Developing a Collision Warning and Collision Avoidance System for WYDOT Snowplows

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1 INTRODUCTION

According to the National Highway Traffic Safety Administration (NHTSA), rear-end collisions are most frequent in traffic crashes causing most traffic injuries and property damages. A rear-end collision typically occurs when the leading vehicle is stopped or travelling at a very slow speed. In addition to this, driver inattention/distraction, following too close, and poor visibility due to adverse weather are the contributing factors behind the majority of such collisions. Most of the automotive companies adopted an emerging safety technology called forward collision warning and collision avoidance system to assist drivers in avoiding head-on crashes, as illustrated in Figure 1. However, rear-end collision warning technologies are still limited to the automotive industry.

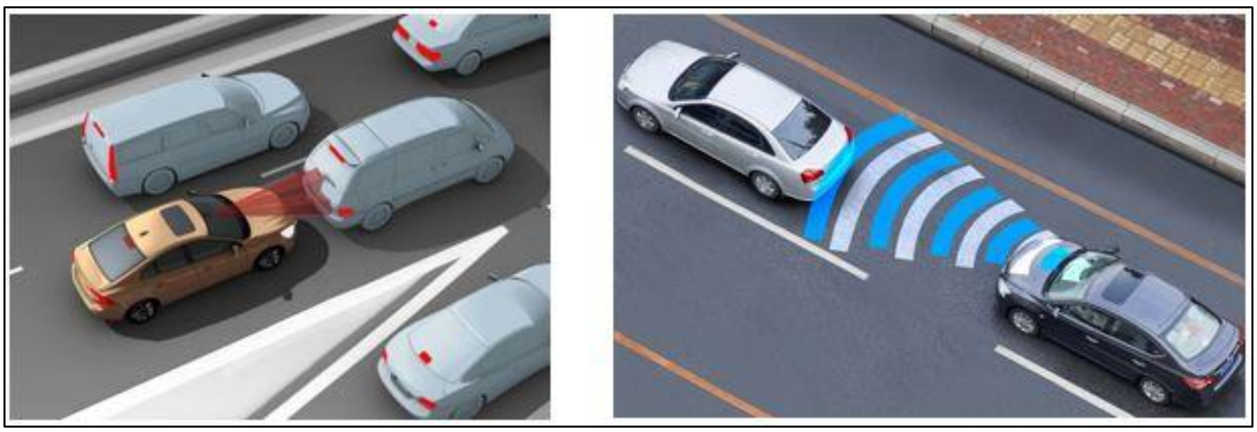


Figure 1: An Example of Forward Collision Avoidance System.
(Source from left: Thiel, 2017; Data Bridge Market Research, 2019)

State Department of Transportation's (DOT's) maintenance vehicles typically operate in hazardous traffic conditions and pose a rear-end collision risk for motorists following them. For instance, snow removal and de-icing using winter maintenance trucks (commonly called snowplows or plow trucks) elevate the risk of rear-end collision between the plow and trailing vehicles as these operations are typically performed at reduced speeds directly in the roadway travel lanes, often under reduced visibility conditions. Collisions involving snowplows and other slow-moving maintenance vehicles in work-zone areas can result in substantive property damage, vehicle repair, and medical costs.

2 PROBLEM STATEMENT

Wyoming Department of Transportation (WYDOT) own and operate various maintenance vehicles for conducting various operations. Winter maintenance of roadways is one of the major challenges for WYDOT since traffic safety and operations are severely affected by the harsh winter climate throughout the state. WYDOT spends a significant portion of its total budget on winter road maintenance. In 2015, WYDOT's winter maintenance costs were about $21 million, but between 2016 and 2020, the costs have fluctuated between $26 million and $32 million annually (Fredregill, 2020). A large number of snowplows are usually out during the winter season, maintaining the roads by clearing the snow and putting down materials to facilitate traffic movement. WYDOT's snowplows typically travel slower at speeds of 25 to 45 mph, depending on conditions (WYDOT, 2021). While operating snowplows in adverse weather, motorists often end up with rear-end crashes for poor visibility due to the disturbance of the snow. As evidenced by the February 2021 snowstorm which resulted in 10 snowplow rear strikes within five days, demonstrated in Figure 2 (The Trucker, 2021).

Public driving into a snow cloud, not realizing they are following too close to the plow and hitting the backend of the operating truck. Although WYDOT officials urge motorists to stay a safe distance behind a plow until it is safe to pass, the occurrence of snowplow strikes has become regular over the past few years. Based on the WYDOT crash database, 121 crashes involving snowplows were recorded for the last five years (2016-2020), resulted in 239 vehicles involvement. Figure 3 provides the year-wise breakdown of those crashes. As seen, there were

22 crashes for the 2015-2016 winter season, 13 crashes for 2016-2017, 25 for 2017-2018, 31 for 2018-2019, and 30 for 2019-2020, indicating an increasing trend. In other words, an average of 24.2 snowplow trucks is hit each year. In the case of a two-lane road, motorists passing a snowplow on the right side often end up colliding with a wing plow that sticks out from the side of the truck.

Figure 2: Collision of Snowplow near Rawlins on Interstate-80.
(Source: The Trucker, 2021)

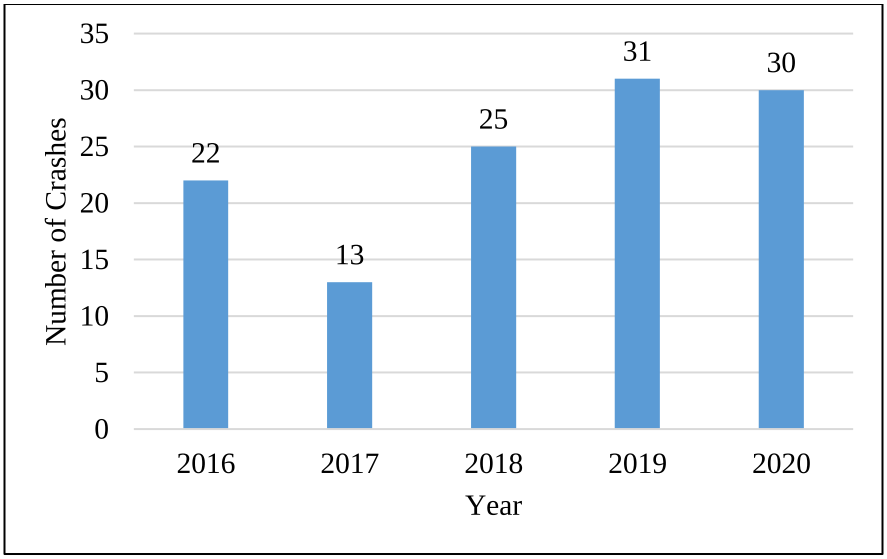


Figure 3: Year-wise Crashes involving Snowplows from 2016-2020.

WYDOT's other pavement operations such as highway stripping, sweeping, pothole filling, and friction testing also involve slower-moving vehicles, as illustrated in Figure 4. These slower-moving vehicles at work zones also face a considerable threat to rear-end crashes due to the absence of properly equipped collision warning and collision avoidance systems. Therefore, developing low-cost rear-end collision warning systems for WYDOT maintenance vehicles should be one of the major concerns nowadays.

Figure 4: An Example of Slower-Moving WYDOT Vehicles.
(Source: WYDOT District 4 Facebook Page)

The color and type of warning lights are always critical components to warn the drivers that they are approaching a maintenance vehicle. The Wyoming state legislature has recognized the need for different colored warning lights to prevent rear-end collisions with snowplow trucks. In 2017, the Wyoming legislature passed a law allowing the use of one or more flashing blue, white, or amber lights, visible from five hundred feet in front of the vehicle (Wyoming, 2017). However, some recent studies recommended the use of green warning lights to detect and recognize the snowplow (Ohio DOT, 2012; Michigan DOT, 2018, 2020; Missouri DOT, 2018), which could be more efficient for the motorists in order to respond appropriately. Therefore, evaluating the type and appropriate color or a combination of the color of warning lights should be necessary to maximize the conspicuity of WYDOT's maintenance vehicles.

3 OBJECTIVES

The main goal of this study is to develop a collision warning and collision avoidance system for WYDOT snowplow trucks and other maintenance vehicles –

- To maximize the capability of preventing crashes and
- To minimize the severity of crashes.

In support of this broader goal, the study is aimed to fulfill the following five objectives:

1. Develop a rear-end collision warning and collision avoidance system using multiple sensors based on the outcomes from an extensive safety analysis, simulation models, and the responses from the surveys.
2. Evaluate the performance of color and type of warning lights in reducing crashes involving snowplows and other maintenance vehicles.
3. Test the performance and effectiveness of the prototype using a WYDOT's winter maintenance truck equipped with the technology and proposed warning lights.
4. Perform a benefit-cost analysis of the proposed collision warning and collision avoidance system before the full-blown implementation of the final products.
5. Develop a guideline on how the subset of multiple sensors with warning lights from the proposed warning system can be transferred and employed in other slow-moving WYDOT maintenance vehicles to reduce the potential risk of rear-end collisions.

To develop a rear-end collision warning and collision avoidance system, the required number and type of sensors (e.g., rear-facing Lidar or Radar) will be developed and tested on the maintenance vehicles. The potential idea is to have technology that will activate if a vehicle enters within a designated distance behind the maintenance vehicle. Once a vehicle is within this designated area, the LED lights would become larger and brighter than the normal lights on the back. If this did not alert the trailing vehicle behind the maintenance vehicle and it continued to get closer, a warning light with a rear-facing air horn would sound to alert both vehicles. Another advantage of this system would provide advance warning to plow operators considering differential speeds, minimum acceptable distance, and appropriate reaction time. While receiving the warning signal, the plow operator could raise the plow to reduce the disturbance of the snow cloud. This action would allow the oncoming vehicle to see the plow and avoid a collision. Also, the advance warning by developing the minimum acceptable distance and adequate perception-reaction time would allow the plow operator to move away from the travel lane and avoid a collision.

4 LITERATURE REVIEW

Historically, a major portion of research on improving winter maintenance technology was focused on its operational aspects, such as evaluating optimal routing strategies for snowplows considering historical and forecasted traffic and weather data (Moss, 1970; Lemieux and Gampagna, 1984; Robinson et al., 1990; Perrier et al., 2007). Automatic vehicle location (AVL) and road weather information systems (RWIS) are fundamental components of effective winter maintenance programs, which allow for real-time management of plowing and deicing operations. Figure 5 shows an example of AVL and control center maintained for real-time management of plowing and deicing operations. However, such technologies cannot be considered user-friendly since they need frequent calibration and modification (Kociánová, 2015; Schneider et al., 2017). Another attempt in improving the operational characteristics of winter maintenance includes an Internet of Things (IoT)-based approach with low-cost sensors gathering meteorological data. However, the limitation of this approach lies in high deployment and maintenance costs (Chapman et al., 2014).

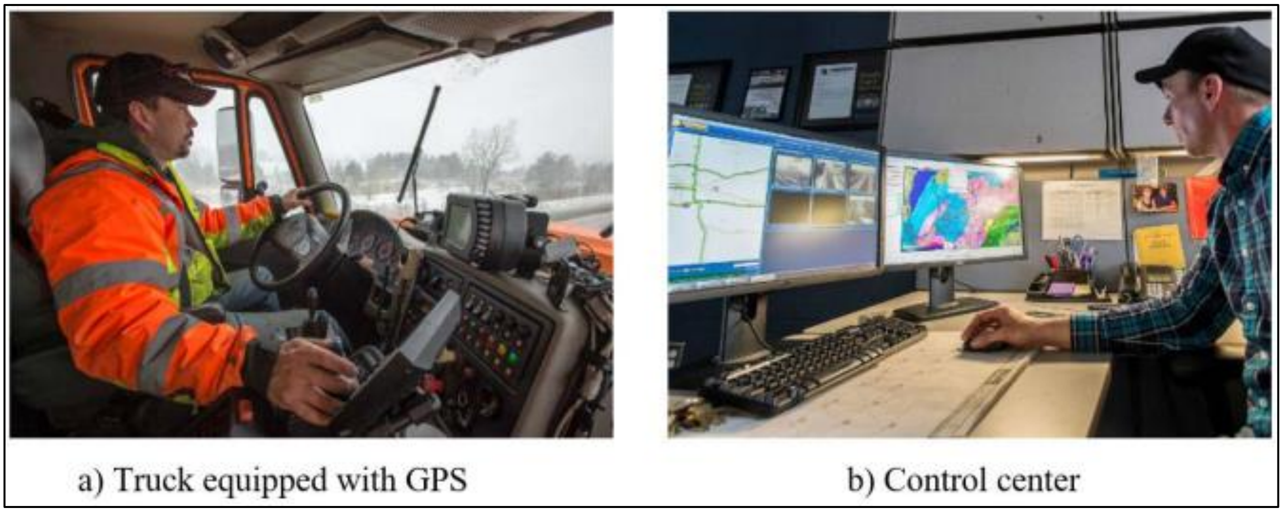


Figure 5: Automatic Vehicle Location (AVL) for Winter Maintenance Vehicles.
(Source: Michigan DOT, 2018)

Despite significant progress in the area of the operational and logistical aspects of winter maintenance, limited research was documented on its influence on traffic safety. Roadway condition is one of the statistically significant factors in causing crashes during the winter season as reported by Usman et al. (2010). Other contributing factors of a snowplow crash may include alcohol or drug use, cell phone use, fatigued driver, manual distraction, driving at high speed, following too close, and poor visibility.

In response to address these concerns, several state DOTs have invested in technology and public outreach programs to assist in creating a safer operational environment for plow trucks. One of the simplest mitigation strategies is to provide education to motorists on how to drive on icy or snow-covered roads, especially around plow trucks. As part of this education program, motorists are advised to accelerate and decelerate gradually, allowing extra time and distance to stop (Iowa DOT, 2017; Michigan DOT, 2017). They are also advised not to follow snowplows too closely and not to drive into the cloud of snow as it could be a snowplow ahead of them (WYDOT, 2021).

Since 2012, various state DOTs have experimented using different types and colors of warning lights to prevent rear-end collisions with snowplow trucks. The results found a reduction in crashes involving snowplow trucks when colored, flashing lights are employed. Also, LEDs were found to work best as warning lights due to their long-lasting, less cost, and closest to actual daylight characteristics. Amber and bright blue warning lights were found as the most preferable for snowplow operations (SnowWolf, 2018). However, recent advancement in this area is the use of green warning lights adopted by the Michigan Vehicle Code to increase visibility over traditional amber warning lights due to the sensitivity of the human eye to the green/yellow spectrum (Heqimi et al., 2017). Figure 6 shows some examples of using warning lights on winter maintenance vehicles.

Figure 6: Warning Lights of Snowplow Truck.
(Source from left: SnowWolf, 2018, Michigan DOT, 2018)

Another method for improving safety during winter maintenance activities is the in-cabin assistive systems for winter maintenance truck (WMT) drivers. A typical example of how a projector and image combiner provides imagery of the roadway under low visibility conditions is demonstrated in Figure 7(a). These displays provide information about the environment, roadway, and weather conditions by collecting data from antennas and sensors installed on the vehicle, as shown in Figure 7(b) (Gorjestani, et al., 2003). However, this system does not have rear-end collision warning technology.

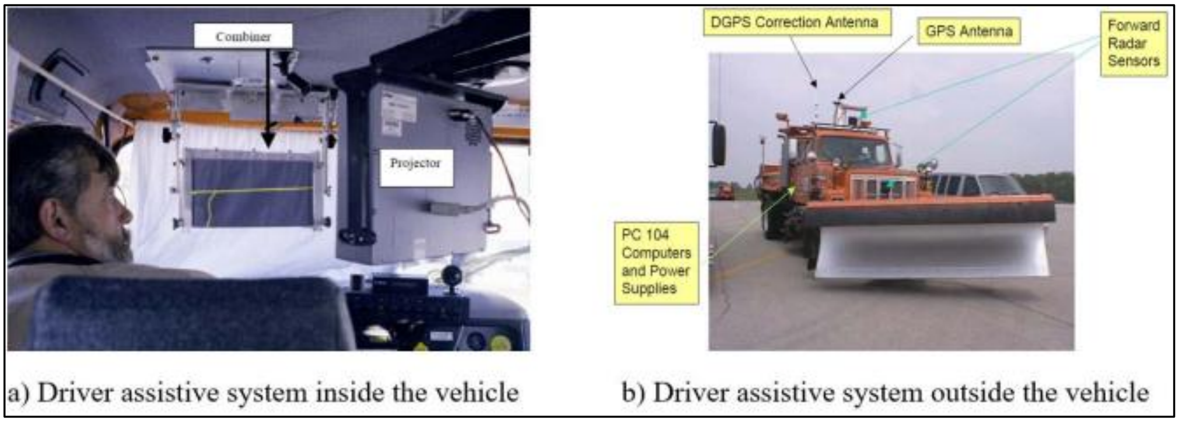


Figure 7: Driver Assistive Systems on Winter Maintenance Vehicles.
(Source: Michigan DOT, 2018)

Minnesota Department of Transportation (MnDOT) in collaboration with Dr. Max Donath from the University of Minnesota, sponsored several research projects to improve the safety of snowplow operations (Donath et al., 2015; 2018; 2019). Their investigations include the application of Driver Assist System (DAS), demonstrating the Connected Vehicle (CV) application through a dedicated short-range communication (DSRC), and developing a lane boundary guidance system for snowplow operations. There was not sufficient evidence to conclude that DAS would be an effective tool to reduce snowplow operator's exposure to collision and road departure risks in the poor visibility conditions due to the lack of snowstorms in the research period and the inadequate time spent developing radar icing mitigation solutions. On the other hand, the results of the CV applications indicated that the positioning accuracy using the DSRC technique was inadequate for providing the plow operator with sufficient information to maintain spacing between two vehicles. However, the lane boundary guidance received the most positive feedback from operators and is recommended for further development.

Recently, the Michigan Department of Transportation in collaboration with Michigan State University developed a prototype called Collision Avoidance And Mitigation System (CAMS) and evaluated the effectiveness of the prototype by mounting it on the rear of WMT in southeast Michigan during the 2017-2018 winter season (Michigan DOT, 2018). The CAMS system includes a rear-facing radar, camera, and warning light bar, in addition to a cleaning/washing system, computer hardware, and an in-cabin display, as shown in Figure 8. Although the CAMS showed potential for positive benefits on driver behavior, in terms of reaction time and encroachments to the rear of the WMT, several operational and performance issues were identified, both during field operation and from operator feedback that requires further investigation and remediation before the system can be recommended for widespread implementation. In summary, no significant evidence was found about the effectiveness of this radar-based warning system. The major limitations concluded from the study are listed below:

- Blockage/occlusion of the camera/radar box caused by the accumulation of debris inhibited system performance.
- The warning alarm did not always activate precisely at the pre-specified relative headway thresholds.
- There are a significant number of recorded warnings due to adjacent lane vehicles when there is no vehicle encroaching in the same lane of the truck (false positive warnings).
- In many cases, the following vehicle was observed to have crossed the warning threshold but did not trigger the warning system at all (false negative warnings).
- The WMT drivers with CAMS experience did not believe the CAMS system to be effective in its current format.

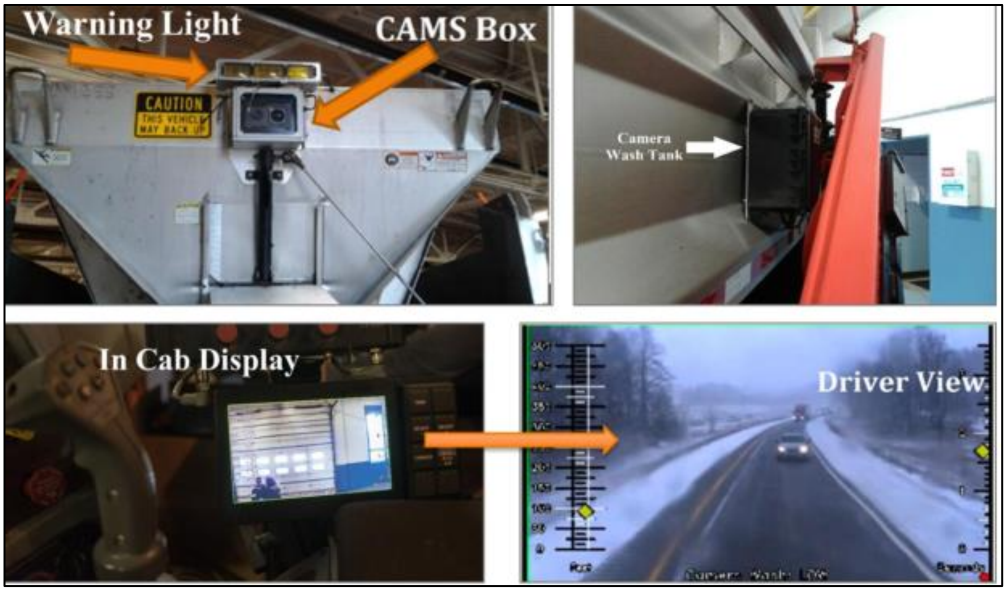


Figure 8: Illustration of Components of CAMS Installed on a Snowplow.
(Source: Verma, 2019)

Another research program called Clear Roads aims to drive innovation in the field of winter highway maintenance. This program brings together transportation professionals and researchers around the country and identifies the most effective techniques and technologies to save agencies money, improve safety, and increase efficiency. Figure 9 shows the member states (red color) under Clear Roads program. A recent study sponsored by this program in collaboration with Virginia Tech Transportation Institute (VTTI) examined key causes of collisions involving snowplows and developed two comprehensive and engaging snowplow operator training modules on safe and defensive driving (VTTI, 2020). Questionnaires, interviews, and crash data were used to identify defensive driving strategies that snowplow operators can use to prevent crashes.

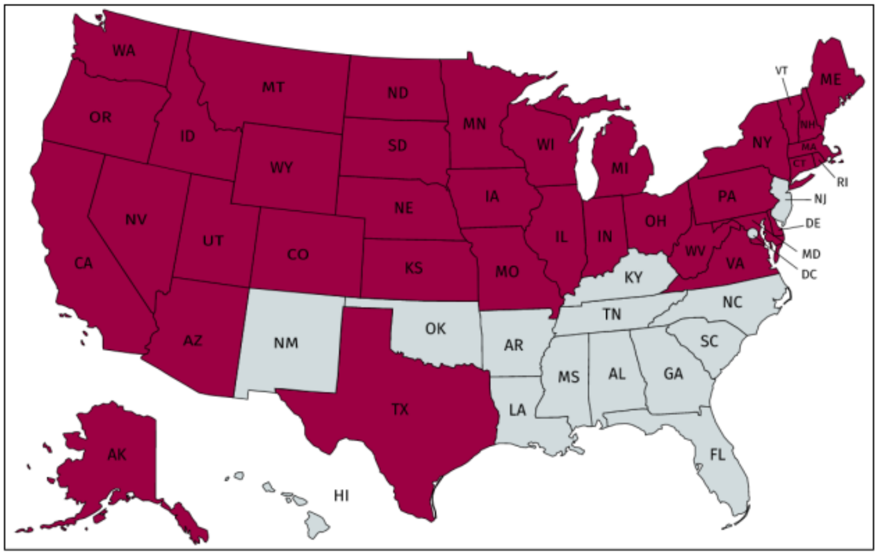


Figure 9: Map of Clear Roads Member States.
(Source: VTTI, 2020)

Despite several attempts from the DOTs and other agencies to improve safety during winter maintenance, and particularly snow removal procedures, the number of crashes involving a snowplow still remains high and represents an opportunity area for improvement.

5 TECHNOLOGICAL BACKGROUND AND PROPOSED PROTOTYPE

Collision avoidance and advanced safety systems are part of an emerging technology that typically uses an array of electronic sensors to detect other approaching vehicles and warn motorists if they get too close (Zhang et al., 2014). This may include a forward or rear-end crash warning system. Automotive companies are currently using multiple types of sensors exploiting their respective strengths to provide driver assistance systems. These sensors include a camera, LIDAR, Radar, and GPS, as shown in Figure 10.

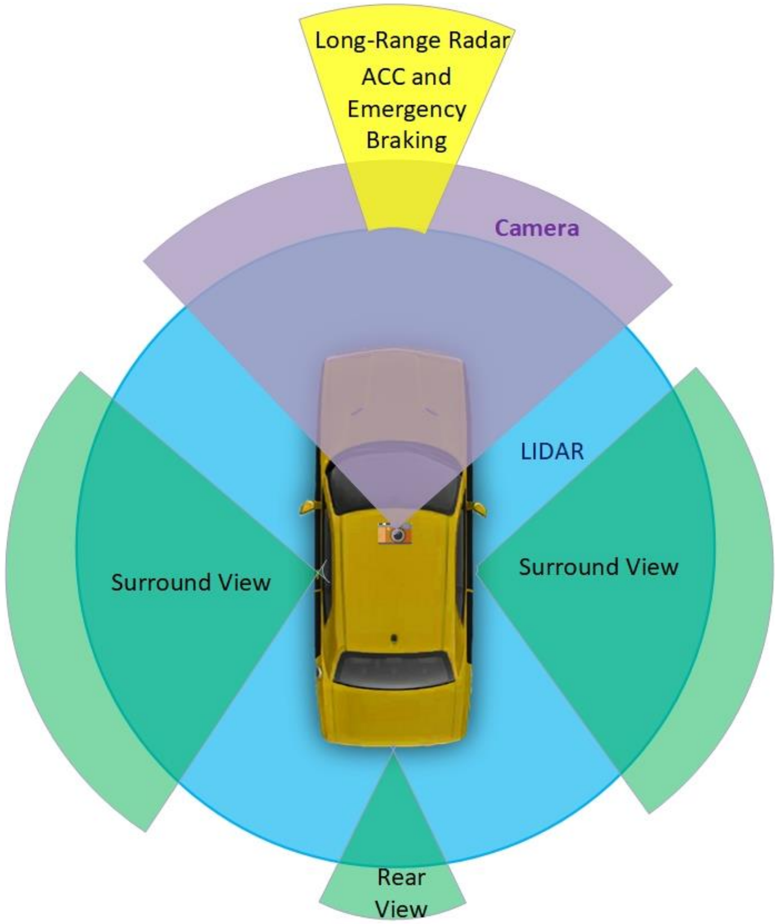


Figure 10: Driver Assistance System.
(Source: Shizhe, 2019)

One of the important fusion modules of the driver assistance system is the forward collision warning and collision avoidance safety system commercially known as the Adaptive Cruise Control (ACC) and Emergency Braking (EB). The ACC and EB is a fusion technique consisting of long-range Radar, LIDAR, and camera sensors, as shown in Figure 10. The ACC involves using either long-range Radar or LIDAR to measure the distance in real-time of a vehicle in front and, depending on the preset following distance, decelerate or accelerate your vehicle to avoid the forward collision. By fusing the LIDAR and camera sensor measurements, the relative speed of the vehicle in front is predicted, and the emergency braking system is activated to prevent forward collisions. In Figure 10, the driver assistance system of the external environment of a vehicle (surround and rear views) consists of data from multiple cameras fused to provide a comprehensive 360^{o} view to the driver of the vehicle.

One of the critical requirements of the rear-end collision warning and collison avoidance system for WYDOT snowplow trucks is the capability to detect a vehicle at a distance of 2000 ft behind a snowplow truck. Furthermore, the system should detect a vehicle in adverse weather conditions such as snow, fog, and rain, a common environment where the snowplow trucks are operated.

Under normal or clear weather conditions, the range of automotive LIDAR (Kondo et al., 2020) and automotive 77.0 GHz long-range Radar (Al-Hourani et al., 2018) is 750 ft and 1600 ft. Recently, the performance degradation of LIDAR and Radar used in the ACC and EB fusion module due to adverse weather conditions has been studied. The results of these studies have demonstrated significant attenuation of both LIDAR and Radar signals due to snowflakes and rain droplets reducing the range of operation.

Performance of Automotive LIDAR Sensors:

Rasshofer et al., 2011, have demonstrated false detections or alarms of objects by an automotive LIDAR due to the backscattering from snowflakes and water droplets. Furthermore, they have shown that in the critical distance range of 30 ft of an automotive LIDAR, the snowflakes or water droplets act as small but efficient reflectors of the laser pulse, resulting in false detection of objects. To study the impact of snow and water droplets on the detection range of LIDAR, Rasshofer and his colleagues developed an artificial indoor rain simulator. The detection range results for two different LIDAR sensors from the simulator shown in Figure 11 clearly demonstrate the decreasing detection range with increasing rain rate.

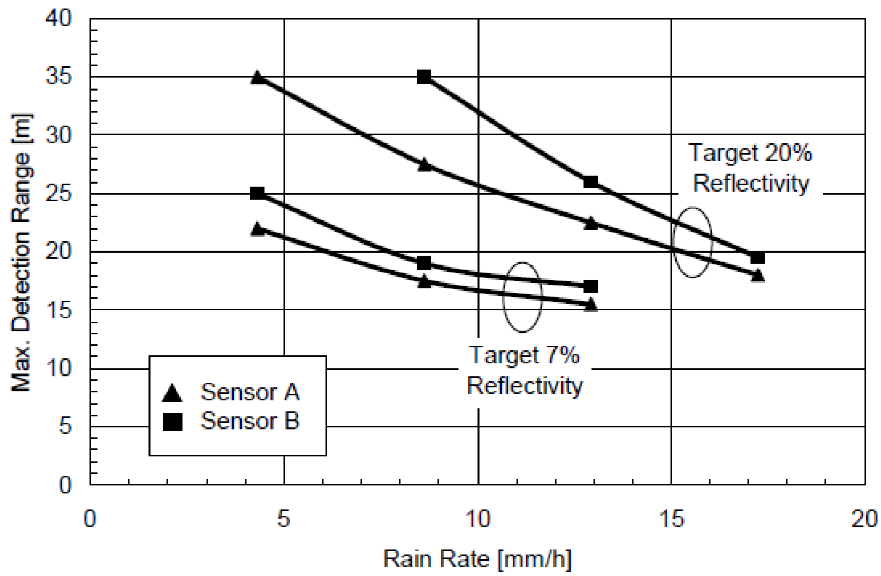


Figure 11: Maximum Detection Range with Increasing Rain.
(Source: Rasshofer, 2011)

Heinzler et al., 2019, demonstrated the detection range of LIDAR sensors due to snowflakes behaves similarly to water droplets due to rain and degrades dramatically by 25% due to snow particles. Also, Michaud et al., 2015, found similar degradation in the detection range of LIDAR sensors due to snowflakes.

<u>Performance of Automotive Radar Sensors:</u>

The frequency band of the radar on automobiles is approximately 77 GHz, dictated by American and European standards, and the radars operating in this band are known as mm-wave radar. Compared with microwave radar, the mm-wave radar can provide a higher resolution up to the detection range of 1600 ft. However, weather conditions, such as rain, snow, fog, and hail, can negatively impact, such as attenuation of the received signal and backscatter. Norouzian et al., 2019, in their research study on automotive radar, have shown the impact of wet and dry snowfall on 77 GHz and 300 GHz frequency radars. The research study findings demonstrated the negative impact of snow on the received signal strength, contributing to reducing the radar range. They also demonstrated the reduction in the radar range due to snow is similar to that with rain. Simulation studies (Shizhe Z. et al. 2019) with varying rainfall rates show a 50% reduction in the radar range, as shown in Figure 12.

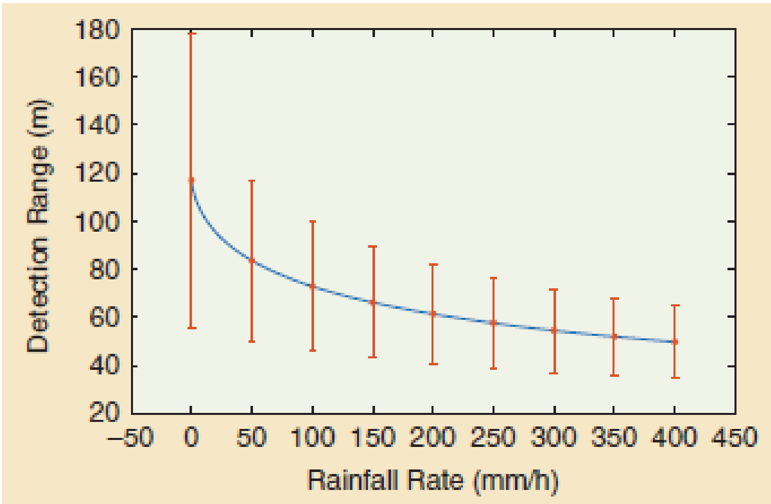


Figure 12: Radar Detection Range with increasing Rainfall Rate.
(Source: Shizhe, 2019)

Experimental analysis conducted by Zang et al., 2019 confirmed a similar negative impact of snow on the distance range of radar and backscattering effects. A list of the advantages and disadvantages of different types of automotive sensors used in the forward collision warning and collision avoidance safety system is presented in Table 1.

Table 1: List of advantages and disadvantages of automotive sensors.

Sensor	Advantages	Disadvantages
Radar	• Long-distance range functionality ahead of the vehicle in good visibility conditions. • Sensors are small, lightweight, and affordable • Requires less power than a LIDAR	• Adverse weather conditions like rain, snow, or fog severely impact the distance range functionality • Poor accuracy and low resolution • Azimuthal and elevation resolution is poor, resulting in error-prone object detection. • radar sensors on multiple vehicles can cause interference
LIDAR	• Long-distance range functionality ahead of the vehicle in good visibility conditions. • Good accuracy and resolution • Can provide full 360° awareness • Multiple LIDAR sensors can be used without interference	• Adverse weather conditions like rain, snow, or fog severely impact the distance range functionality • Mechanical maintenance is high • Under wet conditions, detection is poor • Expensive compared to Radar and Camera
Camera	• High-resolution color data across the complete field of view • Cost-effective compared to LIDAR and easy to deploy	• Inherently, the distance range is limited • Highly sensitive to weather conditions and illumination • Requires powerful computation system to extract information from the camera data

Therefore, the automotive LIDAR, Radar, and camera sensors used in the forward collision warning and collision avoidance safety system cannot be transplanted to WYDOT snowplow trucks for implementing rear-end collision warning and collison avoidance.

We propose developing a rear-end collision warning and collison avoidance system prototype by enhancing the current multiple-sensor fusion solution with Thermal Imaging (TI) and Machine Learning (ML) techniques. TI cameras (or Infrared cameras) operate by converting the Infrared (IR) light spectrum to an image perceivable by the human eye. The TI cameras not being dependent on the visible light can also be used during nighttime. In addition, the longer wavelength of IR waves allows IR radiation to pass through water droplets, dust particles, and fog making it useful in adverse weather conditions like rain and snow (Rankin, 2011). The TI camera will primarily be used to detect and recognize a vehicle behind the snowplow truck at a distance of 2000 ft. After recognizing the vehicle, the data from the TI camera and sensor fusion techniques will be used to eliminate both false positives and negatives and indicate to the driver of the snowplow truck the presence of a trailing vehicle with high confidence. Furthermore, using ML algorithms to analyze the data from TI cameras and other sensors, we will address the computational requirements for near real-time operation.

6 STUDY TASKS

This research is composed of the following study tasks:

1. Literature Review
2. Comprehensive Survey
3. Extensive Safety Analyses
4. Evaluating Color and Type of Warning Lights
5. Simulation Models
6. Prototype Instrumentation Development and Software Set-Up
7. Field Testing of the Prototype
8. Benefit-Cost Analysis
9. Initial Implementation of the System
10. Transferability of the Technology to Other Maintenance Vehicles
11. Establishing Educational Program

12. Preparing the Final Report and Full Blown Implementation Plan

6.1 Literature Review

A comprehensive literature review will be conducted regarding the existing research studies, guidelines, and best practices from different agencies related to winter highway maintenance. The literature review will provide some recommendations to establish the design criteria for rear-end collision warning systems, analysis methodologies, results interpretation, and potential strategies for implementation. Also, a review of available technologies and their effectiveness will be studied to see if any current DOTs have such technology operational.

6.2 Comprehensive Survey

A comprehensive survey will be performed on WYDOT's maintenance personnel including snowplow operators to collect information regarding the current practices, challenges, safety concerns, and expectations while doing maintenance operations. The research team will divide the survey into two sections: 1) Survey on Wyoming Snowplow Operators and 2) Survey on WYDOT's Snowplow Safety Subcommittee. In addition, the responses of several DOT surveys will be collected from the previous study conducted by Michigan DOT in 2018. The questions of the survey will be related to safety for the maintenance vehicle operators and may include the following information:

- Operating speeds of snowplows under different weather conditions.
- Major challenges and safety concerns for winter maintenance/other highway operations.
- Preference on type of warning system (e.g., voice-activated, flashing lights, lights with different colors indicating warning severity, etc.).

- Suggestions regarding corrective actions in response to a warning (e.g., plow lifting, move onto the shoulder, etc.).

6.3 Extensive Safety Analysis

The research team will accumulate historical crashes involving snowplows throughout the state. A comprehensive crash database will be prepared to gather the level of details associated with each crash. The information will include the date and time, location (milepost, longitude-latitude, and name of the road), crash severity, the manner of collision, lighting condition, road condition, weather condition, junction relation, roadway classification, driver improper actions (e.g., distraction, high speed, following too close, etc.), driver impairment (alcohol/drug use, fatigue, sick, sleepy, etc.), involved vehicle information (e.g., car or semi-truck to identify driver's eye height), and many other roadway geometrical characteristics. The research team will collect the exact location of snow fences with other detailed information from the WYDOT Snow Fence Viewer (a web-based inventory tool) to evaluate the effectiveness of the presence of snow fences. Descriptive statistics will be provided indicating the trends of the crashes involving snowplows. The reasons behind significant spikes will be examined. The research team will also investigate the contribution of any unexpected weather conditions (e.g., sudden snowstorm/slush) behind crashes. To overcome any missing information in the crash database, the research team will conduct phone interviews with the drivers involved in crashes. After preparing a comprehensive crash database and analyzing descriptive statistics, an advance statistical model will be developed to identify the significant contributing factors related to the crashes involving snowplows. A special analysis will be conducted to determine if the snowplows crashes are taking place near the turn arounds where the snowplow drviers need to slow down considerably to turn around. In addition to this, a GIS map could be developed for snowplows crash locations. The map will be used to perform a more refined analysis to study hot spots with the intensity of snowstorms. Color coding will be provided to clearly identify trouble locations. Such maps will provide WYDOT with valuable information to determine where to concentrate their efforts on improving snowplow operation and safety with respect to snowfall intensities. Finally, after the installation of the warning systems, a before-after crash study will be performed to see if the number of crashes declines.

6.4 Evaluating Color and Type of Warning Lights

The research team will conduct a comprehensive analysis on evaluating the effectiveness of using different colors and types of warning lights in maintenance vehicles. WYT2/LTAP center will be working in collaboration with the WYDOT's snowplow safety subcommittee to accomplish the task. Two different field tests will be developed and performed. The first test will be conducted by WYDOT's snowplow safety subcommittee to evaluate the effectiveness of green warning lights. A tentative description of the test is outlined below:

- The test will be performed by replacing the single blue light with green at the right rear corner of the sander (passenger side), and replacing an amber cab light with a dual amber/green light on the top left corner (driver side) of the snow plow dump box to investigate the use of green warning lights against blue lights on improving snowplows safety.
- 10 snowplow trucks will be used and equipped with the proposed arrangement of warning lights. WYDOT has five field districts that will provide the testing snowplows (each contributing two, which will sum up a total of 10).

- The testing snowplows will be driven along different classifications of roads. For instance, some will be driven along interstates while some on the primary (principal arterial) or secondary roads (collector and local roads).

The second test will be more comprehensive and it will be performed by the WYT2/LTAP center. Instead of evaluating the use of only green warning lights, the research team will investigate various possible color configurations to identify the most suitable multiple combinations of warning lights under different weather and daylight conditions. A tentative description of the test is outlined below:

- Snowplow trucks will be equipped with different combinations of colors (blue, green, amber, and white) and the type (LED vs. regular) of warning lights, which will be tested to determine the best warning light configuration.
- The tests will be performed under different weather and daylight conditions, while each identical condition will be utilized to determine the appropriate combination of light based on the feedback on visibility distances provided by the driver of the trailing vehicle behind the snowplows.
- Visual impairment (e.g., short-sighted during the night, color blindness, etc.) will also be taken into account while performing the field test.

6.5 Simulation Models

The research team will develop several simulation models to determine the minimum acceptable distance and perception-reaction time for various differential speeds between the snowplow and the approaching vehicle. The simulation models will help to determine the effectiveness of distance measurements by multiple sensors to allow the operator or the approaching vehicle to avoid a crash. In addition to this, the different color combinations of the warning lights will also be evaluated in the simulation environment and the results will be validated using the findings from the field study.

6.6 Prototype Instrumentation Development and Software Set-Up

The rear-end collision warning and collison avoidance system prototype will consist of high-level sensor fusion of thermal imaging, radar, and LIDAR. Each sensor will detect a vehicle in the rear of the snowplow truck with finer granularity and accuracy. By operating the sensors in the fusion module at different levels, the number of false-negative and false-positive detections will be reduced, providing confidence in the warning system to the truck driver.

Thermal imaging cameras operate on the principle that all objects emit infrared energy as a function of their temperature. The thermal camera uses the emitted infrared radiation to create an electronic image. Figure 13 depicts the vehicle thermal images captured using a Forward Looking Infra Red (FLIR) thermal camera at different distance ranges and weather conditions.

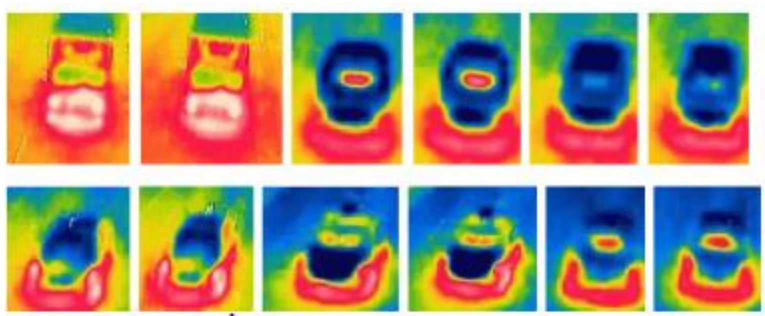


Figure 13: Vehicle Thermal Image at varying distance from the Thermal Camera.
(Source: Yunyoung, 2018)

In Figure 13, the first two images starting at the left in the top row show detection of infrared energy source but not recognizing it as a vehicle known as the detection (D) range. The next four images in the top row show the outline of a vehicle known as the recognition (R) range, and the images in the bottom row show details of a vehicle known as the identification (I) range. The inexpensive thermal camera with a 75 mm focal length lens shown in Figure 14, under extreme weather conditions, has a detection range of 5,900 ft, recognition range of 2,200 ft, and identification range of 780 ft. A vehicle at a distance of 2,000 ft from the snowplow truck can be recognized using a 75 mm focal length TI camera as one of the sensors in the fusion module.

Figure 14: 75 mm Focal Length Thermal Imaging Camera with Heated Lens.
(Source: http://www.infinitioptics.com/cameras/eclipse)

The hardware block diagram of the multi-stage sensor fusion prototype device is shown in Figure 15.

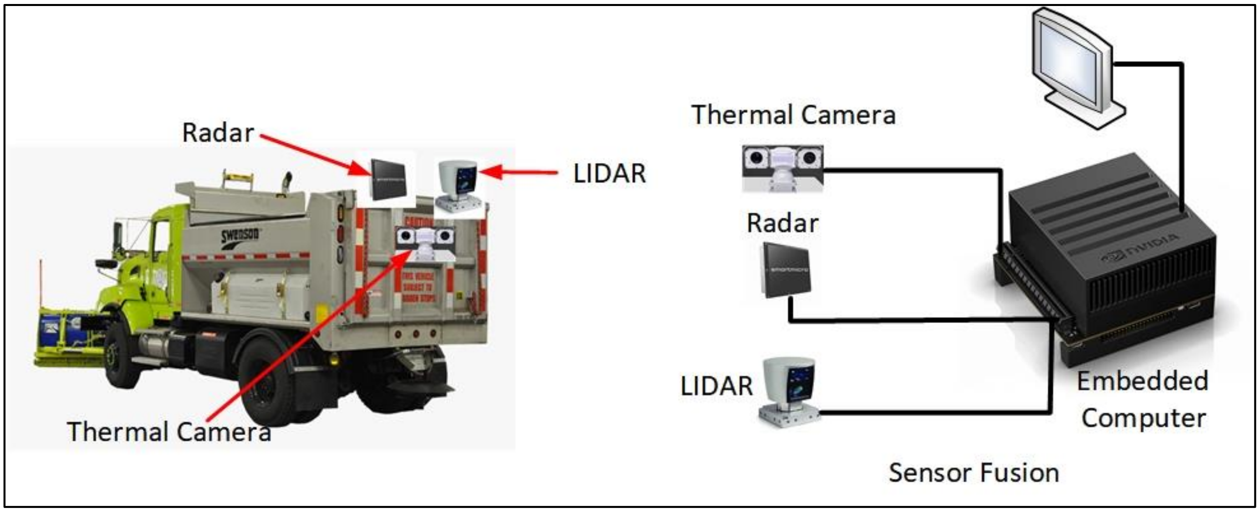


Figure 15: Hardware Prototype.

The hardware of the prototype device shown in Figure 15 will consist of three sensors, namely, the thermal camera with a recognition range of 2000 ft, a radar with a distance range of 600 ft, and a LIDAR with a distance range of 200 ft interfaced to an embedded computer with graphic processing unit compute capability for near-real time analysis and machine learning algorithm execution. The software framework diagram of the prototype device is shown in Figure 16. The stepwise operation to detect a vehicle, vehicle distance, vehicle lane position, warnings to snowplow driver, turn-on warning lights, and raise the snowplow is shown in Figure 16.

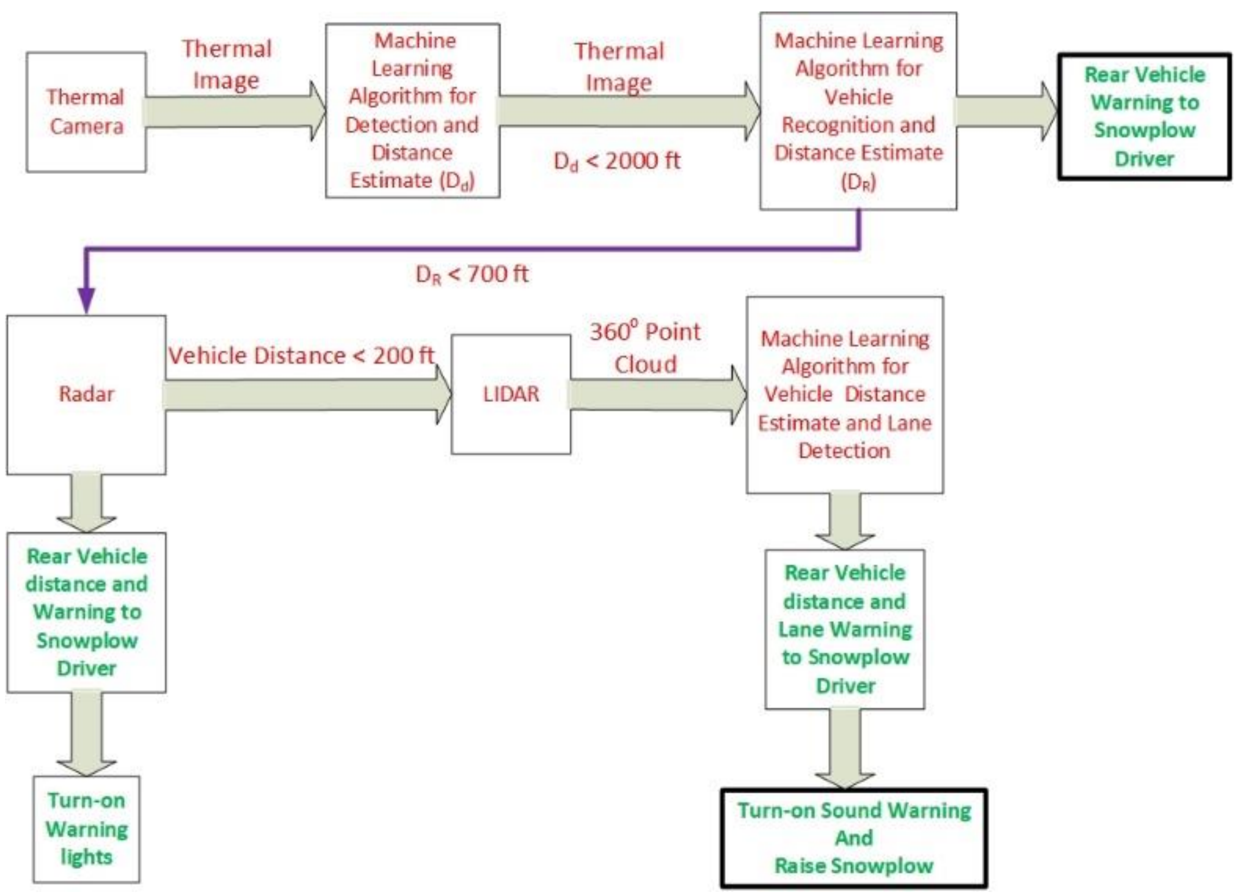


Figure 16: Software Framework of the Prototype Device.

The software framework flow is designed to detect a vehicle, vehicle distance, vehicle lane position, warnings to snowplow driver, turn-on warning lights, and raise the snowplow. The multiple levels of rear vehicle detection operations are as follows:

Level 1: Using the thermal images with a Machine Learning (ML) algorithm, the IR energy source detection and the distance estimate of the energy source will be performed. If the distance estimate is less than or equal to 2,000 ft, the thermal image will be passed to Level 2 recognition operation.

Level 2: In level 2, using the object segmentation ML algorithm, the IR energy source will be classified it as a vehicle or not. If the IR energy source is classified as a vehicle, warning information will be provided to the snowplow driver. Furthermore, the Level 3 distance measurement will be triggered using the radar if the estimated distance from the thermal image is less than 600 ft.

Level 3: The radar being an active device, will provide an accurate distance measurement of the vehicle. By analyzing the distance measurements produced by the radar sensor and thermal camera together, false positive and negative warnings will be eliminated. If the radar distance is below 600 ft, a vehicle close proximity warning will be provided to the driver. Also, the LED warning light of an appropriate color will be turned on, indicating to the rear vehicle driver the presence of a slow-moving maintenance vehicle. If the rear vehicle continues to move further towards the snowplow, and the radar distance measured is 200 ft., the Level 4 LIDAR detection will be triggered.

Level 4: In level 4, the LIDAR sensor will be used to perform a scan to construct a 360^o point cloud. Using another ML algorithm, fine granular distance measurement will be performed along with the detection of rear vehicle position (attempting to pass the snowplow truck). Based on the position of the rear vehicle, a sound warning and LED warning light of an appropriate color will be triggered. If the detected vehicle position indicates a passing attempt, the snowplow will be raised to reduce the snow plumes.

6.7 Field Testing of the Prototype

The prototype testing will consist of multiple phases. The first phase of testing will evaluate the sensitivity of the thermal camera images to weather conditions and distance. A dataset of thermal images and corresponding temperature and distance measurements will be constructed in the first phase of the test. This dataset will be used in the training of the ML algorithm to detect and estimate the distance of the IR energy source. The second phase of testing will simulate scenarios in which the collected thermal images can be labeled as a vehicle or not and distance. Using this second dataset, another ML algorithm will be trained to detect a vehicle in the thermal image and estimate its distance. The third phase of testing involves a thermal camera mounted on a snowplow and evaluating Levels 1 and 2 operations. On successful completion of levels 1 and 2 operation testing, the fourth phase of testing of level 3 with the integration of the radar will be performed. Finally, using the LIDAR, a dataset consisting of point cloud data will be developed and used to train the final ML algorithm for vehicle lane detection. The last phase of testing will evaluate the prototype in adverse weather conditions involving snow. The last phase of testing will include quantitative measurements of false-positive warnings and false negative indications, the accuracy of distance measurements, and correct vehicle lane detection.

6.8 Benefit-Cost Analysis

The research team will estimate the cost of purchasing, installing, and training the operator in this technology. A Benefit-Cost analysis (BCA) will also be performed to compare costs to DOT vehicles and downtime, man-hours lost vs. installation and operation of the protection system. It should be noted that one lost truck at $100,000 plus can buy a few protective systems. In addition to this, the research team will evaluate the monetized value of the crash cost savings for installing the warning systems.

6.9 Initial Implementation of the System

The proposed warning systems will be initially implemented in 2-3 snowplow trucks, which will be operated during plowing activities occurring during the winter season. The potential feedback during the field test and from the operators will be used to further enhance the system by addressing the key issues and challenges of using the technology before a full-blown implementation.

6.10 Transferability of the Warning System to Other Maintenance Vehicles

The research team will develop a guideline on how a subset of multiple sensors along with the warning lights from snowplow trucks can be transferred and employed in other slow-moving maintenance vehicles to reduce the potential risk of rear-end collisions. Mobile work zones for various types of moving operations such as striping, sweeping, and pothole filling often pose a serious threat to collisions due to the distracted driving of the approaching vehicle regardless of having shadow vehicles, arrow boards, and signs using a Truck-Mounted Attenuator (TMA) attached to a construction vehicle. These operations become very risky especially in the summer season because of their higher exposures. The subset of the multiple sensors with the appropriate combination of warning lights is expected to mitigate the impact of a collision from a highway vehicle that fails to recognize the mobile work zone. The system would benefit the following mobile work activities:

- Pothole patching
- Highway Stripping
- Sweeping
- Friction/ FWD testing
- Mowing
- Signage
- Cleaning dirt
- Spraying weeds
- Rolling
- Other maintenance (e.g., bridge)

6.11 Establishing Educational Program

A manual describing how to set up and use the proposed prototype will be documented to train and educate the snowplow operators. A safety checklist will also be outlined for the operators. In addition to this, based on the findings from the above-mentioned tasks (6.1 – 6.10), a more targeted educational/training/outreach program will be established for the general public to teach defensive driving strategies while driving close to snowplow trucks or other maintenance slow-moving vehicles in both favorable and adverse weather condition. A statewide multimedia winter driving safety campaign could be initiated in audio and video formats which can be broadcasted using radio, television, and other social media platforms. This would benefit other state DOTs and local agencies to customize the campaign materials to promote the safety messages within their states.

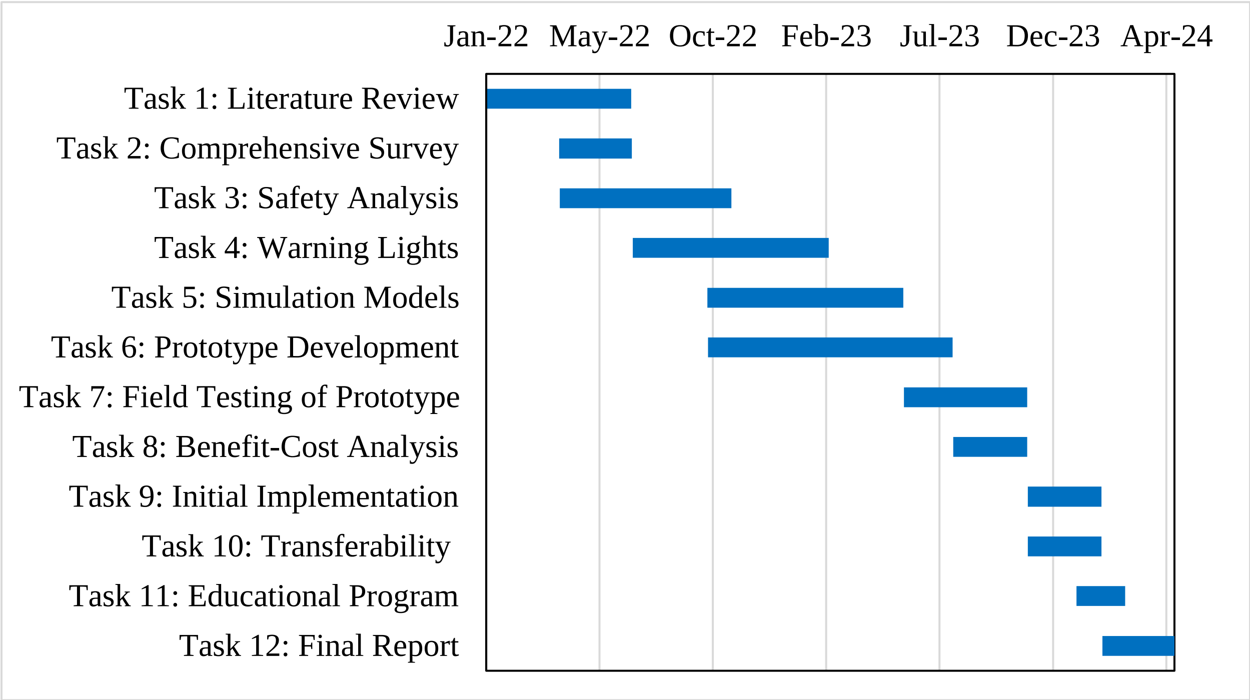
6.12 Preparing the Final Report and Full Blown Implementation Plan

A final report will be prepared in an appropriate format documenting all the tasks used to develop the collision warning and collision avoidance system for WYDOT maintenance vehicles. Also, a presentation to appropriate WYDOT personnel will be delivered to demonstrate a full-blown implementation strategy of the final product at the conclusion of the study. In addition to this, the research team will submit the research findings for presentation in Transportation Research Board (TRB) Annual Meeting and publications in various journals.

7 TIMELINE

The entire study is anticipated to be completed in 28 months after receiving the notice to proceed from WYDOT. Progress reports will be provided to WYDOT quarterly. The proposed timeline of the study is presented in Figure 17. This will be the main timelines, however, some of the tasks will be conducted throughout the entire study (such as literature review with new information, newly available methodology to improve the proposed system, and progress reports). The findings of some of the tasks such as the warning lights can be shared with WYDOT immediately for quick implimentations prior to the completion of the study.

Figure 17: Proposed Study Timeline.



8 BUDGET

The total budget for this study will be $259,256 The breakdown of the study cost is shown in Table 2. The WYDOT cost will be only $170,046 since the Mountain Plains Consortium will contribute $89,210 as a hard match for this study.

Table 2: Proposed Study Budget.

Categories	MPC	WYDOT	Total
Center Director Salary			
Faculty Salaries	$4,000	$34,000	$38,000
Engineer/ Post Doc	$5,000	$27,500	$32,500
Faculty/Engineer Fringe Benefits (36.6%)	$3,294	$22,509	$25,803
Student Salaries	$0	$29,000	$29,000
Student Fringe Benefits (2.4%)	$0	$696	$696
Total Personnel Salaries	$9,000	$90,500	$99,500
Total Fringe Benefits	$3,294	$23,205	$26,499
TOTAL Salaries & Fringe Benefits	**$12,294**	**$113,705**	**$125,999**
Travel	$500	$8,000	$8,500
Equipment	$70,000	$7,000	$77,000
Supplies	$500	$4,000	$4,500
Contractual			
Construction			
Other Direct Costs (Specify)*	$0	$9,000	$9,000
TOTAL Direct Costs	**$83,294**	**$141,705**	**$224,999**
F&A (Indirect) Costs	$5,916	$28,341	$34,257
TOTAL COSTS	**$89,210**	**$170,046**	**$259,256**

*Other Direct Cost includes Graduate Student Tuition, Fees and Insurance

9 DELIVERABLES

The deliverables of this research, to be provided to WYDOT are listed as follows:

1. Responses from the comprehensive surveys.
2. Best operational warning lights configuration.
3. Results of comprehensive safety analyses.
4. Simulation outcomes.
5. Feedback from the snowplow operators equipped with the collision warning systems.
6. Final prototype fully developed with ITS technologies.
7. A manual describing how to set up the advanced prototype, conduct field experiments, and interpret results.
8. A report encompassing all previous study tasks from the literature review to the development of the prototype and its testing.
9. A full-blown implementation plan by the end of the study.

All equipment purchased in this contract will be incorporated in the final prototypes and the prototypes will be delivered to WYDOT for their use.

10 PROPOSAL'S RELEVANCE TO WYDOT'S MISSION

10.1 Project Area

Various programs within WYDOT sponsor and advance research proposals to the Research Advisory Committee (RAC) of the department. This proposal is being submitted to the RAC from the WYDOT's traffic engineering program.

10.2 Strategic Intent

WYDOT has six strategic intent areas, one of which is the safety area. This research project is anticipated to enhance the safety of motorists and snowplows or other maintenance vehicle operators. Therefore, it is classified under the safety area. This study is aimed at significantly cutting the number of crashes, particularly rear-end and sideswipe crashes involving any maintenance vehicle, during snowplowing operation in winter and other maintenance operations in summer in the state. The liability to WYDOT is extremely high if the safety of the maintenance operators is not ensured correctly.

10.3 Project's Outcome

The outcome of this project is a set of collision warning and collision avoidance systems containing multiple sensors and warning lights to be used by WYDOT and other jurisdictions in the state. This system would be essential for not only improving the safety of snowplow operation but also for reducing the potential risks of a collision involving other maintenance vehicles at work zones nationwide.

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