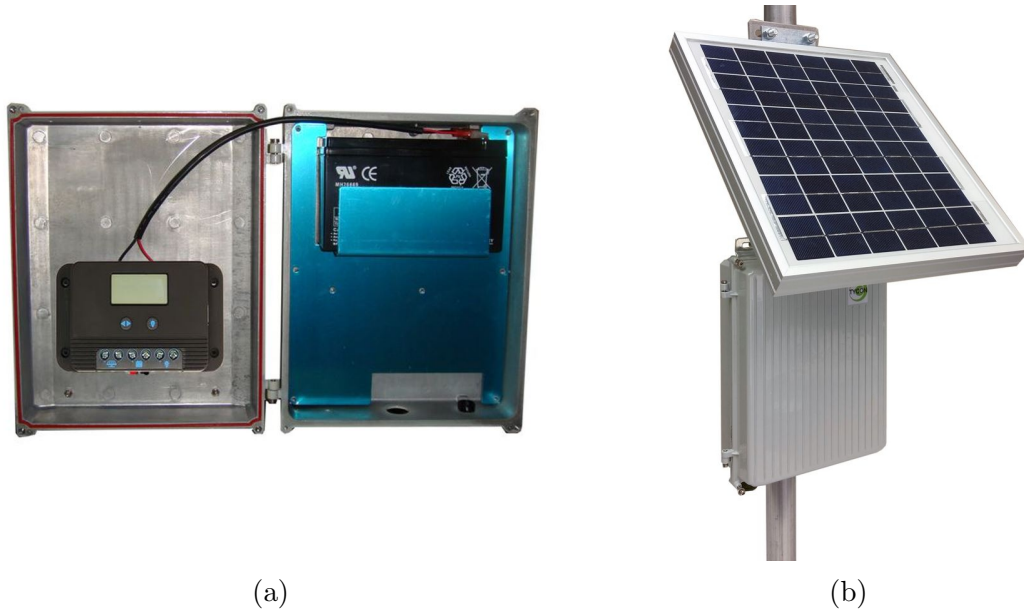


Figure 4.7: Different views of the RPDC12-9-15 outdoor power system [63]. a) Inside components. b) Solar panel complete kit.

4.1.6 Front Light

To contextualize this aspect of the design, during the initial tests, we observed diminished visibility of the numbers on the E-ink display at night. This was attributed to the contrast difference caused by the retroreflective material installed on the SLS and the E-ink displays. When the lights of a testing car illuminated the VSLS, the non-reflective surface of the E-ink displays was easily obscured by the reflected light from the rest of the VSLS. Further details on these tests are provided in Chapter 5, Section 5.1.

Despite considering several ideas to overcome this challenge, the final decision was to remove the retroreflective material, necessitating the use of an illumination system during the night. Although this may seem like a step back in terms of power consumption, the device still offers better power consumption performance compared to traditional LED-based technology. Firstly, the E-ink VSLS does not consume a significant amount of power during the day due to the image-holding characteristics of E-ink technology compared to traditional LEDs who need to be powered continuously to function. This allows the charging system to focus entirely on charging the battery during the day. Additionally, having just a front light, as opposed to a matrix of LEDs, simplifies control and operation.

Due to the construction characteristics of E-ink displays, backlight implementations are fiscally not possible. Therefore, frontlight has been a good solution to improve visibility during the night in E-ink devices. It is currently applied in e-readers, monitors, and even in exterior signage [12]. In the case of the VSLS, things

get more complicated because the sign is not a huge E-ink area. As explained in Chapter 2, Section 4.1.1, the displays will only cover the numbers of the sign.

Based on previously implemented ideas such as e-readers or monitors, the design will include a frontal LED strip surrounding the sign, embedded in epoxy resin, which will act as a waveguide confining the light inside due to the difference in refractive index compared to the air. This construction process will be thoroughly analyzed in Section 4.1.8, where the complete step-by-step assembly process will be described.

As a secondary design option, an external light source is also being considered. The concept is to illuminate the VSLs using an outside light source, such as a spotlight. These are typically constructed using high-lumen COB LEDs. To validate this concept, a commercial spotlight with a luminosity of 1200 lumens will be utilized. As part of future work, various options of COB LEDs will be analyzed and implemented in the design.

4.1.7 Printed Circuit Board

To easily integrate all the selected parts up to this point, a mother PCB board was designed to facilitate assembly. The software used for this task was Altium Designer. This board includes connectivity for all the previously listed components and additional capabilities such as fuse protection, power supply status indication through push buttons and LEDs, dedicated power regulators for the GPS, transistorized power stages for the PWM, independent PWM outputs for each edge of the front light, a solar panel signal input for auto-brightness functions, impedance-controlled

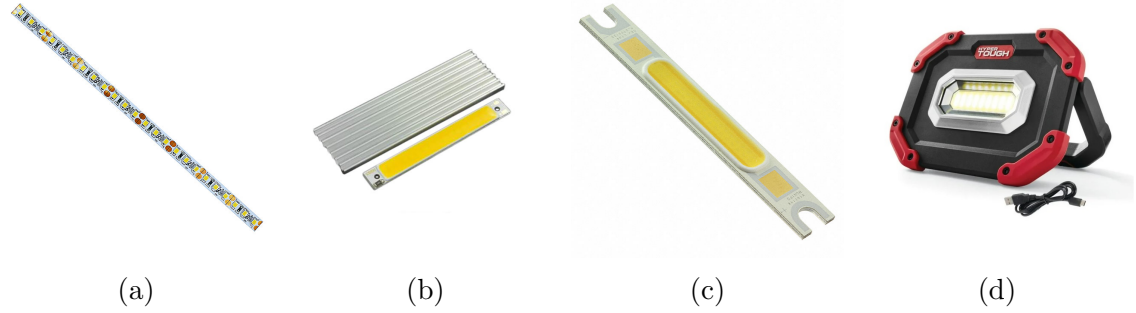


Figure 4.8: Different views of VLS lighting options. a) Inspired LED LLC presents a 12 V flexible LED strip equipped with 2835 diodes, boasting a power consumption of 21 W over a length of 84.5 inches [64]. b) From DFRobot, a 5 V rectangular COB LED offering 300 lumens, with dimensions measuring 12000.00 mm in length and 25.40 mm in width. Its power consumption is 3 W [65]. c) From Citizen, a 9.2 V rectangular COB LED delivering 760 lumens, with dimensions of 50.00 mm in length and 7.00 mm in width. This option consumes 6.5 W of power [66]. d) Lastly, the Hyper Tough 1200 lumen Rechargeable Work Light, features a lithium-ion battery and an LED bulb, providing bright light for up to 4 hours on a low setting and 2 hours on high. It comes with an integrated handle featuring a 180-degree swivel, allowing for flexible positioning [67].

buses for Serial Peripheral Interface (SPI) connection with the E-ink drivers, and two expansion I/O ports, each with one GPIO 5 V and GND. The shape of the board was designed based on the dimensions of the enclosure included with the solar system shown in 4.1.5. Therefore, a good fit is expected. Detailed information about the PCB board is provided in Figure 4.9, and detailed information about the schematic and designs is provided in Annex B

4.1.8 Assembly and Mounting

For the assembly process, a more detailed mockup model was designed using Sketchup software. The main concept for the prototype is to work in layers, as depicted in Figure 4.10. Going from bottom to top, the first layer is the support that will be attached to the enclosure, hence it includes the supporting holes. The next layer

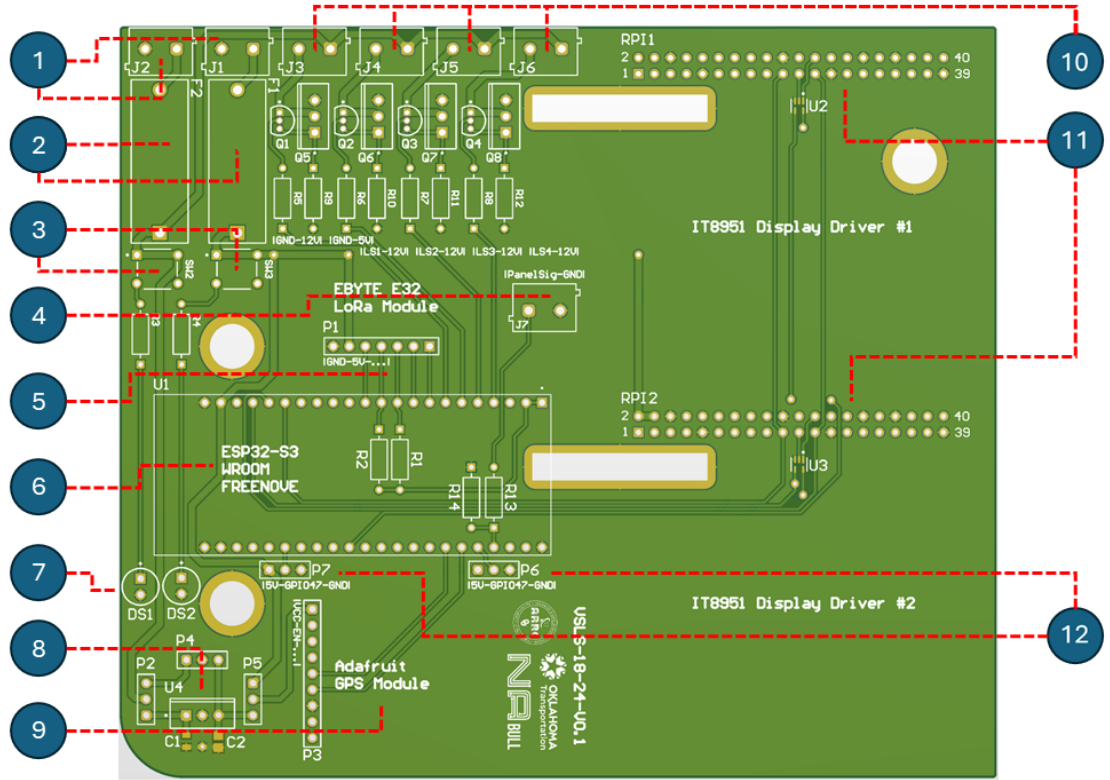


Figure 4.9: VLS PCB motherboard. 1. 12 V and 5 V power inputs. 2. Protection fuses. 3. Power supply test push buttons. 4. Solar panel signal feedback for auto-brightness functions. 5. LoRa module socket. 6. Microcontroller socket. 7. Power supplies status LED. 8. GPS voltage regulators. 9. GPS module socket. 10. Transistorized 12V PWM controlled outputs for frontlights. 11. E-ink drivers sockets. 12. Expansion I/O sockets with one GPIO each.

acts as a spacer, providing clearance for the E-ink display buses. Following that, we have the combination of E-ink displays and the Speed Limit layer; the displays will be glued using epoxy and sealed from the back to prevent any leakage. The subsequent layer consists of the frontlight frame, and along with the final black top frame, it will serve as a cup to pour transparent epoxy polymer, effectively bonding all the layers together and forming a reliable front panel.

The material chosen for the manufacturing process is acrylic due to its ease of cutting with laser machines and manufacturability. These factors were the main

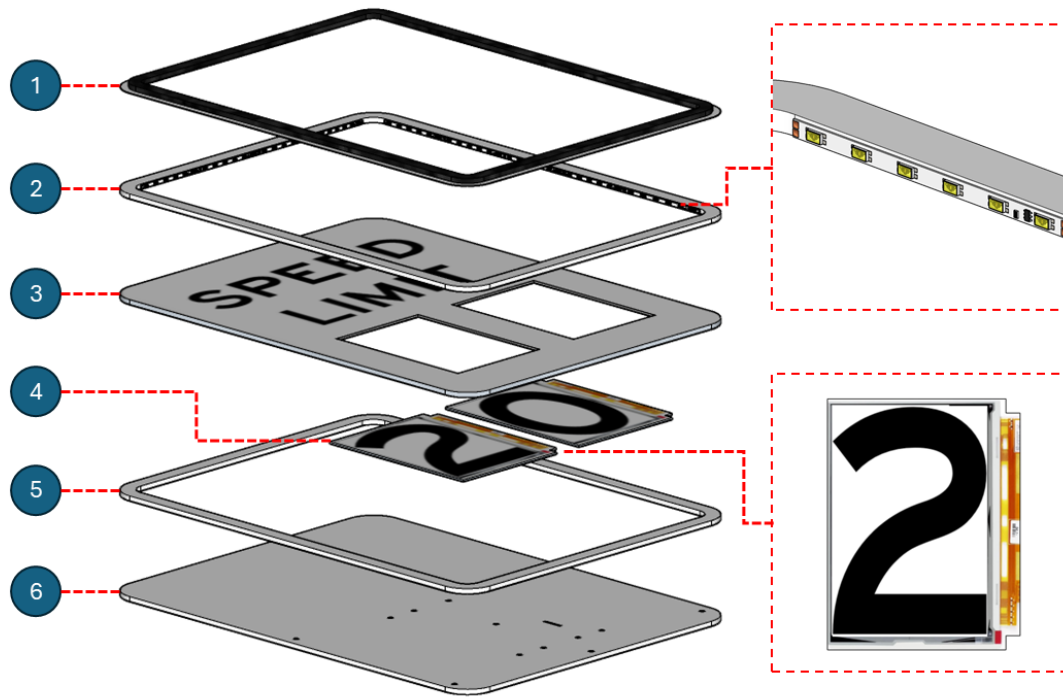
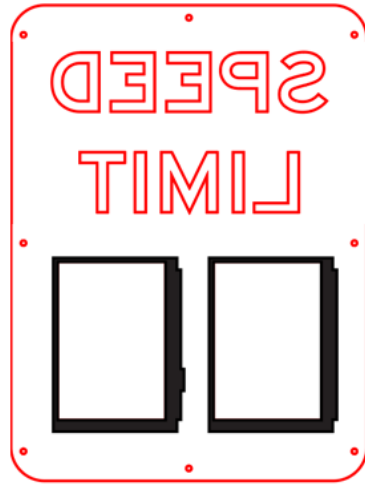


Figure 4.10: Exploded view of the layers for the front panel of the VLSL: 1. Black frame. It will cover the frontlight LED strips to prevent direct light towards the drivers and at the same time, is a characteristic determined by the MUTCD. 2. Frontlight frame conformed by LED strips. Will illuminate the sign, epoxy sealant will be poured along this whole layer, working as a waveguide to keep the light trapped. 3. Signage and pocket for displays. This layer will hold the display in position and cover the black frames of the E-ink displays 4. E-ink displays. this will show the desired speed through the numbers posted. 5. Spacing frame. This will give enough space for the E-ink display buses and circuitry 6. Back layer. It covers the back of the displays and will be attached to the solar panel enclosure, it is the fixture that holds the enclosure and the front panel.

considerations for its use in the manufacturing process of this prototype. The cutting and production processes can be observed in Figure 4.11.

Once all the layers are cut, they are bonded using superglue, the E-ink displays are secured and sealed using silicone caulking, the LEDs for the frontlight are installed in their respective layers, and finally, everything is covered by the black bezel on top. This part of the process is detailed in Figure 4.12.



(a)



(b)



(c)



(d)

Figure 4.11: Acrylic layers manufacturing process using a laser cutting machine: a) The layers from the 3D model design in 4.10 are exported as DXF files and configured for cutting and engraving. b) The laser machine cuts and engraves. c) Results of engraved pockets for E-ink displays. d) Results of letters cut for signage.



(a)



(b)



(c)



(d)

Figure 4.12: Front panel assembly using the acrylic layers includes: a) Bonding the bottom acrylic layer, frame for the frontlight, and letters with super glue and silicone caulking. b) A detailed view of the installed E-ink displays in the front panel. c) A detailed view of the installed LED strips in the front panel. d) Preparing and leveling the front panel for epoxy pouring to complete the manufacturing process.

The electronic components, battery, and charge regulator will be housed in the enclosure selected in Section 4.1.5, and this same enclosure will also hold the front panel of the sign. Figure 4.13 shows how it is drilled to hold the main frame and how it will hold the circuitry. A mockup PCB was used to verify the fit inside the cabinet.

Finally, all the components are mounted inside the enclosure, as seen in Figure 4.14.

The enclosure is mounted on an aluminum self-supported adjustable-height pole. The initial results of the assembled VSLs can be seen in Figure 4.15.

4.1.9 Firmware

The microcontroller was programmed using C++ task-oriented code. Any microcontroller operates in an endless loop, consisting of two parts: the setup, which runs once, and the loop, which is the part that will work repeatedly without finishing.

The setup begins when the VSL is turned on. The code reads the ID and last/default speed limit from the memory and starts the configuration process of the modules and subsystems. Firstly, the LoRa module is tested through a serial connection. If the connection is established, a package with the ID and speed is sent to the BS. Secondly, the connection through SPI with the E-ink display drivers is tested; at this step, the numbers are not yet updated. Thirdly, the GPS module is tested through a serial connection. If it is successfully established, the internal microcontroller clock is configured with the last GPS data. Fourthly, the maximum brightness is set for the frontlights, and they are configured according to the input



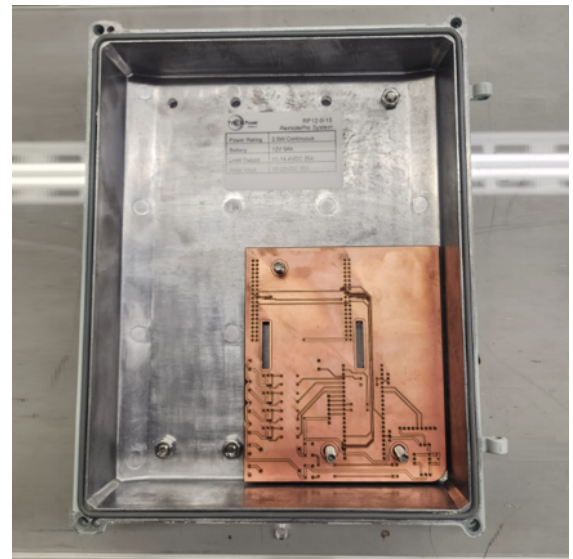
(a)



(b)



(c)



(d)

Figure 4.13: Modifications made to the solar panel system enclosure to accommodate electronics and the front panel. a) Holes drilled using an acrylic fixture that aligns with the bottom acrylic layer. b) Exterior view of the enclosure with the bottom acrylic layer attached. c) Internal view of the empty enclosure. d) Internal view of the enclosure with the mockup PCB.

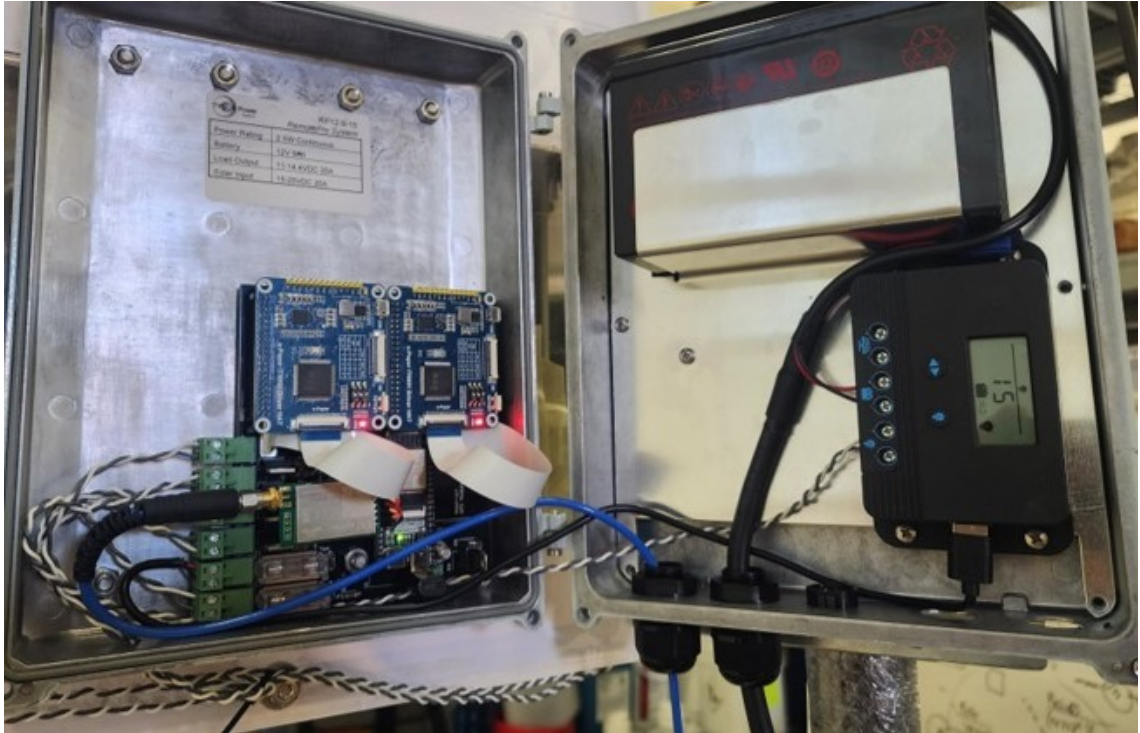


Figure 4.14: Battery, solar regulator, and electronic components mounted inside the enclosure.

signal from the solar panel. Fifthly, the numbers are updated and posted on the E-ink displays. Finally, the Log/Report function allows the VSLs to start working if every function before was performed without error, makes a log of the result of each subsystem, and sends the information through the LoRa module to the BS. If there is an error during the setup process, the controller will log it, transmit the log to the BS, and stay in a blocking loop inside the log/report status function.

Next, the loop will start, and the low power consumption mode will be set. Meanwhile, while the microcontrollers are in this mode, the main core will be turned off, and the ultra-low power consumption core will be used to read the solar panel input and set the brightness of the frontlight. An interrupt function is waiting for data in LoRa or Serial mode. If data is received, it is decrypted and validated. The

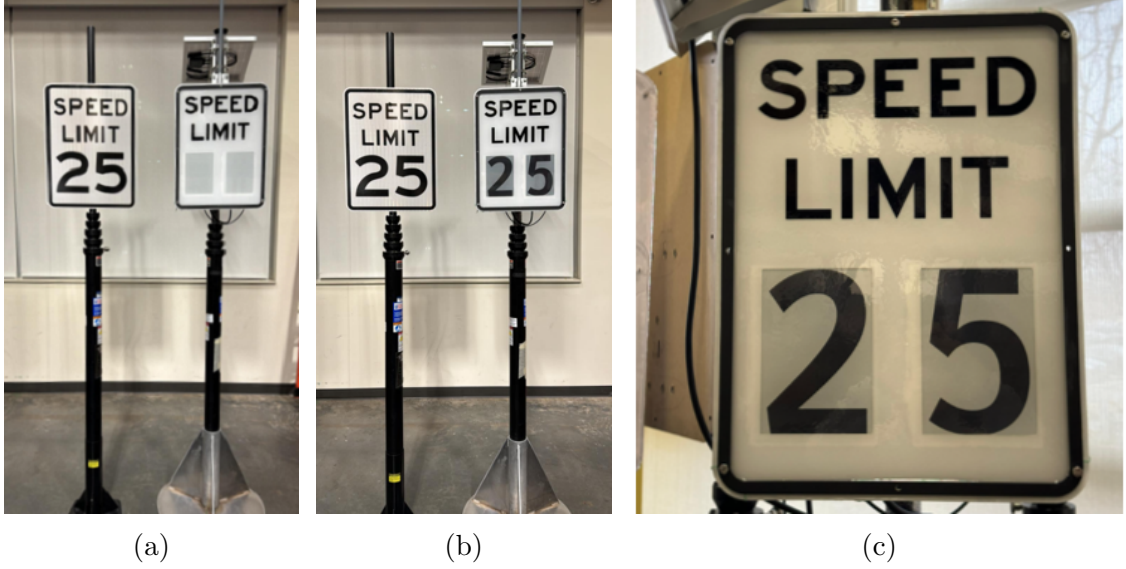


Figure 4.15: Results of the VSLs assembly: a) Comparison between the VSL and a regular SLS, each mounted on an aluminum pole. b) Comparison between the VSL and a regular SLS, both with the same speed limit. c) Close-up view of the VSL front panel.

expected parameters are the ID, the maximum brightness, and the speed to be set. If every parameter is correct, the speed limit is updated, and an acknowledgment is sent to the BS. If at any step the data is wrong or not validated, an answer to the BS is sent, and the microcontroller returns to the low power consumption mode.

4.2 Base Station Design

The base station is designed to be the main controller for each group of VSLs, this device will be able to interconnect the VSLs with the final user through a REST API. At the same time, the base station can monitor the state, subsystem failures, and miscommunications from each endpoint.

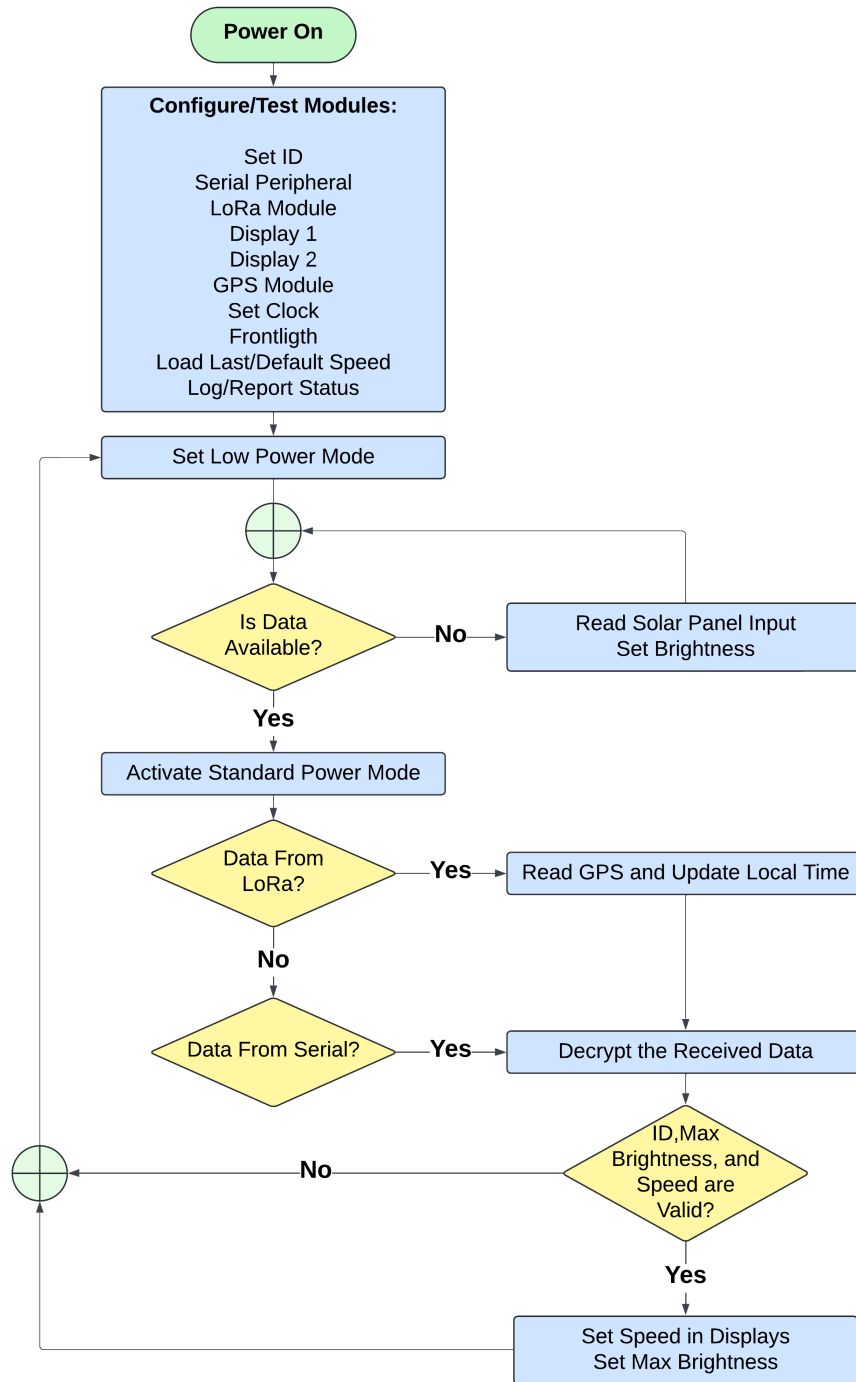


Figure 4.16: Generalized flow diagram of the VSLs firmware

4.2.1 CPU And Operative System

To allow scalability a minicomputer will be used as the main core for the BS.

Table 4.5: Comparative list of available CPUs in the market.

	Raspberry Pi 4	Libre Computer Le Potato	LattePanda V1
Processor	Broadcom BCM2711, Quad-core ARM Cortex-A72 64-bit SoC @ 1.8GHz	Amlogic S905X SoC 4 ARM Cortex-A53 @ 1.416GHz	Intel Atom x5 - Z8350 Quad-core @ 1.92 GHz
RAM memory	2GB LPDDR4-3200 SDRAM	2GB 32-bit DDR3 SDRAM	2GB LPDDR3 SDRAM
Connectivity	2.4 GHz and 5.0 GHz IEEE 802.11ac, Bluetooth 5.0 BLE, and Gigabit Ethernet	Infra Red 100 Mb Fast Ethernet	2.4 GHz IEEE 802.11n wireless, Bluetooth 4.0. 100 Mb, and Fast Ethernet
USB	2 USB 3.0 ports and 2 USB 2.0 ports	4 USB 2.0 ports	1 USB 3.0 port and 2 USB 2.0 ports
GPIO	40 pin GPIO header	40 pin GPIO header	20 pin GPIO header
Data storage	MicroSD card slot	USB ROM Boot, MicroSD card slot and eMMC 5.x interface	Onboard 32 Gb eMMC and MicroSD card slot
Power supply	5V DC via USB-C and GPIO header	5V DC via USB-C and GPIO header	5V DC via USB-C and GPIO header
Operating temperature	32 – 122 °F	32 – 122 °F	32 – 140 °F
Operative system	Linux	Linux	Windows / Linux
Price	61.80 USD	35.00 USD	115.00 USD

Nowadays a large list of development mini computers can be found in the market, in Table 4.5 the three most relevant are compared and shown.

LattePanda v1 is the smallest x86 single-board computer in the world that can execute the complete Windows operation system. Since its launch, LattePanda V1 has evolved into a highly sophisticated product, widely acknowledged and utilized

by numerous users. Moreover, owing to its diminutive form factor, low power consumption, multiple interfaces, and robust expandability, the LattePanda V1 has been extensively applied across various industrial domains, including portable instruments, smart gateways, image recognition, robotics, the Internet of Things, automated retail, and so forth [68].

Le Potato is the Libre Computer flagship hardware platform with support for the latest Android 9/TV, upstream Linux, u-boot, Kodi, and more. Based on a long-term supported SoC family with a proven record of mass deployments by the largest regional content providers, Google, and Amazon, AML-S905X-CC is the perfect development platform for projects that require highly performant ARM Cortex-A class CPUs, secure and non-secure 4K media delivery and playback, Widevine CAS DRM, high reliability, and low power [69].

Raspberry Pi 4 Model B features a high-performance 64-bit quad-core processor, dual-display support at resolutions up to 4K via a pair of micro HDMI ports, hardware video decodes at up to 4K at 60 frames per second, up to 8 GB of RAM, dual-band 2.4/5.0 GHz wireless LAN, Bluetooth 5.0, Gigabit Ethernet, USB 3.0, and PoE capability (via a separate PoE HAT add-on). For the end user, Raspberry Pi 4 Model B provides desktop performance comparable to entry-level x86 PC systems. This product retains backward compatibility with the prior-generation Raspberry Pi 3 Model B+ and has similar power consumption, while offering substantial increases in processor speed, multimedia performance, memory, and connectivity. The dual-band wireless LAN and Bluetooth have modular compliance certification, allowing

the board to be designed into end products with significantly reduced compliance testing, improving both cost and time to market [70].

Something in common for them is that all are Linux compatible, the advantage of this operative system is that is free although every minicomputer has its own distribution, all of them are Debian-based.

Regarding documentation all manufacturers provide a large amount of information, however, the Raspberry Pi community stands out as the largest and most active, this community's significance lies in its ability to provide solutions to common issues, drawing upon the experiences and insights of its members who have encountered and resolved similar challenges.

After comparing the characteristics of the three of them, the minicomputer chosen is the Raspberry Pi 4. Although the price is not the cheapest, the fact of having the large documentation, community, easy scalability, same form factor along the time and version, and the broad availability of expansion boards makes it the better device for the BS.

During the development of this research, the Raspberry Pi 5 was released with the following characteristics: The same form factor and input-output (I/O) header, 2–3× the speed processing of the previous generation, dedicated microcontroller RP1 for I/O, USB 3, and a PCI Express interface that allows the usage of an M.2 SSD as main storage option [71]. Although these improvements compared to the Raspberry 4, this device was not considered yet for the BS for the novelty of the product. According to the “Obsolescence Statement” in [70], “Raspberry Pi 4 Model

B will remain in production until at least January 2031” Therefore in a long-term further version of the BS could be manufactured using newer Raspberry Pi versions.

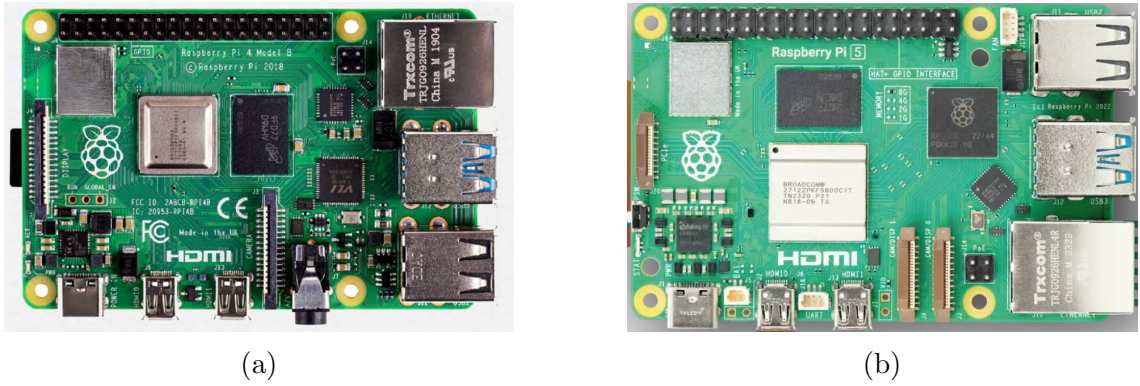


Figure 4.17: Raspberry Pi latest released models. a) Raspberry Pi 4 model B [70]. b) Raspberry Pi 5 [71].

4.2.2 Communications Module - LoRa

The communication options had already been discussed in 3.2.3, and LoRa has been defined as the communication protocol between the BS and VSLS. At the same time, an exhaustive analysis of different LoRa modules in the market had been done in 4.1.2. To maintain compatibility and consistency in the design of the BS, the Ebyte E32-900T30D will be used as well.

4.2.3 Auxiliar Outputs - Relays

As part of the scalability, auxiliary outputs will be included in the design. Relay-based outputs allow the turn on and off multiple alert devices such as lights or sirens and also can be used as feedback for other devices. As this is not a strict requirement general purpose relays will be used. Figure 4.18 shows the chosen relays, Digikey was used to look for different options, and the selection criteria were mostly given

by characteristics such as larger stock quantity at the store, the small size of the package, 5VDC coil voltage, 277VAC, 30VDC - Max and the 10A Current contact rating [72].



Figure 4.18: The AZ943, a 10 A miniature general-purpose PCB relay [72]

4.2.4 Enclosure and PCB Shape

In 2.2.1 requirements for size and shape were given, as said, the SIEMENS - Logo PLC is used as reference and a preliminar model of the enclosure can be seen in Figure 4.19.

The design was realized based on the idea of having the Raspberry Pi attached to the main PCB as an expansion board as can be seen in Figures 4.20a and 4.20b. These designs of a Raspberry Pi and a LoRa module were introduced in a rectangular piece simulating the PCB, The Raspberry pi will be connected to the PCB using an extension socket, which will allow to have more free space in the PCB Board, the dimensions of the PCB were based on the dimensions of the PLC used as reference. The design of the enclosure allows the extension of the width as much as necessary

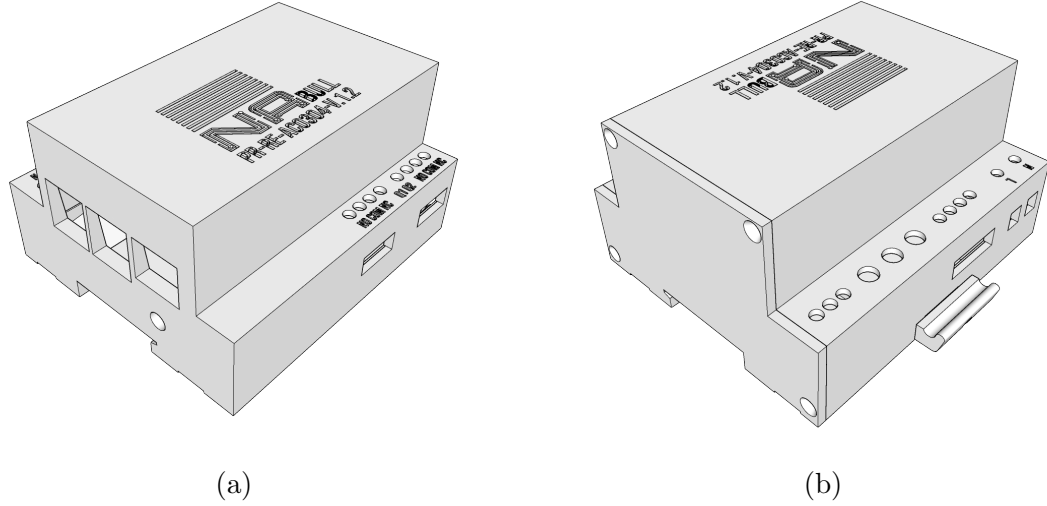


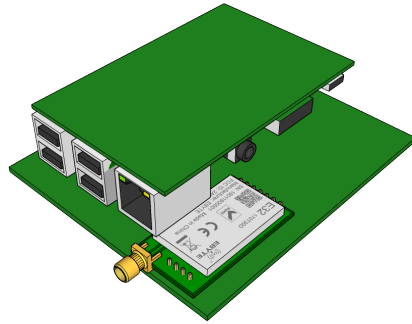
Figure 4.19: 3D model of the base station enclosure designed using Sketchup software. a) Top-front corner view. b) Rear-front corner view

according to the component population in the PCB. Using the PCB mockup the enclosure was designed considering the DIN Rail support in the back, ventilation holes in the top, holes for all the connectors such as USB ports, ethernet, SMA connector for the antenna, two relay outputs, and status LEDs. A transparent view of the construction and how the PCB will fit can be seen in Figures 4.20c and 4.20d.

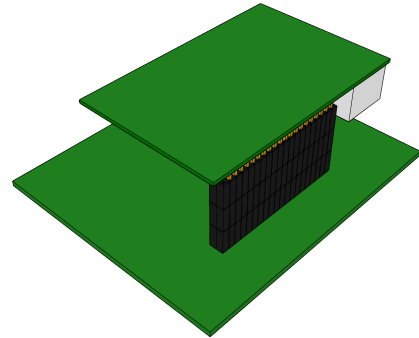
Although the images in Figures 4.19 show a finalized version of the enclosure, to get to this point the design had a back-and-forth between the design of the PCB, the available electronic components, and the conformity of the sponsor.

4.2.5 Printed Circuit Board

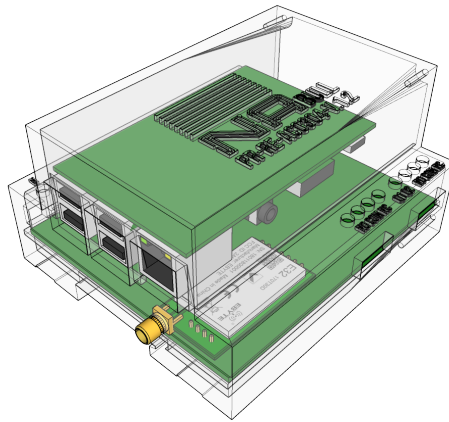
The PCB for the BS was crafted utilizing the CAD software KiCad EDA. This decision was primarily motivated by the fact that a similar project had already been developed using the same software. Leveraging this existing project as a foundation, the design process for the BS PCB commenced. The PCB was designed in



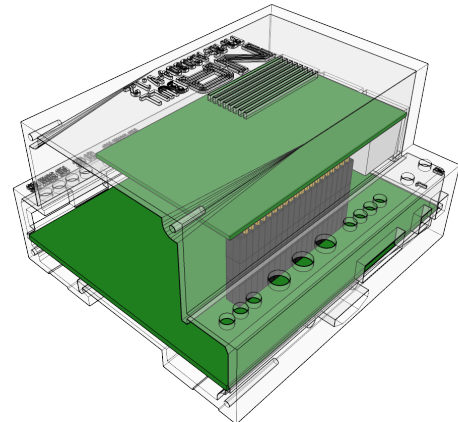
(a)



(b)



(c)



(d)

Figure 4.20: PCB mockup and enclosure 3D models designed using Sketchup software. a) Top-front corner view. b) Top-rear corner view. c) Transparent top-front corner view. d) Transparent top-rear corner view.

FR4 as material. To give robustness and reliability to the device two power supplies Meanwel IRM-10-5 were implemented, One of them will supply the control devices such as the LoRa Module and the Raspberry Pi. The other one will control exclusively the auxiliary relays. The relays are controlled through an optocoupler circuitry, this added to the independent power supply gives maximum isolation between the control area and the power area. In case of a short-circuit or over-power connected in the relay outputs the control area should not be affected. Two general-purpose buttons at the top are software-programmable, at the same time a terminal block with two general-purpose input outputs is accessible from the top. The PCB also has terminal pins directly routed to the Raspberry Pi fan controlling input/outputs. Finally, the LoRa module is routed to the Universal Asynchronous Receiver/Transmitter (UART) pins interface in the Raspberry Pi. A detailed layout of these characteristics can be seen in Figure 4.21.

Currently, the Gerber files, Bill of Material, and other documents for large-scale productions are available, however, for purposes of this research the prototypes were manufactured in the facilities of the Advance Radar Research Center (ARRC) at the University of Oklahoma (OU). The assembled device can be seen in Figure 4.22.

4.2.6 Software and API

As we are using a Raspberry Pi as the main core for the BS, the optimal operative system (OS) provided by the manufacturer is Raspberry Pi OS. This OS is Linux-Debian based and it is installed in a MicroSD card and plugged in the Raspberry Pi. The advantage of this is that Images can be easily created and cloned therefore

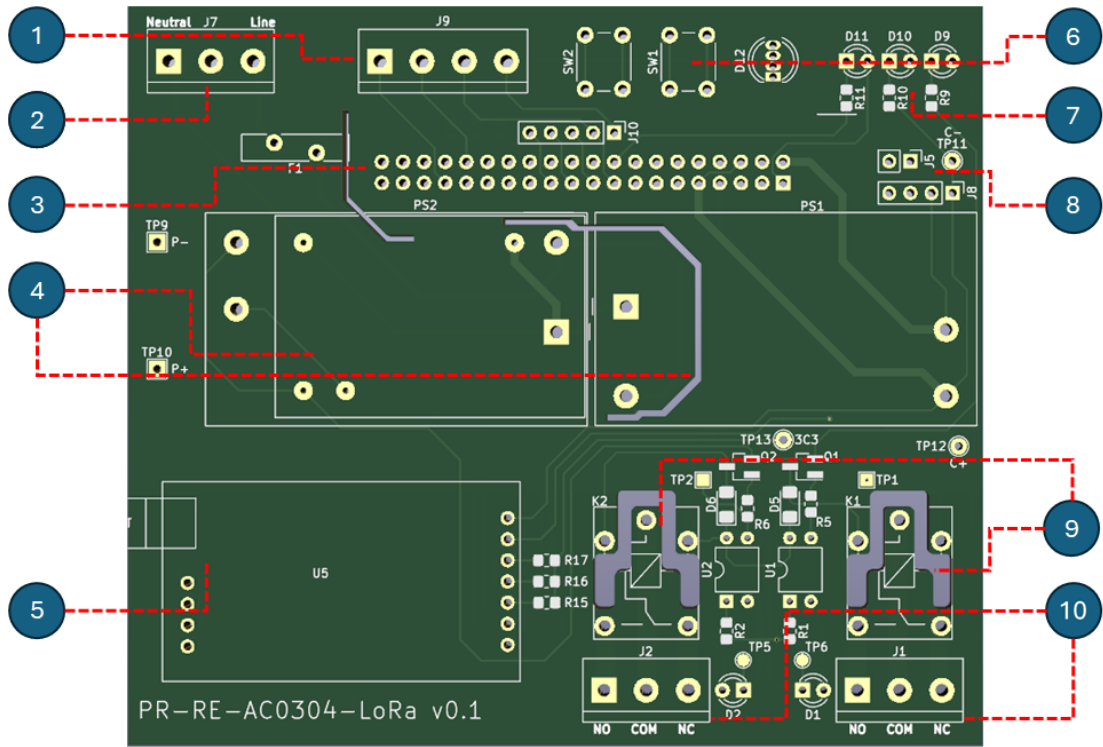


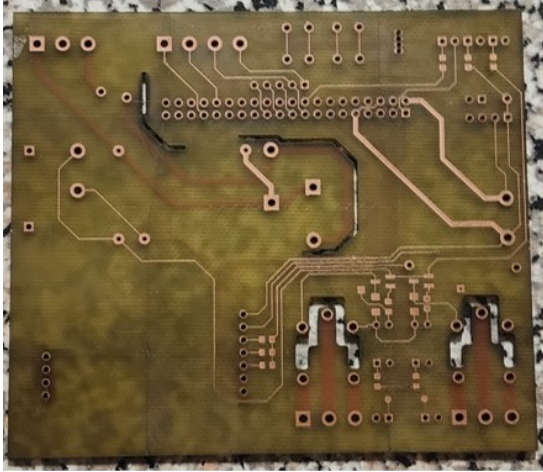
Figure 4.21: Base station printed circuit board functionalities. 1. General purpose inputs and outputs. 2. AC power input. 3. Raspberry Pi socket. 4. Dual 5 V power supply. 5. LoRa module socket. 6. General purpose buttons. 7. Status LEDs. 8. Fan socket. 9. 10 A Relays. 10. Relay terminal blocks

mass production or maintenance becomes easier due to the simplicity of replacing a MicroSD card.

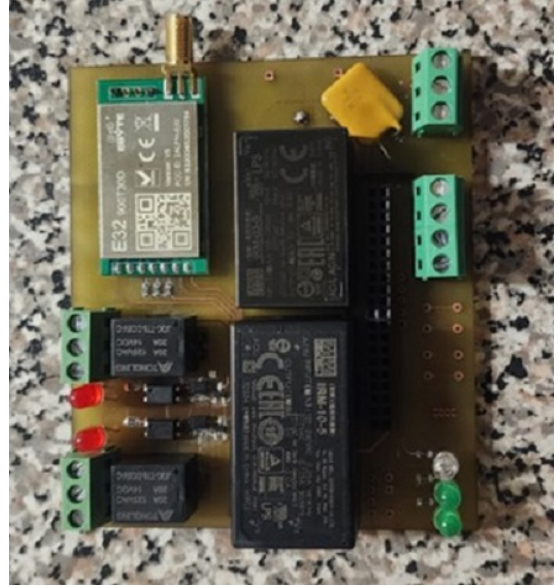
The API was developed using LoopBack4, a highly extensible Node.js and TypeScript framework for building APIs and microservices [73]. the simplicity of this framework allows the easy creation of methods to interact with the BS.

For this research three main methods were designed:

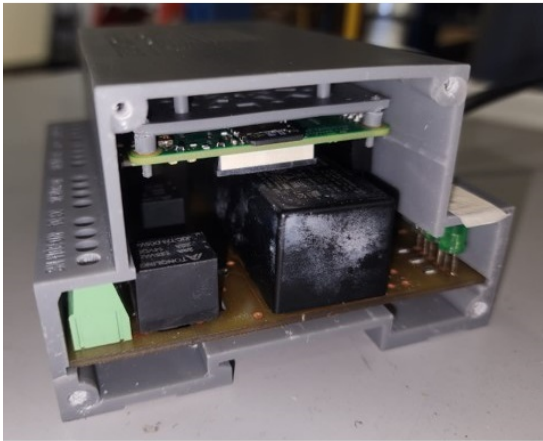
- **/esign/send/signId/speed/brightness:** This method will build a package to be sent throughout the LoRa module. The package will take the sign ID as signID, speed to be set as speed, and brightness to be set as brightness. Then



(a)



(b)



(c)



(d)

Figure 4.22: Base station manufacturing and assembly. a) Printed circuit board manufactured in the ARRC. b) Printed circuit board with electronic components. c) Printed circuit board inserted in the 3D printed enclosure. d) Base station completely assembled.

the software will build the package to be transmitted and communicated to the LoRa module to be spread over the air. This method does not expect an answer from the VSLS.

Example:

/esign/send/001/75/100

This will create a package with the structure **001:75:100** and will be sent by the UART to the LoRa module.

- **/esign/send/signId/speed:** This method will build a package to be sent throughout the LoRa module. The package will take the sign ID as signID, and speed to be set as speed. Then the software will build the package to be transmitted and communicated to the LoRa module to be spread over the air.

This method does not expect an answer from the VSLS.

Example:

/esign/send/003/25

This will create a package with the structure **003:25** and will be sent by the UART to the LoRa module.

- **/esign/sendack/signId/speed:** This method will build a package to be sent throughout the LoRa module. The package will take the sign ID as signID, and speed to be set as speed. Then the software will build the package to be transmitted and communicated to the LoRa module to be spread over the air.

This method expects a confirmation answer from the VSLS which is the same package.

Example:

`/esign/send/010/30`

This will create a package with the structure **010:30** and will be sent by the UART to the LoRa module. Then the process will expect the answer if not a time-out response will be produced.

The API is meant to work inside a private network, therefore security features were not analyzed by the scope of this document.

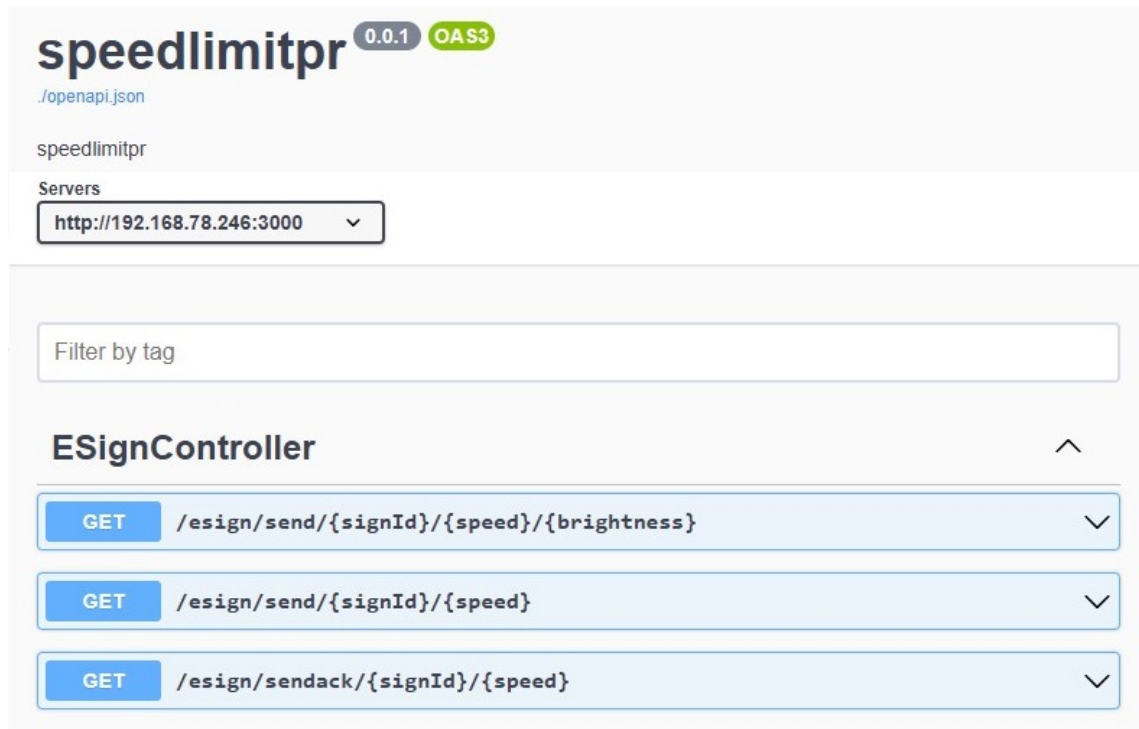


Figure 4.23: Tests of the BS API. The server was deployed using LoopBack 4, a highly extensible Node.js and TypeScript framework for building APIs and microservices.

4.3 Summary

In this Chapter, the design of the system and its components was realized. It can be summarized in two parts:

First, for the VSLS, an exhaustive component selection was carried out. The E-ink displays were selected under consideration of compliance with the MUTCD specification for the regular SLS. However, due to material availability, 9.7-inch E-ink displays were selected for the prototype. For the communications module, different LoRa transceivers were analyzed, and finally, the E-bite E32-900T30D was selected for its superior transmitting power and sensitivity, allowing distances up to 5 miles. Although this was not an explicit requirement of the project, a GPS module was selected to improve communication security. The Adafruit Ultimate GPS breakout V3 will be used to provide better data for internal RTC synchronization. Once all the modules were defined, a list of possible options for microcontrollers was presented. Based on the capabilities to control the modules, the number of pins, and novelty in the market, the ESP-32S3 was selected as the main core.

With these main components already decided, an analysis was conducted to determine the necessary capacity of the solar power system based on theoretical power consumption values from datasheets of the components. The solar system selected was the RPDC12-9-15, which includes the RemotePro 2.5 W continuous remote power system, a 15 W solar panel with mount, a 9 Ah battery, and an aluminum enclosure. This enclosure is not only useful for the solar system itself but will also support the front panel of the VSLS and contain the motherboard PCB to interconnect all the internal modules. The selected solar system was calculated to last up to 7 days alone with the battery.

Next, due to contrast constraints from the E-ink displays related to the retroreflective material in the regular Alternating Current (AC), the design of a front light

became necessary. Although the implementation of an LED light seems to be a step back in the use of E-ink, the fact that the front light is only needed during the night still allows for better expectations than a pure LED conventional VSLs.

The next step was the design of the PCB, including sockets for all the modules, to allow easy component interconnection and facilitate mounting in the enclosure. To finalize this Section, a detailed construction process for the VSLs is presented, starting with the 3D design of the front panel, incorporation of the E-ink displays and front light, assembly of the enclosure and PCB, and mounting on a pole for testing.

The second part of this Chapter is for the BS. Similar to the VSLs, an exhaustive analysis was conducted for the CPU selection, communications modules, auxiliary outputs, enclosure design, PCB design, and software and API functionalities.

Chapter 5

Preliminary Results

This Chapter will present the results of the field test of the system. Firstly, the communication results, such as range and response time, are presented and compared with theoretical specifications for the LoRa transmitter. This Section also includes the usage of the API designed for the base station. Next, the power consumption results of the variable speed sign are presented, with data gathered for different modes such as standby, transmission, or display refresh, and compared with theoretical estimations. Finally, the visibility of the variable speed limit sign will be tested, with comparisons made with a regular speed limit sign during both day and night. The experiment results will be presented accordingly.

5.1 Visibility Day And Night

One of the important characteristics of using E-ink as display technology is its high resolution and capability to recreate the shape of any desired typography. Therefore, specifications already set by the MUTCD can be complied with, and based on this assertion, visibility parameters should already be achieved. However, during the development of this research, two important factors affected this statement. First, during early system tests, a contrast issue was detected at night. According to the MUTCD, regulatory traffic signs must use retroreflective material on top. The

functionality of this material is to reflect as much light as possible toward the source without being affected by the incident angle. This characteristic, along with E-ink displays, which do not have the same property, considerably affected visibility, producing black shadows when car lights pointed directly at the sign, worsening even more with high beams. The second challenge was the size of the displays available in the market. Although the height of the display matches, the width is insufficient to cover the resulting size of the letters. As explained before, the typography varies according to the posted number; for example, the total width of an “11” is not the same as a “44”, which are the widest numbers in the typography. Details of these two challenges can be seen in Figure 5.1.

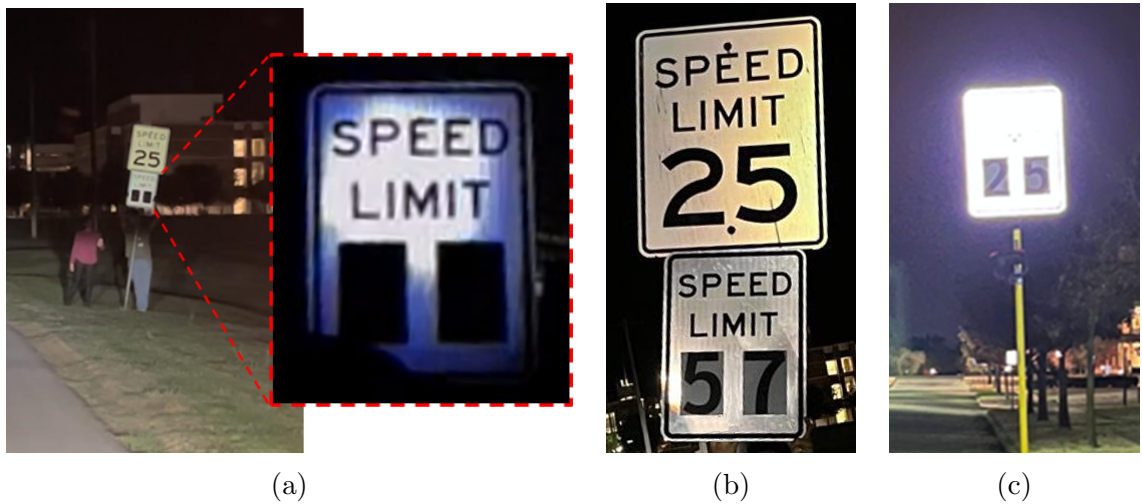


Figure 5.1: Contrast issues arising from the combination of the retroreflective material and E-ink displays. a) A detailed view of the initial test reveals that the E-ink displays are completely obscured due to the reflection of surrounding material. b) As the car approaches and the light is not directly focused, it becomes easier to read the numbers, however, visibility is still insufficient for proper functionality. c) The use of high beams only exacerbates the problem.

Regarding the contrast problem, the approach taken was to remove the retroreflective material at the front and implement a front light to overcome the lack of

visibility at night. This concept was already detailed in Chapter 4, Section 4.1.6, where the two proposed solutions were presented: the first one, a front light embedded in the frame, and the second one, an external spotlight to provide visibility at night. For the challenge of the size, the solution is to use a larger size of displays; however, this increases the price considerably, and for this initial prototype, the display already selected in Chapter 4 will be used.

To design a proper visibility test, two studies were used as references. The first one is a report that analyzes the information as a source of distraction in DMS [30]. It analyzes when a DMS is more distracting for a driver on highways according to parameters such as the distance, colors, message, and size of letter. The second one analyzes the visibility of highway guide signs [31] and is focused on improving the legibility of them according to the distance.

Based on this information, the test was designed to compare the legibility of the designed VSLS versus a regular SLS. To do this, the following steps will be realized:

- In a controlled street, a VSLS or SLS will be installed.
- A car will be used to drive the street, carrying a volunteer for the test.
- The car will must reach the display speed limit in the VSLS or SLS deployed.
- Finally, the volunteer will use a stopwatch to measure the times according to the following procedure:

1. The volunteer will start the timer of the stopwatch when they are able to see the posted number.
2. Next, they will press the lap button when they are able to read the phrase "Speed Limit" on the sign.

3. Finally, they will stop the timer once the car is next to the sign.

By doing this we will be able to get three parameters:

1. The current speed of the car.
2. The total time to read the number in the sign.
3. The total time to read the phrase in the sign.

By using this information we can determine the distance by using the formula

$d = v \times t$, where (d) is for the distance, (v) for velocity, and (t) for the elapsed time.

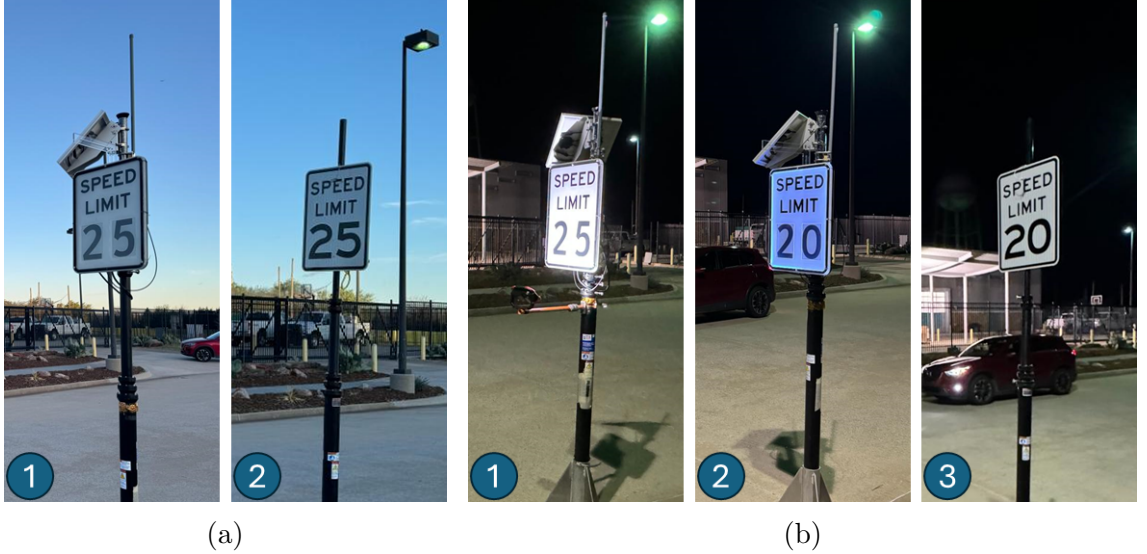


Figure 5.2: Visibility tests setups. a) During the day, VLS (1) and SLS (2) are deployed, and each test is conducted separately to avoid confusing the participants and producing biased data. b) During the night, three configurations are possible: VLS with spotlight (1), VLS with front light (2), and SLS (3). Similar to the day-time setup, each configuration is deployed individually to prevent confusion among participants. Due to street restrictions and sign sizes, three speeds were used: 15, 20, and 25 mph.

Due to the size of the signs and the street dimension, the maximum speed limit usable was 25 mph; then, two speeds of 20 and 15 mph were included to have more data to compare. This test was realized during the day and during the night. During the day, the VLS had no need of front illumination, and that is why only two trends

are visible in the results for the night. However, during the night, the front light was necessary, and both types of illuminations were used, creating three trends in the graphics. The implemented speed limits and the setup can be seen in Figure 5.2

After collecting and processing the data, the plots in Figure 5.3d were generated, leading to the following conclusions. Visibility tests were conducted during both daytime and nighttime, with participants using stopwatches to measure distances while traveling at speeds of 15, 20, and 25 mph. In the daytime tests (Figure 5.3a), differences in visibility between VSLs and SLS were evident, mainly due to the smaller size of the VSL display. Comparing the readability of the "Speed Limit" phrase (Figure 5.3b) helped confirm this observation. Nighttime tests, which included spotlight and front light configurations, showed different behaviors (Figure 5.3c). Comparing VSL-frontlight versus SLS revealed similar trends observed during the day, but changing the illumination source to compare VSL-spotlight versus SLS resulted in closer and similar results. This similarity is due to the darker nighttime environment, which helps focus on well-illuminated signs. Finally, the results of reading the phrase at night followed the same trend as during the day (Figure 5.3d), as participants needed to be closer to the sign to read the phrase, making the illumination source more effective as they got closer.

5.2 Power Consumption And Battery Autonomy

In this section, the power consumption of the VSL will be analyzed. Data such as the consumption of individual components and the consumption of the complete

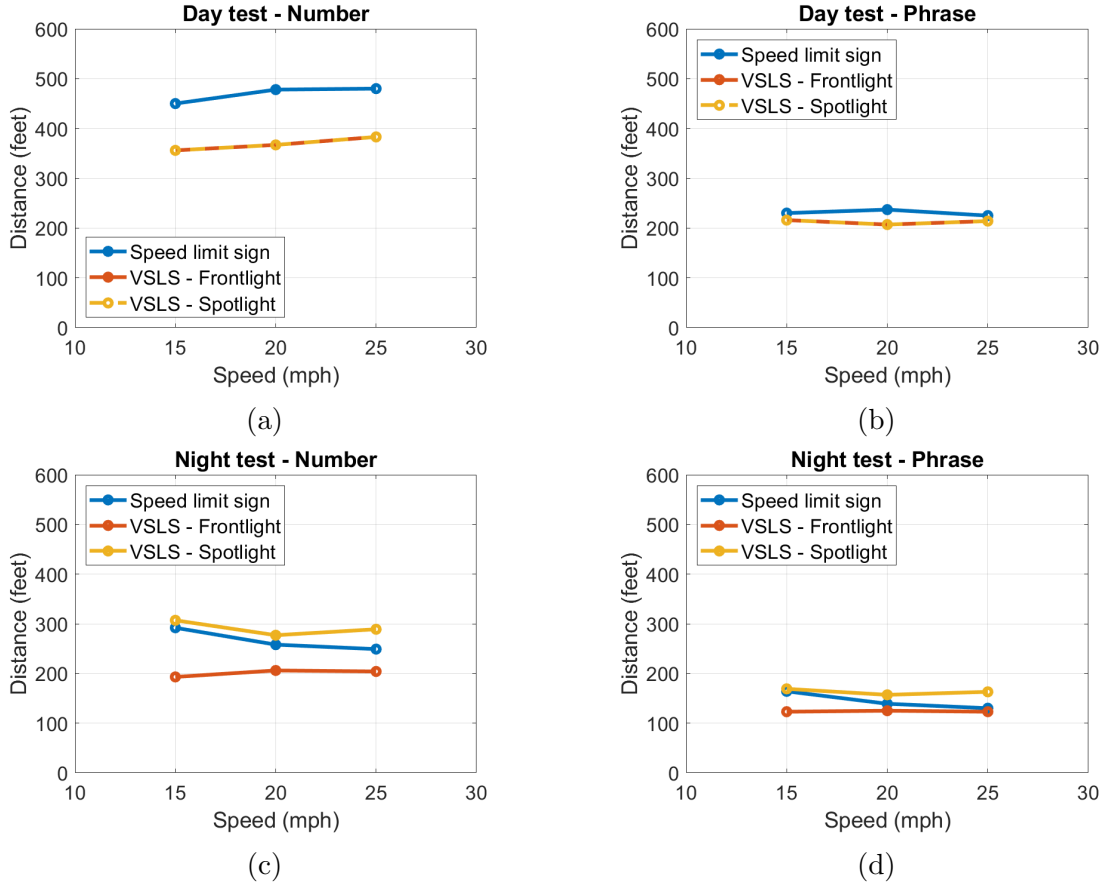


Figure 5.3: Visibility test results showing the measured legibility distance for a specific traveling speed. Tests were conducted during the day (Top figures) and at night (Bottom figures). In these tests, participants were asked to take time measurements using a stopwatch. They were placed in a car traveling at a constant speed. When they were able to read the number posted on the sign, they started the stopwatch. Then, when they were able to read the “Speed Limit” phrase, they marked a lap on the stopwatch. Finally, when they passed next to the sign, they stopped the timer. The total time divided by the traveling speed is the “Number” distance, and the last lap time divided by the traveling speed is the “Phrase” distance. The speeds used for this test were 15, 20, and 25 mph. The plots show the average distances for each speed. a) During the day the visibility of the number comparing the VLS versus SLS is noticeable. The size of the displays does not cover the same width size as a regular SLS; therefore, this difference is entirely coherent. b) To corroborate that the display size was affecting the results in (a), the phrase “Speed Limit” is used as a point of reference because it is the same size in the SLS and the VLS. In this case, as expected, the trend of the graphics are more similar. c) During the night, the two illuminations can be tested. Results show that the use of a spotlight has similar trends to a regular SLS. Unlike during the day in (a), this is determined by the fact that having a dark environment allows more focus on the well-illuminated sign. d) Similar to (b), the same size of the phrase allows for similar trends for the three different configurations.

PCB, as well as consumption in different modes such as standby, receiving, and transmitting, will be measured and compared with theoretical expectations.

The power consumption tests were performed at the Advance Radar Research Center (ARRC) facilities. The main controller of the VSLS was taken to the laboratory, and using a controlled voltage power supply, the consumption of the individual elements was measured inside the PCB board. The setup built in the lab is depicted in detail in Figure 5.4.

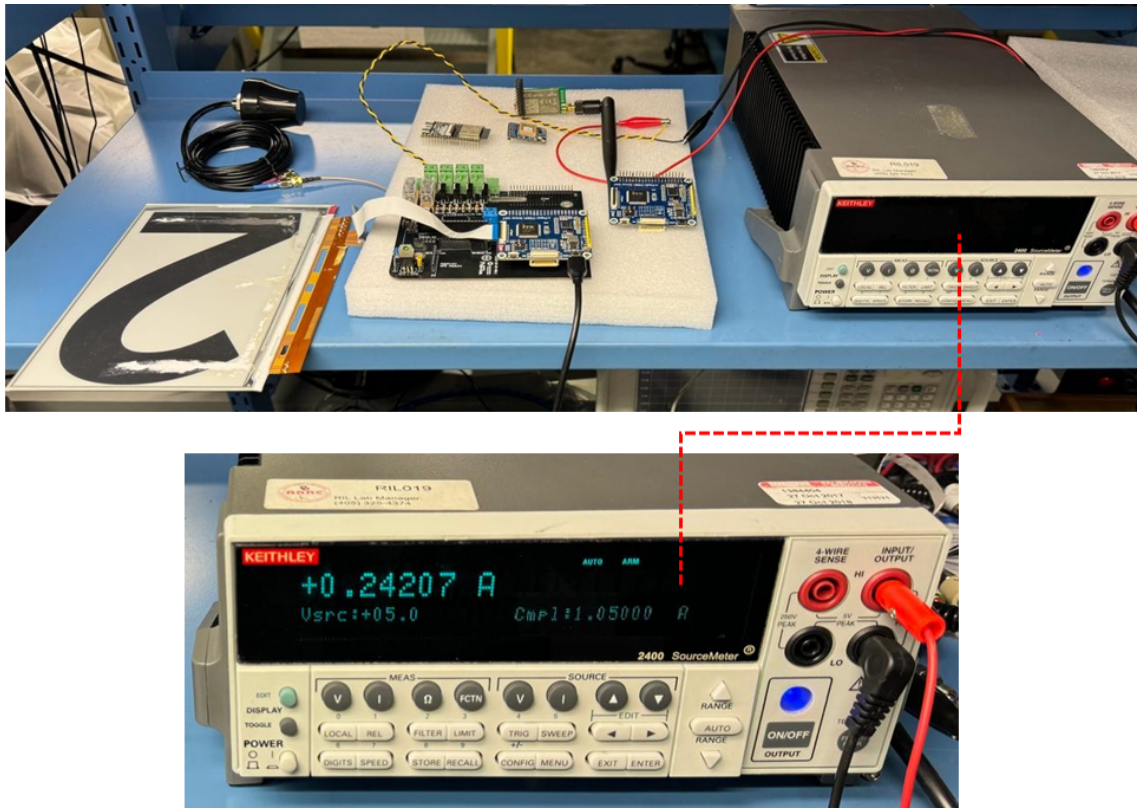


Figure 5.4: Setup for power consumption measurements for individual components in the VSLS PCB. The Keithley 2401 SMU Low Voltage SourceMeter Instrument was used to measure the current at 5 V fixed. The main PCB was connected to the power supply and component by component where tested. For the LoRa transmitter a combination of microcontroller and module was needed to measure the transmitting power during a package sending.

In Table 5.1, the results of the measurements using the Keithley 2401 SMU Low Voltage SourceMeter Instrument can be observed and are compared against theoretical values used during the design stage, which can be found in Tables 4.3 and 4.4. Although the instrument provides the current consumption, the Table will show the values in watts derived from the product of the measured current and the set voltage, which was 5 volts.

Table 5.1: List of the measured power of different VLS components.

Item	Standby power theoretical (W)	Standby power measured (W)	Transmit power theoretical (W)	Transmit power measured (W)
9.7 E-Ink and driver	0.3	0.2	0.6	0.225
LoRa module	15×10^{-6}	0.07	3.25	3.5
GPS module	26.85×10^{-6}	0.055	0.125	0.125
External GPS antenna	0	0.02	0.066	0.2
Microcontroller	26.85×10^{-6}	0.1	0.0783	0.3475
Total	0.3	0.445	4.119	4.398

From Table 2.1.3, we can see that the measured transmit power is very similar to the theoretical value: 4.398 watts compared to 4.119 watts, respectively. This indicates a good estimation. However, a significant discrepancy is noticeable in standby power consumption, where the measured power is almost double the theoretical value. Upon deeper analysis, several considerations emerged. Firstly, idle LEDs in the GPS module, and microcontroller seem to be impacting the measurement but are not considered in the datasheet. Secondly, the theoretically ultra-low power consumption for the LoRa module listed disconnects and turns off the RF receiver,

thus preventing communications establishment. To address this, the datasheet was reviewed, revealing a receiving mode with an expected power consumption of 0.125 mW. Comparing this with the measured 70 mW, we can conclude that we are within the expected performance parameters.

Finally this results are used to calculate the lasting days and compared with estimations made in Section 4.1.5:

Table 5.2: Power consumption analysis of the VLS components using the measured power values (Active Mode).

Item	Qty	Time per task (s)	Occurren- ces per day	Total time (h/day)	Power con- sumption (W)	Consump- tion (Wh/day)
9.7 E-ink display and driver	2	2	24	0.0133	0.225	0.01
LoRa module	1	14	24	0.0933	3.5	0.33
GPS module	1	60	3	0.05	0.125	0.01
External GPS antenna	1	60	3	0.05	0.2	0.010
Microcontroller	1	60	24	0.4	0.3475	0.14
Total						0.49

As we did before, the total power consumption per day will be given by the addition of the standby consumption plus the consumption when the elements are performing a task:

$$\text{Total power consumption} = \text{Active mode} + \text{Standby M=mode}$$

$$\text{Total power consumption} = 0.49 \text{ Wh/day} + 15.42 \text{ Wh/day}$$

$$\text{Total power consumption} = 15.91 \text{ Wh/day}$$

Table 5.3: Power consumption analysis of the VLS components using the measured power values (Standby Mode).

Item	Qty	Standby time (h)	Standby power (W)	Standby consumption (Wh/day)
9.7 E-ink display and driver	2	23.987	0.2	9.6
LoRa module	1	23.907	0.07	1.67
GPS module	1	23.95	0.055	1.32
External GPS antenna	1	23.95	0.02	0.48
Microcontroller	1	23.6	0.1	2.36
Total				15.42

The solar system selected for the design has a 12V battery and 9 Ah capacity or 108 Wh. Using this battery capacity as reference we can compare the 15.91 Wh/day measured consumption against the 14.76 Wh/day theoretical consumption:

$$\text{VLS Lasting theoretical (days)} = \frac{\text{Battery capacity}}{\text{Power consumption per day}}$$

$$\text{Lasting theoretical (days)} = \frac{108, \text{Wh}}{14.76, \text{Wh/day}}$$

$$\text{Lasting theoretical (days)} = \frac{108}{14.76}$$

$$\text{Lasting theoretical (days)} \approx 7.32, \text{days}$$

$$\text{Lasting measured (days)} = \frac{108 \text{Wh}}{15.91 \text{Wh/day}}$$

$$\text{Lasting measured (days)} = \frac{108}{15.91}$$

$$\text{Lasting measured (days)} \approx 6.78 \text{days}$$

5.3 Communications, Range, and Response Time

To measure the range and response time results of the system, the base station will be deployed in the ARRC facilities, and a main PCB from a VSLS along with an antenna will be installed in a truck. A route will be designed to cover the theoretical coverage area using the truck, which in this case will act as a VSLS. When the VSLS PCB receives a package from the BS, it will respond with an acknowledgment package. Since this test solely pertains to range and response time, there is no need for the battery and front panel with the E-Ink displays. For more precise data in this specific test, the acknowledgment package from the VSLS to the BS will include the GPS location, which is typically discarded.

As previously explained in Section 2.2.4, LoRa was selected as the communication protocol for this research. In Section 4.1.2, during the design phase, the LoRa module E32-900T30D was chosen. According to its datasheet [53], due to its 30 dBm transmitting power, it can reach distances of up to 8 km or 5 miles under the following conditions: clear and open area, 5 dBi antenna gain, antenna height of 2.5 m, and air data rate of 2.4 kbps. The conditions will be recreated as closely as possible to validate the theoretical data.

The BS was installed on the top floor of the ARRC because it was the place with the clear and open area possible. Since it was deployed indoors, the device was placed on a table in an area equipped with available ethernet connections and power outlets. The antenna was mounted on the ARRC terrace using the fiberglass handles as a base or mounting structure. This setup can be observed in Figure 5.5.



Figure 5.5: Installation of the BS for range tests: 1. The ARRC facilities were used to mount the BS. 2. The BS was placed on a table on the top floor where ethernet connections and power outlets were available. 3. The antenna was mounted on the terrace, with fiberglass handles serving as the mounting structure.

Since the handles are not made from metallic material, no interference with the antenna is expected.

The VSLS PCB was installed in a truck, the antenna was mounted on a structure at the back, and a computer was used to check the serial data output. It will also have a connection to ARRC's VPN to monitor the BS while the measurements are being taken. This setup can be seen in the Figure. 5.6

The locations to be covered will extend to a radius of 5 miles. A tour will be planned to reach the farthest theoretical points possible. This will be limited by the fact that we are using a car for this purpose, restricting us to highways and avenues. However, this approach will provide us with insights into the range of



Figure 5.6: Installation of the VSLS PCB in a truck for the range and response time tests: 1. An ARRC truck is prepared for the tests. 2. The VSLS PCB is placed on the dashboard in a way that the internal GPS antenna has a clear line of sight to the sky, and its serial output is connected to a computer to log the data. 3. The same antenna used for the final prototype is mounted on a structure in the bed of the truck.

our communications in a highway environment, which typically offers clear sightlines throughout. During the tour, data was collected at specific positions where packages were received, and this information was recorded. With all this data, four maps can be generated: The theoretical distance, the planned tour, the received data, and the overlap of all of them. This information can be seen in Figure 5.7.

The results depicted in Figure 5.7 demonstrate that environmental conditions reduce the range of LoRa communications. Therefore, the installation points must be analyzed to ensure the clearest possible view from the BS to the VSLS. This may pose a more common problem in cities due to the density of buildings. However, the ultimate goal of this project is implementation on highways, where achieving

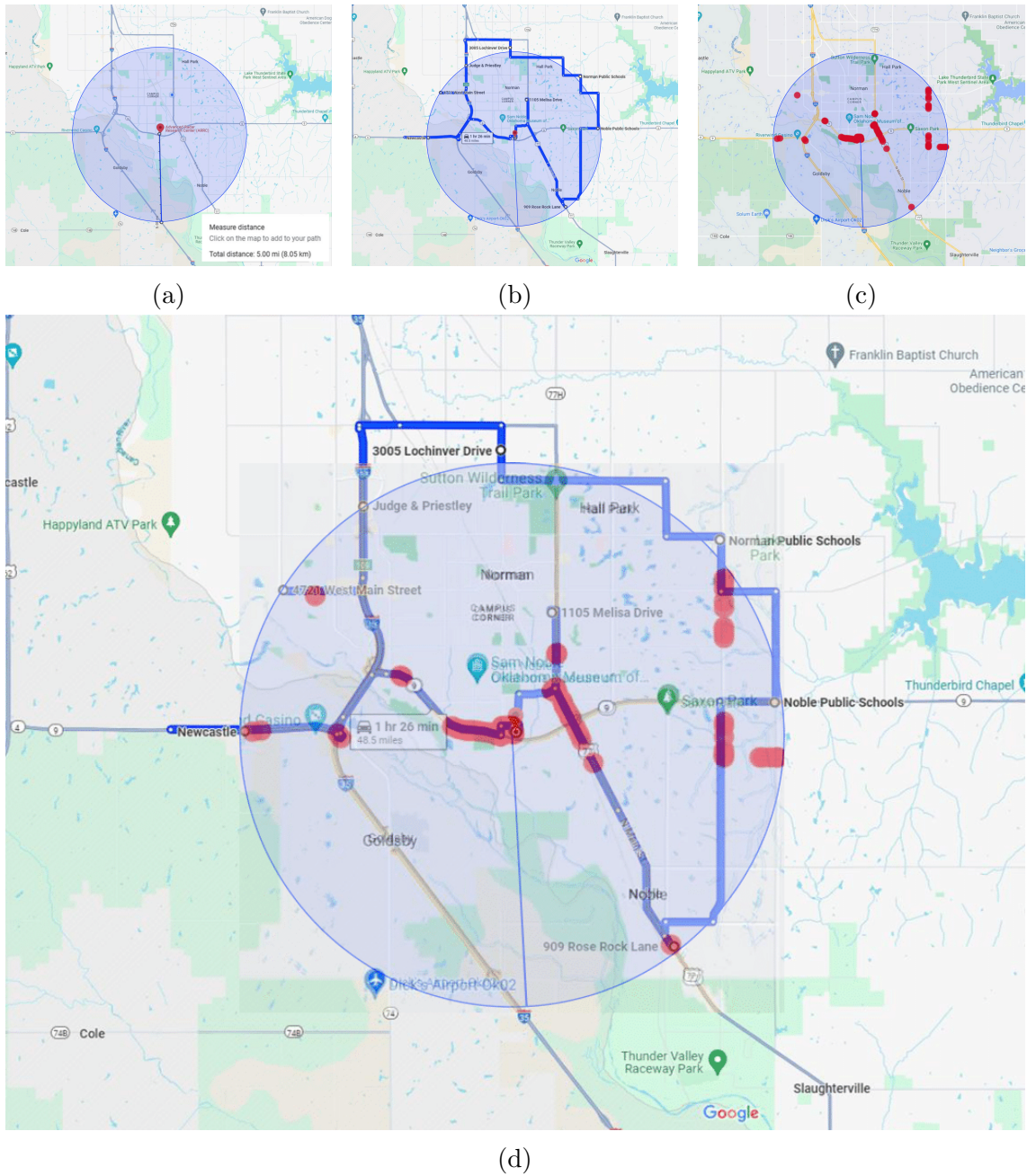


Figure 5.7: Planning and results of the range and response time test using a map of Norman city from Google Maps. a) The theoretical range of 8 miles round is shown in a translucent blue circle, with the base station located at the center of the circle in the ARRC facilities. b) The planned tour in the truck is shown along the highways, covering the farthest possible points. c) The places where data was received by the VLS PCB are marked as red points. d) The overlay of the three maps shows coherence between the captured data and the travel performed. Theoretical ranges were reached in certain locations.

a clear line of sight from BS to VSLs is easier due to lower building density, an expedited view of the road, and the advantage of using illumination poles or other structures to install the BS as high as possible. Curves, valleys, mountains, and other elements could be detrimental to communications; therefore, a thorough analysis of the topography will be the determining factor in achieving good results on highways. In [36], it is stated that the cost-benefit analyses showed, in their case, that the placement of VSLs with an average density of 1.0 mi had the best benefit/cost effect. In our best-corroborated scenario of 5 miles round, if the BS is installed at an intersection with straight crossing highways, we should be able to control up to 40 signs, considering both ways.

From the data acquired from this test and the results obtained by overlapping maps in Figure 5.7d, the following information can be highlighted:

- **Number of packages transmitted:** 1245
- **Time between packages:** 5 seconds
- **Number of packages received:** 152
- **Average package receiving time:** 4.2 seconds
- **Maximum distance reached:** 5 miles

5.4 Summary

This Chapter presented the results of field tests conducted on the system. Three main characteristics of the system were tested. First, the visibility of the VSLs was assessed. A specific test was designed to compare the capability of a road user to

read a VSLS and a regular SLS under different conditions. The test was conducted during both day and night, using three different sets of speeds. The results were presented in different plots based on distance measurements and the readability of displayed information. Essential findings included differences in visibility between the VSLS and SLS during the day, primarily due to display size that was different from the regular SLS typography. However, during the night, the use of the spotlight configuration for the VSLS showed similar performance to a regular SLS. Similar trends were observed in reading the "Speed Limit" phrase during both day and night tests.

Second, the power consumption and battery autonomy were analyzed. The power consumption of the VSLS, including data for individual components and overall power consumption in different modes such as standby, receiving, and transmitting, was analyzed in the laboratory of the ARRC. With this information, a comparison of theoretical design values against measured ones could be made, showing the following results: Total power consumption (Theoretical) = 14.76 Wh/day, Total power consumption (Measured) = 15.91 Wh/day, Theoretical lasting (days) = 7.32 days, Measured lasting (days) = 6.78 days. The tests showed that similar values were reached, but two main findings could explain this difference. First, status LEDs in the microcontroller, GPS, and display drivers were not taken into account in the initial calculation, as the data provided by the datasheets doesn't include them. Second, the ultra-low power consumption mode of the LoRa module doesn't allow the reception of packages; therefore, the receiving mode should be used, which has significantly different power consumption.

Finally, communication range and response time tests were conducted. For these tests, the goal was to compare the theoretical range distance against a real implementation of the system. During the test, the BS was deployed in the ARRC facilities, and the main PCB of a VSLS was installed on a truck. A tour based on the theoretical maximum range was planned, and all the transmission and reception data were captured. Key findings showed the following results: Number of packages transmitted = 1245, Time between packages = 5 seconds, Number of packages received = 152, Average package receiving time = 4.2 seconds, Maximum distance reached = 5 miles. The theoretical distance provided in datasheets was 5 miles, therefore the objective was achieved. Furthermore, using the captured data, detailed maps were generated, and the results demonstrated that environmental conditions can impact the LoRa communication range, highlighting the importance of a clear line-of-sight from the BS to the VSLS.

Chapter 6

Conclusion

The presence of VSL systems along highways considerably improves driving conditions, but their implementation is complex and costly due to the traditional technologies used for the VSLs. This is what has driven the development of this thesis. Implementation of these systems in the United States can be traced back as early as the 1960s, first in Michigan [16] and then in New Jersey. Both examples used technologies such as incandescent bulbs, neon lights, mechanical moving parts, and miles of buried cables to interconnect the systems. Over time, the advent of LED technology allowed for more efficient, multipurpose signs. An example of this is the ATDM system implemented in Washington by WSDOT in 2010 [24]. Although technology has improved, the system in general still remains bulky, complex, and requires larger structures for mounting. The implementation of E-ink technology and LoRa communications in the work that has been done so far has shown to overcome all these issues, being a system energetically efficient, compact, and easy to deploy.

Characteristics for a VSL made out of E-ink displays were defined. Based on achieving the same results as conventional SLS, standards for size and dimensions were taken from the MUTCD. After implementing the tradeoffs due to the contrast between the retroreflective surface of conventional SLSs and the available size of E-ink screens to display the speed limit numbers, the results of visibility tests

showed that the use of this technology is feasible for this kind of systems. Similar visibility between this VSLS and a conventional SLS during both day and night was corroborated for the size of 18 x 24 inches developed in this research, providing good insights for the future design of larger sizes of signs.

The ultra-low power consumption of the system was proven, with a lasting time of up to 7 days using a 12 V 9 Ah Lead Acid battery. The best-case scenario of power consumption for other options in the market, as exposed in Chapter 2, Section 2.1.3, shows a power consumption as small as 3.5 W or 84 Wh/day just for the LED display in a conventional VSLS. On the other hand, the power consumption of the proposed VSLS has been measured as little as 15.91 Wh/day, being just 20 % of the power consumption of the traditional option.

This thesis has laid down requirements and tradeoffs for the implementation of a modern VSL system and has established the proof of concept. With the proposed system, characterized by its use of E-ink displays for the VSLS and LoRa modules for communication, significant advancements have been made in terms of energy efficiency, compactness, and ease of deployment. The integration of these technologies addresses the complexities and costs associated with traditional VSLS implementations, crafting a more efficient and user-friendly solution in traffic management systems. The implementation of an API interface in the BS allows remote access for the end users and easy integration with any web service.

Bibliography

- [1] United States Department of Transportation, “Manual on Uniform Traffic Control Devices (MUTCD).”
<https://mutcd.fhwa.dot.gov/hm/2003/html-index.htm>, 2023.
- [2] Daktronics, “Intelligent Transportation Systems (ITS) Dynamic Message Signs (DMS).” <https://www.daktronics.com/en-us/products/its-dynamic-message-signs>, 2024.
- [3] Barco Products, “Cloud Connected Radar Signs.”
<https://www.barcoproducts.com/cloud-connected-radar-signs>, 2019.
- [4] United States Department of Transportation, “Proven safety countermeasures - Variable Speed Limits (VSL).” <https://safety.fhwa.dot.gov/provencountermeasures/variable-speed-limits.cfm>, 2020.
- [5] Wanco Inc., “Folding Frame Radar-Speed Trailers.”
<https://www.wanco.com/product/folding-frame-speed-trailer/>, 2023.
- [6] ALFAZETA, “Electromagnetic large 7-segment displays.” <https://flipdots.com/en/products-services/large-7-segment-displays/>, 2016.
- [7] TAPCO, “LegendViz.”
<https://www.tapconet.com/product/legendviz-traffic-sign>, 2024.
- [8] TAPCO, “BlinkerSign Flashing LED SPEED LIMIT Sign R2-1.”
<https://www.tapconet.com/product/blinkersign-flashing-led-speed-limit-sign-r2-1>, 2024.
- [9] Skyline Products, “ITS-Grade Variable Speed Limit Signs.” <https://www.skylineproducts.com/transportation/variable-speed-limit/>, 2016.
- [10] E Ink, “Our Company, Who we are, About Us .”
<https://www.eink.com/about?company>, 2021.
- [11] E Ink, “Electronic ink how it works..”
https://www.eink.com/tech/detail/How_it_works, 2016.
- [12] E Ink, “E Ink Applications.” <https://www.eink.com/application>, 2023.
- [13] United States Department of Transportation, “Speed Limit Basics.” <https://highways.dot.gov/safety/speed-management/speed-limit-basics>, 2017.

- [14] United States Department of Transportation, “USLIMITS2 A Tool to Aid Practitioners in Determining Appropriate Speed Limit Recommendations.” <https://highways.dot.gov/safety/speed-management/uslimits2>, 2023.
- [15] V. Idoni and WTOL Television, “Variable speed limit signs becoming more common.” <https://www.wtol.com/article/news/variable-speed-limit-signs-becoming-more-common/512-3ccb477b-fd47-44f6-b96e-453aa9baa0af>, 2019.
- [16] United States Department of Transportation, “Synthesis of Variable Speed Limit Signs - FHWA Office of Operations.” <https://ops.fhwa.dot.gov/publications/fhwahop17003/index.htm>, 2017.
- [17] United States Department of Transportation, “Enhancing Active Transportation and Demand Management (ATDM) with Advanced and Emerging Technologies and Data Sources - FHWA Office of Operations.” <https://ops.fhwa.dot.gov/publications/fhwahop19010/>, 2020.
- [18] ERICSSON GROUP, “The transistor an invention ahead of its time.” <https://www.ericsson.com/en/about-us/history/products/other-products/the-transistor--an-invention-ahead-of-its-time>, 2019.
- [19] Texas Instruments, “The chip that changed the world.” <https://news.ti.com/the-chip-that-changed-world>, 2020.
- [20] General Electric, “LED Inventor Nick Holonyak Reflects on Discovery 50 Years Later.” <https://www.ge.com/news/press-releases/led-inventor-nick-holonyak-reflects-discovery-50-years-later-0>, 2022.
- [21] Vintage Scoreboards, “Comiskey Park’s ”exploding” scoreboard was installed by Bill Veeck, who owned the Chicago White Sox from 1959 to 1961 (and later from 1976 to 1981). You can tell how it was added on to, to add Sox-O-Gram messages and more out-of-town scores..” <https://twitter.com/VintScoreboards/status/1269333658332098560>, 2024.
- [22] Chicago History Museum, “Pinwheel From Comiskey Park’s Monster Scoreboard.” <https://images.chicagohistory.org/asset/29178/>, 2016.
- [23] P. Weckesser and J. Kraft, “New jersey turnpike automatic traffic surveillance and control system performance observation,” *Transportation Research Record*, no. 816, 1981.
- [24] Washington State Department of Transportation, “Active Traffic and Demand Management.” <https://wsdot.wa.gov/travel/operations-services/active-traffic-and-demand-management>, 2024.

- [25] Georgia Department of Transportation, “Variable Speed Limits To Take Effect Sunday On Top Half Of I- 285.” <https://www.dot.ga.gov/PartnerSmart/Public/PressReleases/VSL--9-30-14.pdf>, 2014.
- [26] Georgia Department of Transportation, “Variable Speed Limits (VSL).” <https://www.youtube.com/watch?v=Hvb2ngNA1ME>, 2014.
- [27] AA Roads, “Interstate 285 - Atlanta Perimeter Highway.” <https://www.aaroads.com/guides/i-285-ga/>, 2016.
- [28] The Atlanta Journal-Constitution, “Speed limit signs malfunctioning on I-285.” <https://www.ajc.com/blog/commuting/speed-limit-signs-malfunctioning-285/HvpQxLFsNW8pULqWOAqBKM/>, 2015.
- [29] United States Department of Transportation, “Standard Highway Signs.” https://mutcd.fhwa.dot.gov/ser-shs_millennium_eng.htm, 2024.
- [30] United States Department of Transportation, “Information As A Source of Distraction.” <https://www.fhwa.dot.gov/publications/research/safety/15027/004.cfm>, 2015.
- [31] D. Gordon, “Legibility of Highway Guide Signs.” <https://onlinepubs.trb.org/Onlinepubs/trr/1982/855/855-001.pdf>.
- [32] SWARCO, “Variable Speed Limit Signs (VSLS).” <https://www.swarco.com/products/signs/dynamic-message-signs/variable-speed-limit-signs-vsls>, 2023.
- [33] LED Lighting Solutions, “Solar Powered Variable Speed Limit Driver Feedback Sign - SP550.” <https://ledlighting-solutions.com/solar-powered-variable-speed-limit-driver-feedback-sign.html>, 2019.
- [34] Carmanah, “SPEEDCHECK - Variable Speed Limit Sign Data Sheet.” https://carmanah.com/wp-content/uploads/Carmanah_DATA_SPEEDCHECK-VS.pdf, 2023.
- [35] Hill and Smith Inc., “VSL Variable Speed Limit Trailer.” https://hillandsmith.com/wp-content/uploads/2022/03/STA-137_VSL.pdf, 2019.
- [36] C. Xu, Z. Li, Z. Pu, Y. Guo, and P. Liu, “Procedure for determining the deployment locations of variable speed limit signs to reduce crash risks at freeway recurrent bottlenecks,” *IEEE Access*, vol. 7, pp. 47856–47863, 2019.
- [37] Polycase, “Outdoor Junction Boxes - Waterproof Electrical Junction Boxes.” <https://www.polycase.com/junction-boxes>, 2017.

- [38] SIEMENS, “Logo! basic modules.”
<https://www.siemens.com/global/en/products/automation/systems/industrial/plc/logo/logo-basic-modules.html>, 2024.
- [39] Oklahoma Department of Transportation, “Ok traffic.”
<https://oktraffic.org/#/map>, 2024.
- [40] IEEE, “IEEE Get Program - IEEE 802.15: Wireless Specialty Networks.”
<https://ieeexplore.ieee.org/browse/standards/get-program/page/series?id=68>, 2024.
- [41] Ginsei Corporation, “Wireless Sensor Network (WSN).”
<http://www.ginsei-jp.com/wsn.html>, 2024.
- [42] T-Mobile, “4G LTE and 5G Coverage Map - Cell Phone Coverage.”
<https://www.t-mobile.com/coverage/coverage-map>, 2024.
- [43] SEMTECH, “LoRa Platform for IoT.” <https://www.semtech.com/lora>, 2023.
- [44] Arduino.cc, “The Arduino Guide to LoRa and LoRaWAN.”
<https://docs.arduino.cc/learn/communication/lorawan-101/>, 2023.
- [45] Oklahoma Historical Society, “The Encyclopedia of Oklahoma History and Culture - Climate.”
<https://www.okhistory.org/publications/enc/entry?entry=CL015>, 2024.
- [46] United States Energy Information Administration, “One of the largest wind farms in the United States was completed in Oklahoma last spring.”
<https://www.eia.gov/todayinenergy/detail.php?id=54739>, 2024.
- [47] Oklahoma Secretary of Energy and Environment, “Renewable Energy.”
<https://ee.ok.gov/resource/renewable-energy/>, 2020.
- [48] United States Department of Transportation, “Standard Alphabets For Traffic Control Devices.”
<https://mutcd.fhwa.dot.gov/shse/alphabets.pdf>, 2023.
- [49] E Ink, “E Ink Online Shop - ePaper Display Kits.”
<https://shopkits.eink.com/en/product>, 2024.
- [50] Waveshare, “e-Paper, E Ink Display, EPD.”
<https://www.waveshare.com/product/displays/e-paper.htm>, 2024.
- [51] Reyax Technology Corporation, LTD, “RYLR998 868/915MHz LoRa Antenna Transceiver Module.” <https://reyax.com/products/RYLR998>, 2024.

- [52] Digi-Key Electronics, “RA-02.” <https://www.digikey.com/en/products/detail/ai-thinker/RA-02/16694420>, 2015.
- [53] EBYTE, “E32-900T30D SEMTECH’s LoRa solution Wireless Serial Port Transmitter LoRa Modulation 30dBm 868/915MHz 1W CDEBYTE Antenna DIP 8km.” <https://www.cdebyte.com/products/E32-900T30D>, 2022.
- [54] Semtech, “Semtech’s LoRa Devices Integrated Into REYAX Technology’s New Antenna Transceiver Module.” <https://www.semtech.com/company/press/semtechs-lora-devices-integrated-into-reyax-technologys-new-antenna-transceiver-module>, 2022.
- [55] Ai-Thinker Technology, “Ra-01/Ra-02 LoRa Module User Manual.” <https://docs.ai-thinker.com/en/lora/man>, 2024.
- [56] Adafruit Industries, “Adafruit Ultimate GPS Breakout - 66 channel w/10 Hz updates - PA1616S.” <https://www.adafruit.com/product/746>, 2021.
- [57] Espressif Systems, “ESP8266EX Datasheet.” https://www.espressif.com/sites/default/files/documentation/0a-esp8266ex_datasheet_en.pdf, 2023.
- [58] Espressif Systems, “ESP32 Series Datasheet.” https://www.espressif.com/sites/default/files/documentation/esp32_datasheet_en.pdf, 2024.
- [59] Espressif Systems, “ESP32-S3 Series Datasheet.” https://www.espressif.com/sites/default/files/documentation/esp32-s3_datasheet_en.pdf, 2023.
- [60] Digi-Key Electronics, “ESP8266-DEVKITC-02D-F.” <https://www.digikey.com/en/products/detail/espressif-systems/ESP8266-DEVKITC-02D-F/9649768>, 2015.
- [61] Digi-Key Electronics, “ESP32-DEVKITM-1.” <https://www.digikey.com/en/products/detail/espressif-systems/ESP32-DEVKITM-1/13532113>, 2024.
- [62] Digi-Key Electronics, “ESP32-S3-DEVKITM-1-N8.” <https://www.digikey.com/en/products/detail/espressif-systems/ESP32-S3-DEVKITM-1-N8/15295895>, 2022.
- [63] Tycon Systems, “RPDC12-9-15.” <https://tyconsystems.com/homepage/shop/rpdc12-9-15/>, 2024.
- [64] Digi-Key Electronics, “12V-MB-CW-12M.” <https://www.digikey.com/en/products/detail/inspired-led,-llc/12V-MB-CW-12M/5866510>, 2017.

- [65] Digi-Key Electronics, “FIT0876.” <https://www.digikey.com/en/products/detail/dfrobot/FIT0876/15997367>, 2015.
- [66] Digi-Key Electronics, “CL-L104-C6N-F.” <https://www.digikey.com/en/products/detail/citizen/CL-L104-C6N-F/5820585>, 2024.
- [67] Walmart, “Hyper Tough 1200 Lumen LED Rechargeable Portable Work Light, Red, Black.” <https://www.walmart.com/ip/Hyper-Tough-1200-Lumen-LED-Rechargeable-Portable-Work-Light-Red-Black/739410692>, 2019.
- [68] LattePanda, “LattePanda V1 - The smallest intel atom x86 windows Single Board Computer.” <https://www.lattepanda.com/lattepanda-v1>, 2018.
- [69] Libre Computer, “Le Potato AML-S905X-CC.” <https://libre.computer/products/aml-s905x-cc/>, 2019.
- [70] Raspberry Pi Ltd, “Raspberry Pi 4 Model B specifications.” <https://www.raspberrypi.com/products/raspberry-pi-4-model-b/specifications/>, 2024.
- [71] Raspberry Pi Ltd, “Raspberry Pi 5 - The everything computer. Optimised..” <https://www.raspberrypi.com/products/raspberry-pi-5/>, 2024.
- [72] Digi-Key Electronics, “AZ943-1CH-5DE.” <https://www.digikey.com/en/products/detail/american-zettler/AZ943-1CH-5DE/14307553>, 2015.
- [73] OpenJS Foundation, “LoopBack 4 A highly extensible Node.js and TypeScript framework for building APIs and microservices..” <https://loopback.io/>, 2017.

Base station PCB schematics

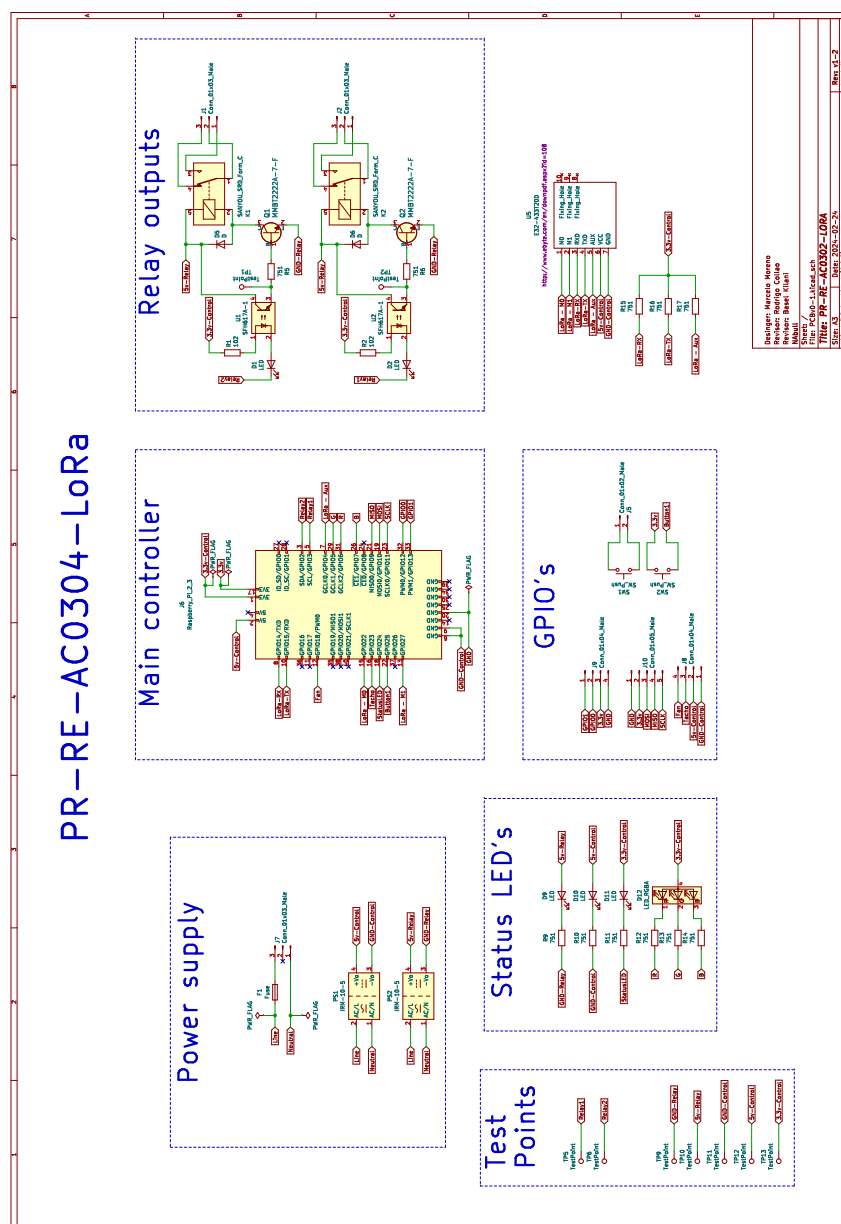


Figure A.1: Base station electronics schematic diagram.

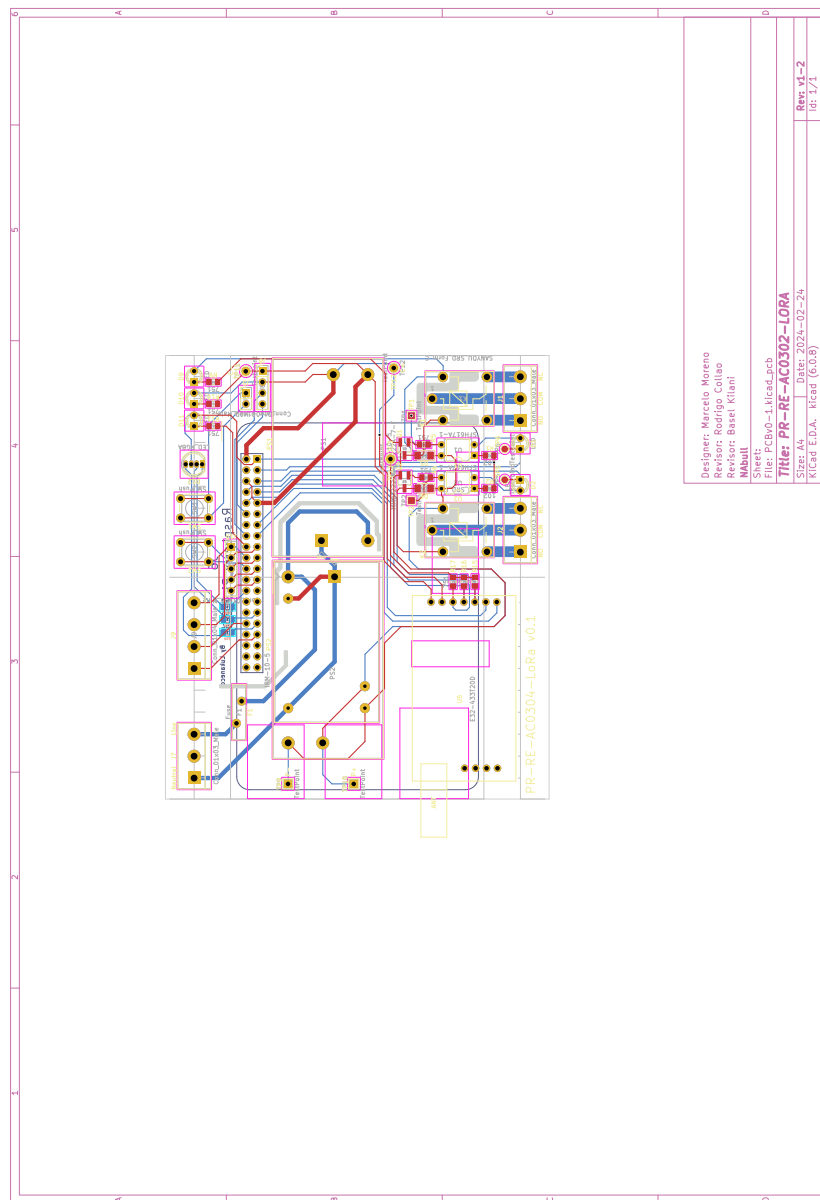


Figure A.2: Base station printed circuit board diagram.

Appendix B

Variable speed limit sign PCB schematics

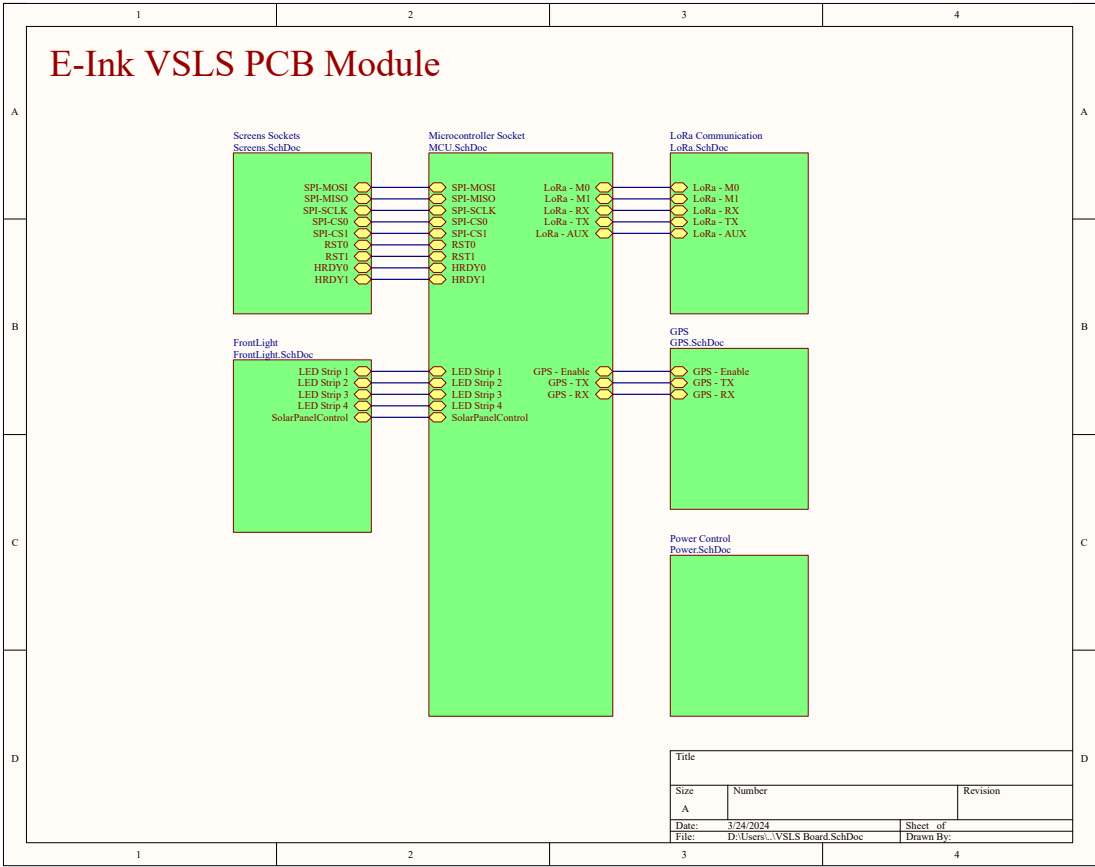
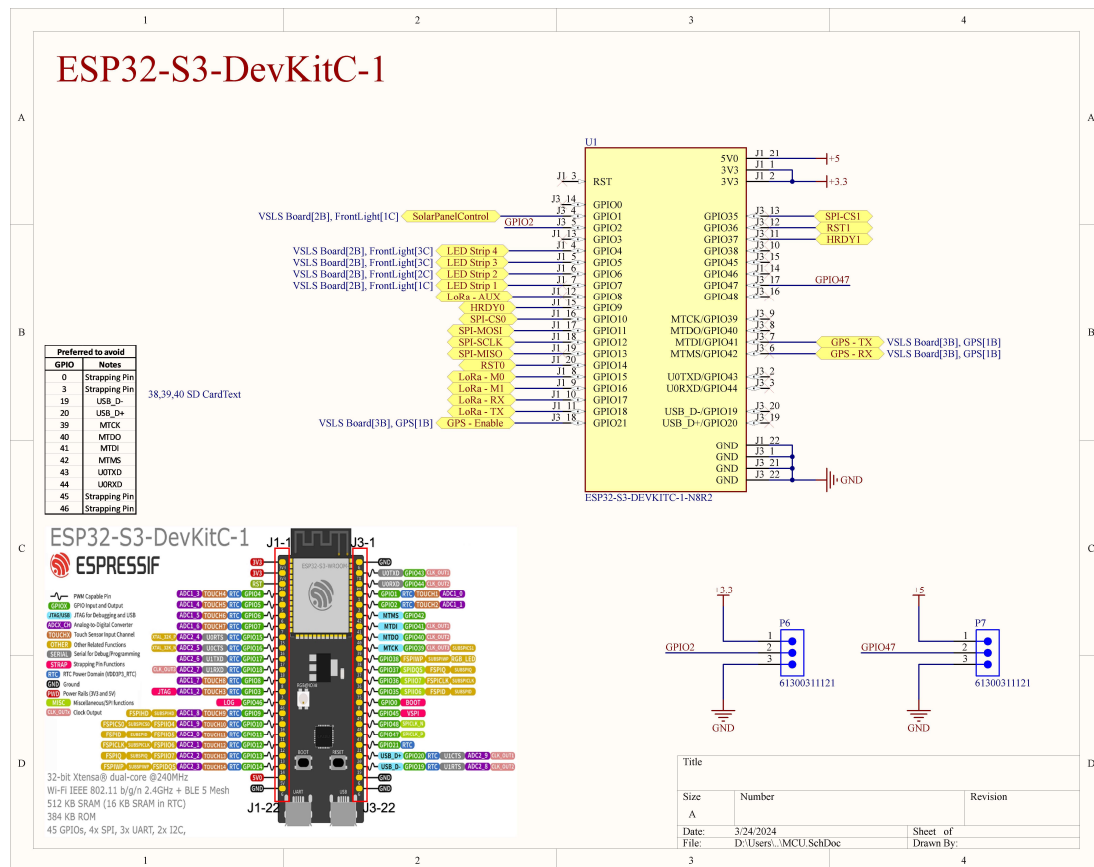


Figure B.1: Variable speed limit sign electronics schematic diagram page 1.



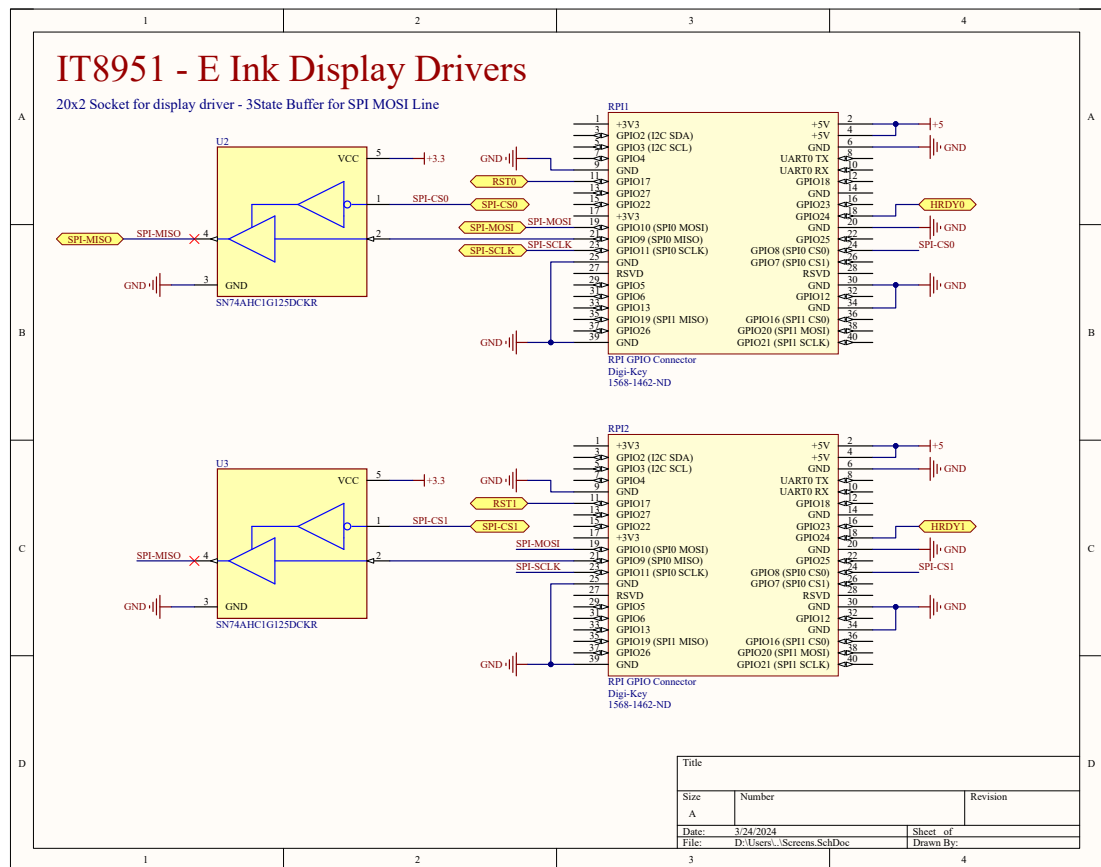


Figure B.3: Variable speed limit sign electronics schematic diagram page 3.

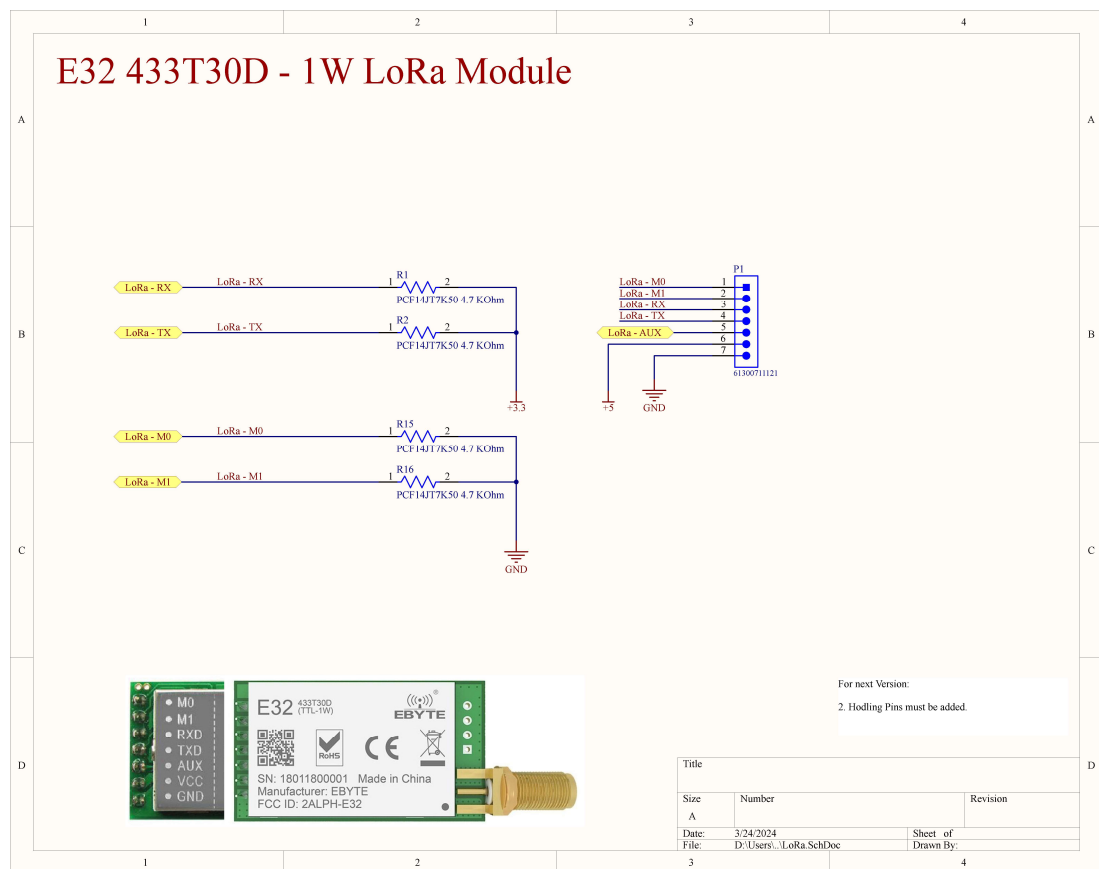


Figure B.4: Variable speed limit sign electronics schematic diagram page 4.

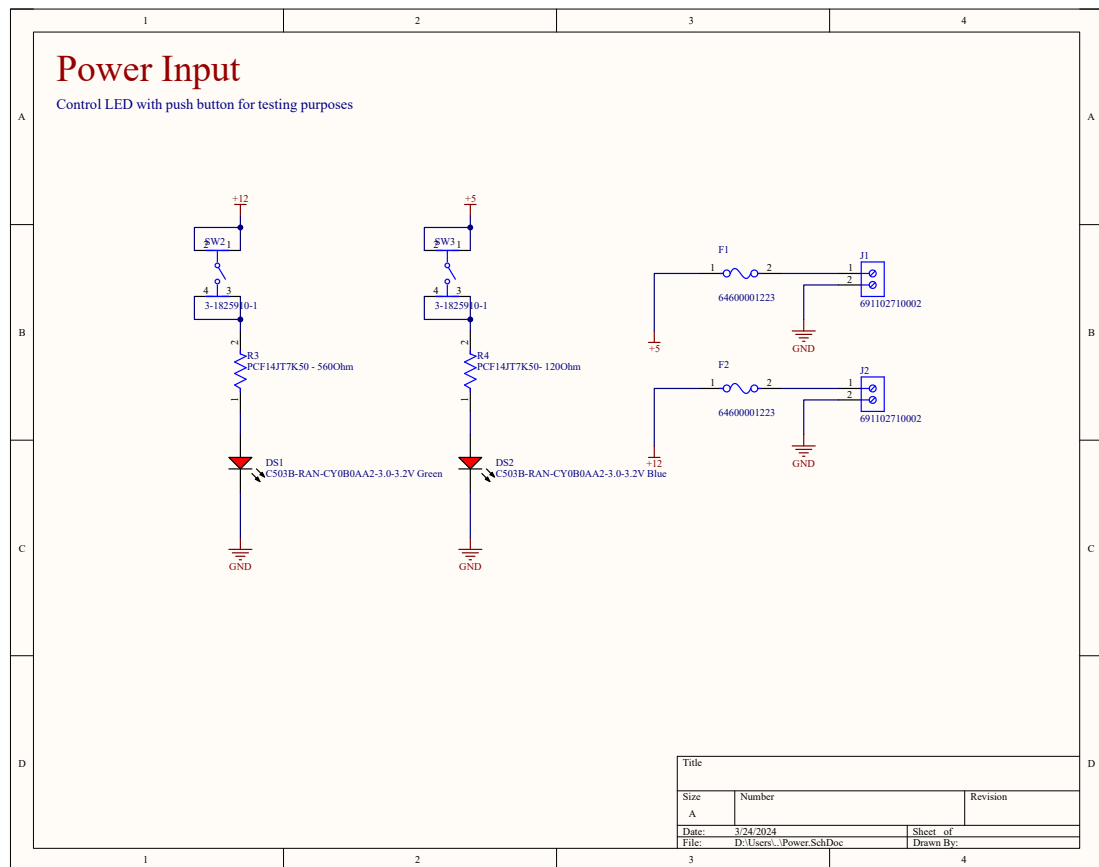


Figure B.6: Variable speed limit sign electronics schematic diagram page 6.

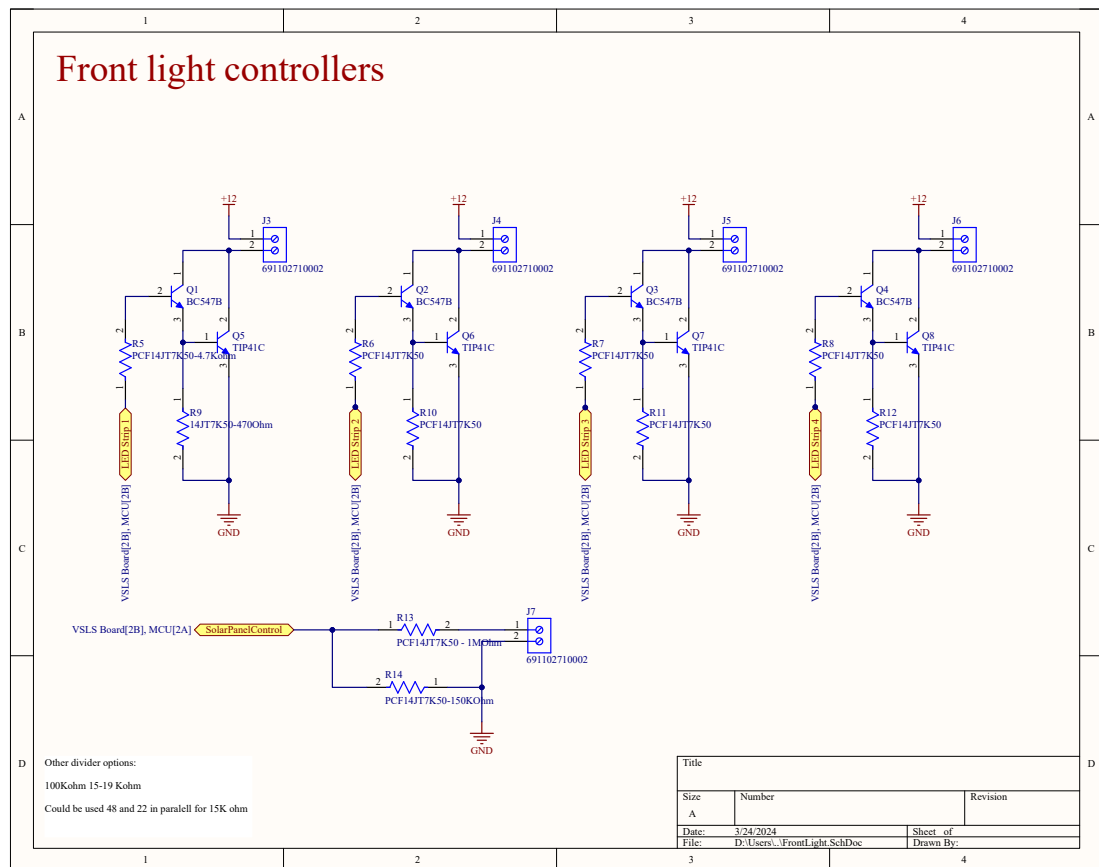


Figure B.7: Variable speed limit sign electronics schematic diagram page 7.

