Feasibility of Employing AI Computer Vision and Distributed Fiber Optic Sensing for Traffic and Weather Monitoring

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1. Problem Statement

Traffic monitoring and collecting data on the performance of the transportation systems and the environment are essential for the successful management of the system. Traffic operations (or management) centers (TOC, TMC) have historically had the role of monitoring traffic in real (or near real) time, collecting, archiving, and disseminating data, and, most importantly, implementing management strategies to improve the flow and safety of traffic, as needed. Real-time traffic monitoring is used in a variety of applications, such as traffic management, safety, congestion reduction, incident management, freight and transit management, or emergency response. The data collected by the TOCs/TMCs have also been used for predicting future traffic patterns and selection of planning and implementation strategies. As Connected Vehicle technologies continue to expand, the need for comprehensive and efficient traffic and weather monitoring becomes increasingly critical. This emphasizes the importance of technically refining methods to optimally utilize existing infrastructure data.

As a standard practice, TOCs/TMCs use video feeds from traffic cameras as an important component of their efforts to manage the transportation system effectively. These video feeds provide real-time visual insights into traffic and environmental conditions, as well as incidents. Agencies deploy these feeds for diverse functions, including real-time traffic surveillance, incident detection, congestion identification, traffic flow optimization, emergency response, weather observation, and road surface assessment, snowplow allocation optimization, and traveler information systems. State DOTs and transportation agencies, own and operate hundreds of cameras on their systems, and these cameras can be an invaluable source of real-time traffic information, which is still being underutilized. The main reason is that the usage of video feeds requires an operator to manually observe and control the cameras for each individual location, which is infeasible considering the sheer number of them.

The Wyoming Department of Transportation (WYDOT) operates a network of approximately 230 traffic cameras statewide, which are used to monitor road, weather and surface conditions, provide real-time information to the public, and improve operations and safety on the State’s highways. The camera feeds, albeit as still screenshot images, are available to the general public, through WYDOT’s traveler information website, and the Wyoming 511 app.

Recently, the emergence of artificial intelligence (AI), machine learning (ML) and computer vision technologies has opened up new opportunities for leveraging real-time video feeds for traffic monitoring, vehicle counting and classification, and the estimation of traffic flow parameters. Furthermore, with the decreasing cost and greater accessibility of surveillance cameras, they can now serve as dynamic sensors for specific purposes, including special events, work zones, or incident management.

Traditional monitoring systems such as microwave sensors and traffic cameras face challenges in real-time data acquisition, scalability, and environmental constraints. A

cutting-edge technology named Distributed Acoustic Sensing (DAS) presents a promising solution to these limitations. Utilizing the inherent properties of fiber optics, DAS uses fiber optic cables to detect vibrations and acoustics. It essentially “listens” to its surroundings, picking up acoustic signals which are converted to data points, offering high-resolution, continuous monitoring capabilities over extended areas (several miles of highways). Importantly, DAS technology is less susceptible to environmental factors like snow, fog, rain, or darkness as it relies on acoustic signals. Furthermore, compared to traditional video surveillance, which can pose privacy concerns and demand substantial storage and bandwidth, DAS provides a more discrete and efficient data collection solution, primed for real-time applications.

AI/ML computer vision and DAS technologies have the potential to play a pivotal in addressing the current challenges of traffic monitoring. They excel in real-time data processing, providing detailed insights into traffic parameters, automating monitoring processes, ensuring scalability over extensive areas, and displaying resilience to environmental constraints like adverse weather. These technologies, compared to traditional monitoring systems, offer resource-efficient and privacy-conscious solutions. Moreover, they are adaptable to various scenarios, including special events, work zones, and incidents, thereby, have the potential to revolutionize the efficiency and safety of transportation systems.

This research will explore the feasibility and practicality of implementing AI/ML computer vision systems in estimating and optimizing traffic flow in real-time. The traffic flow information extracted and processed through the computer vision algorithms will encompass a range of essential parameters, such as vehicle classifications, flows, speeds, densities, headways, spacings and queue lengths. The research will develop a Decision Support System (DSS) model with the capability to automatically extract real-time traffic flow data from video feeds and offer strategic recommendations for enhancing both the efficiency and safety of traffic at a specific location. An emphasis will be placed on harnessing the DSS model's potential to optimize operations and management in unique scenarios, including special events, incidents, and work zones. To complement video surveillance efforts, a feasibility study on DAS implementations will be conducted. The feasibility study will focus on identifying lessons learned from other state departments of transportation utilizing DAS, synthesizing DAS systems and algorithms, conducting benefit-cost analysis, pinpointing locations where DAS implementation would be most effective, identifying limitations in its implementation and recommending approaches to overcome them, and offering recommendations on specifications and requirements for seamless DAS integration with existing and future fiber optic maintenance and installations.

The research team consists of personnel from the University of Wyoming (UW), led by Co-PIs Milan Zlatkovic and Diksha Shukla, and the University of Cincinnati (UC), led by Co-PI Mohamed Ahmed. Among them, they have significant experience in various areas of transportation engineering (such as operations, safety, ITS, facility design,

simulation), machine learning and AI, including research and practical applications. The team has been thoughtfully formed on the principles of a transdisciplinary approach, involving researchers and stakeholders with diverse expertise. Co-PI Zlatkovic has 18 years of experience in transportation engineering, with specialties in traffic operations and control, ITS, multimodal transportation, safety and traffic simulation. His recent research projects with WYDOT included the development of connected-vehicle based traffic control algorithms for freight transportation (Zlatkovic et al., 2021), operational and safety assessment of heavy trucks on I-80 (Zlatkovic, Ksaibati and Haq, 2020), and a state-wide motorcycle safety study (Zlatkovic, Baah and Cvijovic, 2022; Zlatkovic and Baah, 2023). The research on heavy truck traffic on I-80, which he led, was selected as a High-Value Research Sweet Sixteen project for Region 4 in 2021 by AASHTO RAC. His previous research included analysis and optimization of traffic operations, as well as significant use of traffic simulation modeling. He is currently leading the seed fund project, funded by the College of Engineering and Physical Sciences at UW, to develop a pilot study in the use of computer vision for traffic flow parameter estimation. Dr. Diksha Shukla (Co-PI) is an Assistant Professor in Computer Science, with proficiencies in AI/ML, computer vision, and cybersecurity. She is also the Co-PI on the pilot study on computer vision applications in transportation, funded by the College of Engineering and Physical Sciences. Dr. Shukla has expertise developing and applying computer vision techniques for various application areas (Gopal et al., 2023; Shukla et al., 2019; Shukla and Phoha 2014), and developing secure AI/ML techniques for computing applications (Song et al., 2019; Gopal et al., 2021; Shukla et al., 2018). Dr. Mohamed Ahmed, Co-PI and subcontractor on this study, is a Professor and Director of the CEAS Transportation Center at the University of Cincinnati. His expertise include ITS, traffic safety and roadway design, among other areas. Dr. Ahmed has a substantial track record on performing research projects for WYDOT. He and his team has have previously worked on machine learning and computer vision research using videos from the Naturalistic Driving Study, as well as WYDOT's traffic cameras (Khan and Ahmed, 2019; Khan and Ahmed, 2020; Khan and Ahmed, 2023; Khan et al., 2021). The Co-PIs will be assisted by graduate and undergraduate students at UW and UC. These students will play a pivotal role in supporting the investigators throughout the research, design, and development phases of the proposed computer vision-based and DAS tools. To ensure the successful execution and assessment of our project, regular meetings will be convened involving all stakeholders who will actively participate in the project at WYDOT, UW and UC.

2. Background Statement

A widespread implementation of Intelligent Transportation Systems (ITS) among the U. S. transportation agencies started in the 1990's, including installations of sensors, computer systems, traffic management software and traffic cameras for various purposes. WYDOT followed suit, and among other ITS applications installed approximately 230 cameras to continuously monitor traffic, weather and surface conditions on the State's highways. To utilize the full potential of the video feeds, it is

required to have trained operators who can make management decisions in real-time. It is unfeasible to monitor all important locations at the same time, as it would require significant manpower. On the other hand, the cameras are active all the time and send videos/images to the operations center, so a lot of traffic and environmental information goes unused.

One way to harness the massive amount of information coming through the video feeds is to develop a system that will utilize computer vision and machine learning to automate the process of data collection, estimation of traffic flow parameters and recommendation of management strategies to optimize traffic flow efficiency, as needed. Recently, computer vision and machine learning modules have advanced significantly, providing a good starting point for customization and optimization for a specific purpose.

The research team at UW has been awarded a seed fund from the College of Engineering and Physical Sciences, under which we have begun developing and customizing computer vision modules for vehicle detection and counting. The initial results show promise in detecting and counting vehicles from recorded (Fig. 1) or live streaming videos (Fig. 2). One potential issue with WYDOT camera feeds is that some do not provide video streams, but rather images updated at certain intervals. For that purpose, the modules will need to be adjusted to use image processing for extraction of traffic flow parameters, such as in the example shown in Fig. 3. Co-PI Ahmed at UC has extensive experience in machine vision utilizing various detection and tracking algorithms (Fig. 4). With his team, they achieved high detection and tracking accuracy while overcoming multiple challenges including occlusions, scale variability, background clutter, and temporal consistency.

Figure 1: Screenshot. Traffic flow counts from recorded videos using computer vision

Figure 2: Screenshot. Vehicle detection and classification from live streaming videos using computer vision

Figure 3: Screenshot. Vehicle counting and classification from still camera images

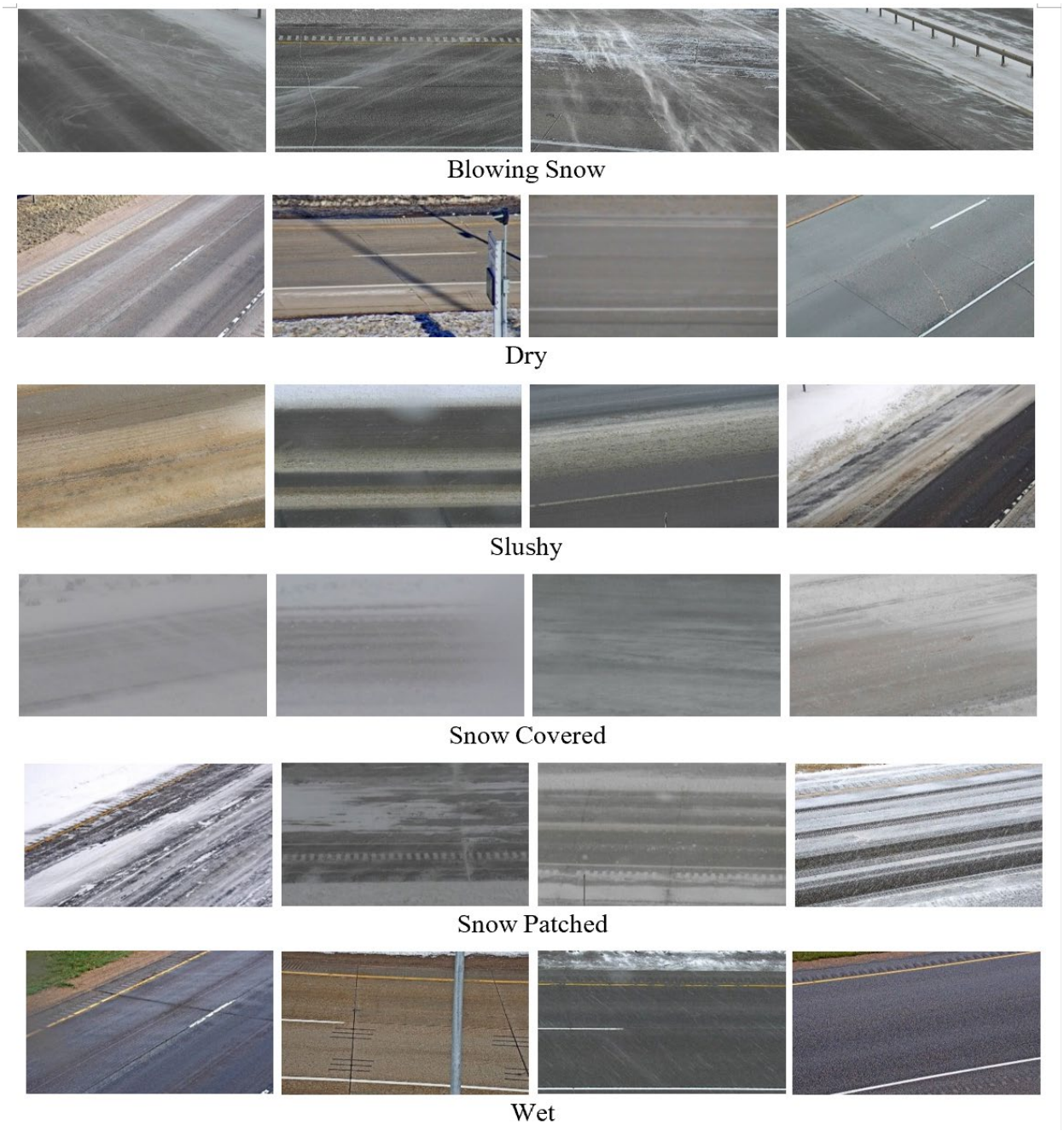

Figure 4: Illustration. Weather and surface condition detection based on road-side webcams. Source: Khan and Ahmed, 2022

The current traffic microsimulation models are capable of representing actual traffic with great accuracy, as well as providing high-fidelity 3D models of vehicles and infrastructure. Due to this performance of microsimulation models, the vehicle detection and counting modules tested in the pilot study are capable of identifying, tracking and counting vehicles from microsimulation videos, as shown in Fig. 5. This is an additional

advantage of the proposed research, as the team will be able to utilize microsimulation for additional testing and verification. As the research team has worked on microsimulation modeling for WYDOT in the past, we have models ready that can be used in this research.

Figure 5: Screenshot. Vehicle counting and classification from microsimulation videos

Currently, WYDOT operates approximately 150 Automatic Traffic Recorders (ATRs) and Automatic Vehicle Classifiers (AVCs) which report traffic volumes and vehicle classes. Reporting this information is a requirement from the FHWA, and it is also used for various applications, such as management, operations, planning, design and redesign of facilities, and similar purposes.

ATRs/AVRs and traffic cameras are two different technologies used in traffic monitoring and management. However, they can be used in conjunction and complement each other, which would provide a more comprehensive and accurate picture of traffic conditions. There are many ways in which traffic cameras, combined with computer vision, can complement the data obtained from ATRs/AVRs. First, the cameras provide real-time visual data. Once processed through the computer vision module, it will provide information on the number of vehicles, classes, section densities updated in real time. This would allow for an almost immediate identification of any issues in the traffic flow, such as increase in densities and reductions in speeds, which would indicate slowed/stopped traffic and queueing. Second, the information from traffic cameras would increase the accuracy in the recorded data, such as vehicle classifications, lane distributions and occupancies, updated in real time and complementing the results

obtained from the road sensors. Combining data from video cameras and road sensors can help traffic management systems make more informed decisions about traffic management strategies and other measures to improve traffic flow.

The biggest advantage of using traffic cameras for traffic flow estimation and management is the ability to use them as dynamic sensors, and install them when, where and for how long it is needed. Also, they can easily be installed on sections of roadways not covered by road sensors, where traffic monitoring needs to be conducted. The cameras are becoming more available, with lower prices and increased capabilities and reliability. Furthermore, cameras can be placed on Unmanned Aerial Vehicles (UAVs) (drones) and provide a bird-eye view of the roadway section of interest, or placed in vehicles as dash cameras. This would make them convenient for use in special purposes, such as planned events, work zones or incidents. The DSS modules proposed in this research would have a potential to significantly increase the capabilities of real time traffic management and optimization of traffic flow. Computer vision technology can be integrated with ITS to create a comprehensive traffic management solutions for recurring or non-recurring transportation problems. By combining real-time data from the computer vision systems, ITS can make informed decisions and optimize traffic operations.

Wyoming has made significant efforts to expand and upgrade its broadband infrastructure, including fiber optic network, to serve its widely dispersed population. Given the state's vast geography and relatively low population density, ensuring high-speed internet connectivity through fiber optics and other broadband technologies has been both a challenge and a priority. It is worth noting that major arterial roads in Wyoming are covered with a vast fiber optic network as illustrated in Figure 6.

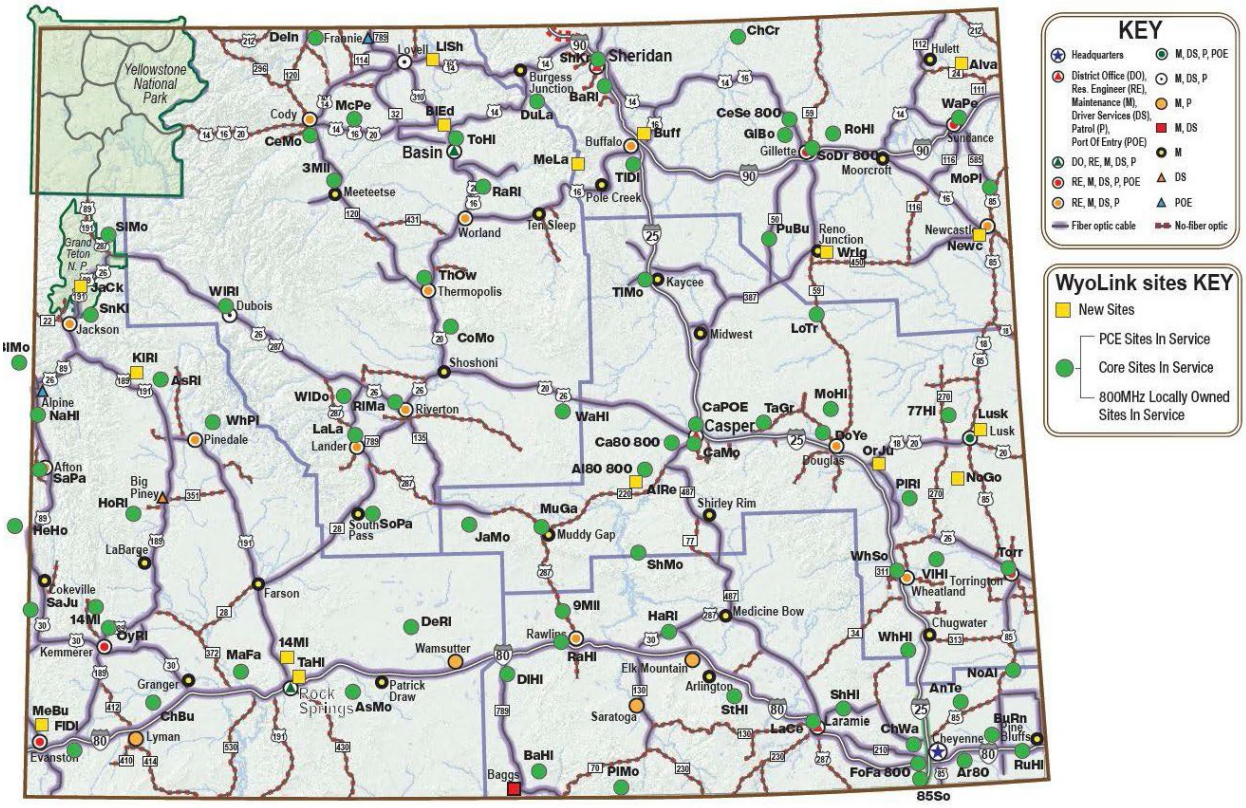

Figure 6: Illustration. Wyoming fiber optic network. Source: Broadband Task Force Presentation, 2020

Distributed Acoustic Sensing (DAS), with its ability to detect subtle vibrations and acoustic variations across vast stretches, stands as a pioneering technology in the realm of monitoring and surveillance. When integrated with machine vision from surveillance cameras, DAS can significantly amplify detection capabilities. While cameras visually capture the environment, often facing challenges with lighting, occlusions, and environmental interferences, DAS acts as an unerring 'ear' to the ground, filling sensory gaps and offering a comprehensive, multisensory surveillance solution. Together, they provide a synergistic approach to monitoring, where the strengths of one complement the weaknesses of the other, promising unparalleled accuracy and reliability.

The research presented in this proposal would bring significant value to WYDOT when it comes to data collection, traffic monitoring and management, and optimizations in real time. It is not expected that the current WYDOT policies and practices would need to change, as this would be an additional tool to assist in current operations. The review of literature and practice shows that the interest in this topic is increasing among researchers.

3. Literature Review

Computer vision is a subfield of AI that enables computers to extract meaningful insights from digital images, videos and other visual data sources (IBM, n.d.). Over the recent years, it has undergone rapid advancements and expansions, gaining prominence in various domains encompassing science, technology, engineering, medicine, and more. The transformative potential of computer vision extends to the realm of transportation, with applications spanning self-driving vehicles, safety enhancements, efficient traffic management, parking administration, real-time traveler information dissemination, and comprehensive monitoring of environmental conditions, among many others.

The U.S. Department of Transportation (USDOT) considers AI a promising tool to improve safety and innovation in transportation system applications (USDOT, 2019). One of the focus points of these activities is “adopting and deploying AI-based tools into internal operations, research, and citizen-facing services”, which, among others, includes the use of computer vision and machine learning in improving the efficiency and effectiveness of transportation systems, and advancing research.

In the development and training of object detection machine learning models in recent years, vehicle detection and tracking has been one of the popular areas. In their study, Ho et al. (2019) developed a computer vision-based roadside surveillance system which automatically analyzed loading, unloading and roadside parking activities. The system can be used to optimize fleet schedules by logistic companies, and optimize the use of roadside parking in busy urban areas. Liu et al. (2022) developed models for automatic congestion, and vehicle speed detection and estimation using computer vision and edge computing. They tested the system on the NJIT campus network, and showed that the model can provide correct estimates of traffic conditions. Similarly, Tran et al. (2023) developed a system that employs detect-and-track mechanism, which detects vehicles, tracks them and is able to create trajectories. The system can run on edge devices, instead of transferring video feeds to centralized processing systems. Azimjonov et al. (2023) developed a vision-based real-time traffic flow monitoring system that utilizes deep learning and machine learning techniques for vehicle detection and tracking at intersections. The study applies YOLOv3 (You Only Look Once, version 3) module, which is an object detection algorithm that is implemented with Fully Convolutional Neural Network (FCNN). They used live video feeds from traffic surveillance cameras to test the module. The results showed high accuracy in vehicle detection and counts, showing promise for real-time traffic management. Shao et al. (2022) developed a smart traffic monitoring system based on remote camera sensors and computer vision algorithms. The study used both historical and real-time traffic video information at the USDOTs Oak Ridge National Laboratory to develop optimal transportation management strategies. Computer vision algorithms were developed and applied to process the real-time camera data to obtain complete traffic information. The system simultaneously observed entry and exit points, signalized intersections and parking lots, as well as

electric vehicle charging locations. The results showed that real-time information can significantly improve the quality of management data and assist with decision making.

Nanda, Singh and Singh (2023) developed a computer vision algorithm based on YOLOv5 that can detect and count vehicles, and estimate densities on a section of a roadway. The algorithm is using video feeds from traffic cameras in India, and can be used to improve the operation of traffic signals and estimate future traffic projections when integrated with traffic simulation software. Alomari and Lebdeh (2022) developed an integrated computer vision-based system that detects and tracks vehicles, and computes related traffic statistics in real time using road surveillance cameras. The system operates in two stages. The first one is detection and identification, where the vehicles are detected and classified into corresponding vehicle types. The second stage is tracking, where the vehicle is tracked along its trajectory path to its target destination. The results showed that the system can perform reliably in real time with close to 100 percent accuracy.

The utilization of artificial intelligence approaches in traffic safety has been gaining a noticeable momentum through the past decade. Machine learning and deep learning techniques were used for detection of several weather and road surface conditions utilizing video data. Several datasets were examined by the Co-PI Ahmed research team including the Second Strategic Highway Research Program (SHRP2) Naturalistic Driving Study (NDS) and the WYDOT webcam datasets (Khan et al., 2021; Khan and Ahmed, 2019, 2020, 2021, 2023; Khan et al., 2022). Detecting weather and road surface conditions using machine learning and deep learning approaches has a substantial impact on transportation safety and can effectively contribute to Connected Vehicle (CV) applications.

Khan and Ahmed (2019) addressed the negative impact of snowfall on road conditions and its contribution to winter motor vehicle crashes. The study highlighted the need for real-time roadway weather information to enhance driver safety. It developed an affordable in-vehicle snow detection system using machine learning techniques and SHRP2 NDS video data. Two texture-based image features; Gray Level Co-occurrence Matrix (GLCM), and Local binary Pattern (LBP), and three classification algorithms; Support Vector Machine (SVM), K-Nearest Neighbor (K-NN), and Random Forest (RF), were utilized to train the snow detection models. Three weather conditions were tested (clear, light snow, and heavy snow), with the LBP-based features to achieve a high prediction accuracy of 96 percent. The results revealed that simple mobile apps, utilizing smartphone cameras and data connectivity, can effectively provide real-time roadway weather information with high detection accuracy.

Their research efforts were expanded to include another critical adverse weather condition, fog, to ensure safe driving (Khan and Ahmed, 2020, and Khan and Ahmed, 2023). The primary goal was to develop an affordable in-vehicle fog detection method that can offer accurate trajectory-level weather information in real-time. The study used SHRP2 NDS video data and employed various deep learning techniques, including

Deep Neural Network (DNN), Recurrent Neural Network (RNN), Long Short-Term Memory (LSTM), and Convolutional Neural Network (CNN). The analysis involved a dataset with three weather conditions: clear, distant fog, and near fog. Two optimizers, Adam and Gradient Descent, were used during training. The results showed that using the Adam optimizer significantly improved the overall prediction accuracy, with the CNN model achieving the highest accuracy of 98 percent. Similarly, the proposed fog detection method required only a single video camera, making it a cost-effective option for installation in departments of transportation maintenance vehicles to collect real-time trajectory-level weather information.

A rain detection system using an in-vehicle video camera was developed by (Khan et al., 2022) to provide real-time trajectory-level road surface weather information. The study utilized SHRP2 NDS video data and employed image-based classification techniques. Automatic annotation of extracted images from the video data was achieved through k-means clustering analysis. LBP-based image features were used as classification parameters to train detection models, with artificial neural network (ANN), RF, and SVM as classification learners. The overall detection accuracy of the trained RF, ANN, and SVM models was approximately 99.3 percent, 98.8 percent, and 99.8 percent, respectively.

Khan et al., 2021, developed a weather detection system based on trajectory-level video data extracted from the SHRP 2 NDS that could classify seven levels of weather conditions, including clear, light rain, heavy rain, light snow, heavy snow, distant fog, and near fog. The study leveraged advanced image processing techniques to extract relevant features from the image and subsequently, utilized these features to train three machine learning models namely, gradient boosting (GB), RF, and SVM. The overall detection accuracy of the weather detection models was found to be 81 percent, 82 percent, and 86 percent for GB, RF, and SVM models, respectively. Furthermore, the study advanced the methodology and developed a multilevel model based on a unique hierarchical structure which significantly improved the performance of weather detection with remarkable accuracy of more than 91 percent. The study was extended by (Khan and Ahmed, 2021) to generate a novel CNN architecture named RoadweatherNet that was meticulously designed for the detection of the pre-mentioned seven weather conditions. The evaluation results based on a test dataset demonstrate RoadweatherNet's excellent performance in detecting weather conditions, achieving an overall accuracy of 93 percent. Moreover, RoadweatherNet was compared to six pre-trained CNN models, such as AlexNet, ResNet18, ResNet50, GoogLeNet, ShuffleNet, and SqueezeNet, showcasing nearly identical performance with significant reductions in training time. The authors claimed that the proposed detection models are affordable and can be integrated into the smartphone platform aiming at facilitating weather-based variable speed limit systems (VSL) in connected vehicles environments

Khan and Ahmed, 2022, leveraged the available roadside webcam data to develop an affordable automatic road weather and surface condition detection systems. The

models focused on three weather conditions (clear, light snow, and heavy snow) and three surface conditions (dry, snowy, wet/slushy). Pre-trained CNN models, including AlexNet, GoogLeNet, and ResNet18, were modified through transfer learning for classification tasks. The best performance was achieved using the ResNet18 architecture, with an impressive overall detection accuracy of 97 percent for weather detection and 99 percent for surface condition detection. The authors recommended the utilization of the proposed models for accurate and consistent real-time weather information that can be readily available to road users and transportation agencies. Moreover, it could also be used to generate temporal and spatial variations of adverse weather for optimizing maintenance vehicle routes and schedules.

While another study was performed by (Mohamed et al., 2023) to develop an automated system for real-time detection of snow-related road-surface conditions, particularly focusing on blowing snow conditions, using existing webcams along interstate freeways in Wyoming. Blowing snow is a significant hazard that impairs visibility, affects drivers and vehicle performance. The study involved a thorough process of image reduction to create two distinct reference datasets. Six pre-trained convolutional neural networks (CNNs) were employed for classifying road-surface conditions, including AlexNet, SqueezeNet, ShuffleNet, ResNet18, ResNet50, and GoogleNet. For Dataset 1, AlexNet showed excellent performance with a training time advantage and an overall detection accuracy of 97.56 percent. Irrespective of training time, ResNet50 achieved the highest overall accuracy of 97.88 percent, along with the best recall and F1-score values. In Dataset 2, ResNet18 reached an optimal overall accuracy of 96.10 percent, while AlexNet had the shortest training time with an overall accuracy of 95.88 percent. The study also conducted a comprehensive comparison between pre-trained CNNs and traditional machine learning models. Analysis of confusion matrices indicated that AlexNet is the most effective model for detecting blowing snow events. The proposed models have the potential to automatically deliver real-time, accurate, and consistent surface condition information for use by road users and transportation agencies, ultimately enhancing traffic safety.

Ahmed et al. (2023) developed an AI tool for rapid traffic safety assessment utilizing video feeds at intersections. This innovative tool incorporates a novel framework that ensures precise vehicle and pedestrian detection and tracking, resolves issues related to object projection and camera mounting, transitions coordinate systems, and pinpoints of traffic conflicts, as depicted in Figure 7. This research serves as a foundational step in harnessing computer vision to enhance safety and mobility on roadways. In their 2024 study, Mohamed et al. addressed various limitations in vehicle and pedestrians' detection and tracking using computer vision. Their study utilized the latest YOLOv7 and CenterTrack monocular 3-D bounding cuboids algorithms to improve detection and tracking of road users with 95 percent precision and close to 93 percent recall. The study also enhanced post-processing algorithms to project vehicles' speed and acceleration trajectories more accurately on different planes.

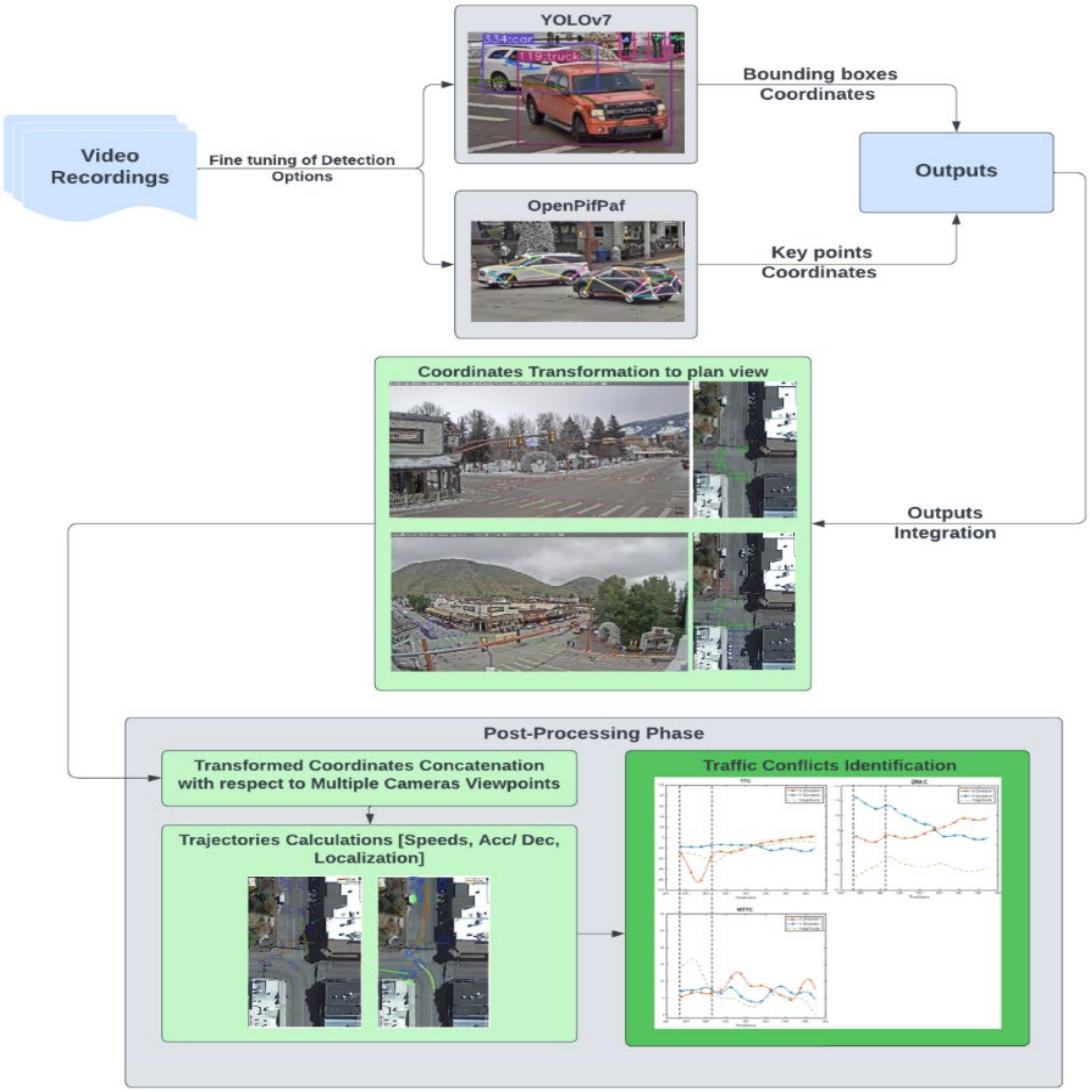

Figure 7: Illustration. Vehicle detection, tracking, post-processing, and conflict analysis framework. Source: Ahmed et al., 2023

Distributed Acoustic Sensing (DAS) technologies are based on detecting vibrations and capturing acoustic energy along optical fibers (AP Sensing, n.d.). It can use the existing fiber optic networks, and turn them into distributed acoustic sensors capable of capturing real-time data. There are currently many potential uses of DAS, such as perimeter security, earthquake monitoring, seismology research, structural health inspection, energy exploration, underwater positioning, railway monitoring, infrastructure monitoring, as well as monitoring flow of traffic (Shang et al., 2022).

Chiang et al. (2022) analyzed the use of fiber optic-based DAS, integrated with deep learning, in certain ITS areas. The results showed that the model they developed was capable of determine the size of vehicles with 92 percent accuracy, classify the level of

occupancy in managed lanes with 97 percent accuracy, and estimates the number of occupants in vehicles with 92 percent accuracy. In a follow-up study, Chiang et al. (2023) developed an algorithm able to classify vehicles with a 94 percent accuracy, and detect the size of vehicles with 95 percent accuracy.

Ende et al. (2021) introduced an analytical tool designed to provide exceptional temporal and resolution, aiming for optimal detection and monitoring of individual vehicles in dense urban settings. Their work presented two beamforming models specifically for vehicle detection, leveraging the rich spatio-temporal granularity offered by DAS measurements. Figure 8 (a) depicts two vehicles moving adjacent to the DAS cable set up on one side of the road: one heading away from the interrogator device and the other approaching it. In Figure 8 (b), one car is seen moving away from the interrogator at approximately 10 seconds, while two cars move in its direction. Given the positioning of the fiber cable on just one side of the road, the two cars advancing toward the interrogator register with more pronounced amplitudes. Existing literature indicates that distinct signal patterns emerge depending on various factors, such as the location, depth, installation technique, backfill procedure, soil composition, and conduit type related to fiber optic cables. As such, cataloging these characteristics becomes vital when evaluating the viability of DAS.

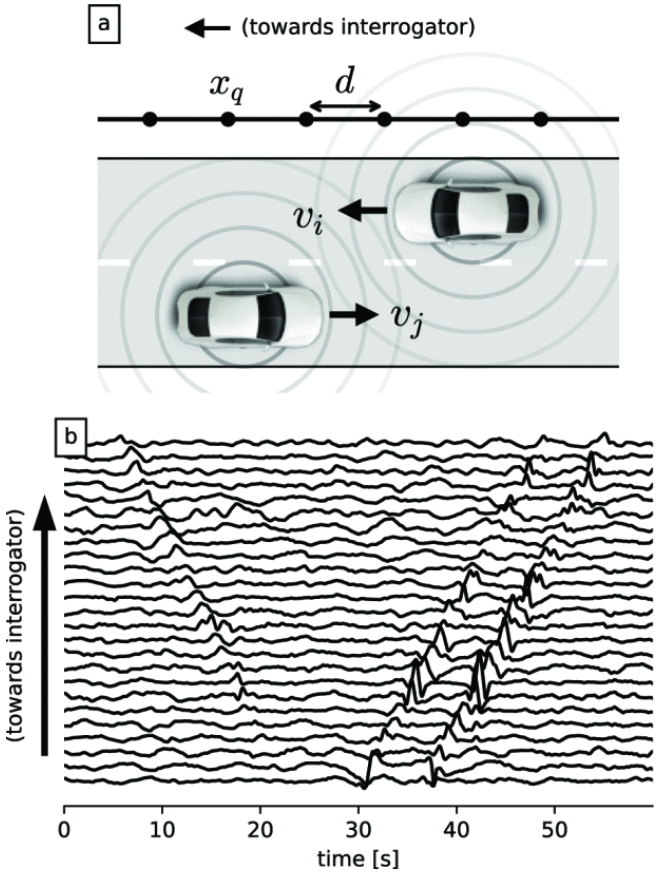

Figure 8: Illustration. Two beamforming models based on the proximity to the fiber cable. Source: Ende et al., 2021

Wiesmeyr et al. (2021) introduced a DAS-based module for traffic monitoring applications. The module estimates vehicle flows and speeds by utilizing fiber-optic cables installed parallel to a highway. The ground vibrations induced by passing vehicles are converted into signals, enabling the module to estimate traffic information along a road segment in one-minute intervals.

Ye et al. (2023) integrated DAS with deep learning technologies to monitor traffic conditions along a 500-meter section of fiber optic along a roadway in Beijing. The algorithm was able to perform vehicle detection, traffic flow estimation and speed analysis with high accuracy in near-real time.

DAS is increasingly garnering interest from transportation agencies both in the US and globally. However, it's essential to acknowledge that as DAS is in its early stages of deployment, multiple investigations will be necessary to assess its feasibility. An et al. (2023) examined the impact of coupling between the fiber optic cables and the ground layer on obtaining high-quality vibration. The study utilized DAS to detect vehicles vibration signals utilizing three distinct deployment methods. Among the three methods, cement-bonded fixed fiber optic cable installed on the road shoulder was the most effective, followed by the uncoupled fiber on the road, while the underground fiber optic cable ducts were the least effective.

This review is focused on representative research contributions in the realm of computer vision and DAS, specifically concerning their applications in traffic management systems. Among related research papers, the primary focus is of the exploration of similar algorithms and models, with the main goal of identifying the most effective approach for vehicle detection and tracking. Our selection of prior studies is based on their alignment with the goals of our research and chosen methodologies, which include the utilization of YOLO modules, among other techniques. It is worth noting that most of the past research in this domain has been conducted by computer scientists with the goal of developing and training computer vision and DAS models. The proposed research aims to advance the use of computer vision, DAS, machine learning and AI technologies for practical applications, and propose a comprehensive solution that WYODT can utilize to improve the efficiency and safety of traffic on Wyoming’s highway and transportation facilities.

4. Study Objectives and Outcomes

WYDOT’s mission is to provide a safe, effective and reliable transportation system. The proposed research is expected to benefit WYDOT’s mission and goals, by providing an automated tool to monitor and manage the transportation system.

Traffic monitoring is an essential component in transportation planning, traffic operations and management, and traffic safety. Accurate and efficient traffic monitoring systems can help identify congestion, improve traffic flow, enhance safety, and reduce

environmental impacts. With the rapid advancements in computer vision and DAS technologies, there is a great potential in utilizing these capabilities to enhance traffic monitoring and management.

The primary goal of this study is to assess the feasibility and practical utility of implementing computer vision and DAS technologies for traffic monitoring and weather applications in Wyoming.

The main research objectives of the study are as follows:

- Develop computer vision and machine learning applications with the capability to effectively utilize video feeds (real-time and recorded) from various visual sensors in Wyoming to monitor and estimate traffic conditions on the State's highways, as well as provide vision-based weather warnings and information. The applications will possess the ability to track and analyze traffic parameters, including traffic volumes, vehicle classifications, densities, and speeds, while also identifying potential issues in the system, such as congestions and queue formations. The emphasis of the applications will be on real-time monitoring.
- Evaluate the accuracy and reliability of the developed computer vision applications, such as their ability to correctly track vehicle volumes, classify vehicles into classes, determine their speeds, and calculate roadway densities, with an emphasis on real-time operations. The evaluation will be performed using recorded and real-time video feeds obtained from WYDOT and other state and local agencies, still images from WYDOT traveler information system, as well as from traffic microsimulation models for selected locations in Wyoming.
- Assess the capability of the applications to be applied to various scenarios, such as recurrent congestions, work zones, special events and incidents.
- Assess the feasibility and capability of the applications to serve as a DSS to assist WYDOT personnel in making traffic management decisions in real time.
- Assess the feasibility of integrating computer vision systems with the current traffic monitoring and management systems used by WYDOT and partnering agencies.
- Perform a feasibility study on utilizing DAS applications in Wyoming for traffic and weather monitoring and estimation, including advantages and disadvantages, required hardware and software, recommended locations for installation, limitations and solutions, costs of installation, and benefits to WYDOT, the traveling public and local communities.
- Assess the capabilities of DAS applications to successfully detect and monitor traffic along Wyoming's highways.
- Perform benefit-cost analysis in applying computer vision systems alongside current traffic monitoring and management applications in Wyoming.
- Perform benefit-cost analysis for implementation of DAS applications in Wyoming.

The outcomes of the study are expected to be as follows:

- A computer vision module for automatic estimation of traffic flow parameters and weather conditions, which uses video feeds and images from static and dynamic traffic cameras on Wyoming's roadway facilities.

- A DSS module based on computer vision with a capability of assisting transportation personnel with traffic management decisions.
- Traffic microsimulation models of selected sections and facilities, which can be used for other purposes in the future.
- A benefit-cost ratio for implementing computer vision systems within WYDOT and partnering agencies.
- Recommendations on the feasibility and practicality of implementing DAS technologies
- A benefit-cost ratio for implementing DAS applications in Wyoming.

This research is expected to provide WYDOT an additional tool for traffic management applications, which will have the capability to improve the effectiveness of the transportation systems in Wyoming.

5. Benefits to WYDOT

The effectiveness and reliability of the transportation systems in Wyoming is of a great interest to WYDOT. The effective management and traffic operations are highly dependent on quality and timely data on the systems' performance. WYDOT is investing a lot of resources into data collection, analysis, and decision making to improve traffic operations, especially considering the challenging traffic, roadway and environmental conditions in the State. This research is expected to bring significant benefits to WYDOT in data collection, assessment and decision making applications. Visual, real time data can provide the most information for any facility. However, one issue is that visual data can be difficult to process quickly, and would require significant manpower. Automated computer vision is becoming a powerful and effective tool that can successfully replace humans when it comes to object detection, identification and tracking. Its application to traffic management, operations and safety has a significant future potential. A pilot study currently being performed by the UW research team shows that computer vision modules are capable of accurately detecting, classifying and counting vehicles using recorded videos, real-time video feeds, still images, as well as from 3D traffic microsimulation.

WYDOT already operates approximately 230 traffic cameras along its roadways, and some cities (such as Laramie and Jackson Hole) have traffic surveillance cameras which provide live video feeds that can be accessed on YouTube. Therefore, there is a significant amount of real-time video information that is typically underutilized. An automated computer vision system could be connected to these video feeds, and monitor traffic, analyze traffic conditions, and assess environmental and weather conditions. One issue could be caused by the fact that some of the traffic cameras do not provide video feeds due to low bandwidths, but rather still images updated at certain intervals. However, the computer vision is also capable of processing still images, and can still provide useful information.

Another expected benefit will be the use of cameras for special purposes, such as work zones, special events and incident management. In many occasions, the roadway

sections and facilities that need temporary traffic management are not covered by roadway sensors. Cameras, which are becoming more affordable and available, can be temporarily installed at these locations and connected to the computer vision module to monitor traffic flows and assist with management and operations.

In addition to traffic monitoring, the modules will have the capabilities of analyzing traffic conditions in real time, provide useful information and assist with decision making. This will lead to a better traffic management, therefore improving traffic mobility at the given location. Research and practice have also shown that better traffic mobility improves traffic safety, so the benefits will be multifold.

The benefits and costs of these applications will be determined throughout the study, taking into account specific locations, needed initial investments, operation and maintenance costs, delay reduction, value of time for various vehicle classes, as well as added safety improvements. The UW research team previously performed similar analysis for mobility and safety improvements along I-80 in Wyoming (Zlatkovic, Ksaibati and Haq, 2020), and can reuse some of the methodologies in this research.

Current research on the application of DAS technologies shows a great potential of using these systems for accurate estimation of traffic conditions, including vehicle classifications, vehicle occupancies, vehicle sizes, traffic flows and vehicle speeds, in near-real time. The system uses acoustic signals transmitted by the passing traffic, so it is expected that it will be less prone to environmental disturbances, such as extreme weather conditions in Wyoming. The State's fiber optic network in undergoing an expansion, so it will provide countless opportunities for DAS installations. This research will assess various potential installation locations, and recommend those that might bring the biggest benefits to WYDOT. In addition to traffic monitoring, DAS can also be used in structural health monitoring and security.

Mobility improvements are well accepted in the community at large, as they can reduce queuing, delays and associated costs, as well as improve safety. Therefore, it is expected that this research, its results and implementation will be well accepted among the traveling public and local communities.

6. Applicable Questions

The research team does not anticipate any significant barriers and issues regarding the implementation of the proposed systems. It is expected to be an addition to the current traffic monitoring and management systems, and add value to their operations.

The implementation can be segmented into phases, as needed. In essence, the systems can be implemented for selected locations which experience more traffic issues. There are still many highways and road facilities in Wyoming that do not experience issues due to low traffic volumes, so a system like this might not be justified. There are many locations and special circumstances where the computer vision and system would be very beneficial, such as freeway sections with challenging geometry

and high truck volumes, interchanges in the vicinity of large traffic generators, urban sections with high traffic volumes, busy intersections in cities, but also work zones, incident locations and special events. The research will examine the benefits of installations, and recommend a road map that would be most suitable. Similarly, the DAS applications can be implemented at areas where there would bring most benefits, such as sections of highways not covered by other types of sensors, or sections where road sensors experience significant disruption in their operations due to the environmental conditions.

The recommended system installation will not include any major redesign or reconstruction, in fact it will mainly use the existing infrastructure, and therefore the National Environmental Policy Act (NEPA) process will not be required. There will not be any impact on the surrounding lands either. The data produced by this project is not expected to be confidential or sensitive, as it will not consist of any identifying information. There will be no evident evolution of any technologies associated with this project.

The products of this study are not expected to be patented or trademarked, however the research team and WYDOT will prefer to keep the copyrights on the reports and other publications.

7. Statement of Work

Performance period of this study is estimated to 18 months, split into eight main tasks. The estimated start date is December 15, 2023, and the end date June 15, 2025. The tasks related to the computer vision system will be led by the UW team, while the DAS-related tasks will be led by the UC team. The entire team will work collaboratively and assist in each task as needed, in order to ensure a successful completion of the study.

As there are two systems that will be analyzed in this research, some of the tasks are split for each system separately. The tasks necessary to implement the study successfully are detailed as follows:

Task 1: Review of Literature and Practice (Dec 2023 – Jan 2024, and updated throughout the study)

The research team will review the existing research studies, developments in the computer vision and DAS areas, implementation capabilities and recognized issues. The finding from the literature will assist the team with updating tasks and approaches to the research.

Task 2: Development of Computer Vision Algorithms (Dec 2023 – Jun 2024, and updated throughout the study)

Within this task, the research team will develop functional computer vision algorithms, capable of working with real time video feeds, recorded videos, still images and traffic microsimulation videos. At the minimum, the algorithm needs to be capable of

classifying and counting vehicles, estimating their speeds, and calculating roadway densities, as well as identifying weather conditions.

Task 3: Feasibility of Applying DAS Applications in Wyoming (Dec 2023 – Dec 2024, and updated throughout the study)

DAS is a relatively novel technology applied to transportation systems. The main task related to the DAS applications in Wyoming is to determine the feasibility of its installations and operations. Within this task, the research team will determine how feasible those applications would be, what would be the best locations for installation, what are the potential limitations and issues and how they can be addressed, what would be the hardware, software and technology requirements, what is the needed expertise of the personnel who will be using the systems, and how those applications would benefit WYDOT and partnering agencies. This will be conducted by surveying DOTs and stakeholders to identify lessons learned and challenges in implementing DAS. The research team will perform market research on the advancement and limitations of DAS and its wide spectrum of applications. To provide guidelines on seamless and most cost-effective integration of DAS in Wyoming, road asset inventory of locations, types, condition of fiber optic cables, conduits, backfill, as-built specifications of fiber optic cables in the state will be performed.

Task 4: Testing of Computer Vision Algorithms for Regular Conditions and Special Purposes (Jul – Dec 2024, and updated throughout the study)

The functionality of the algorithms will need to be validated and verified for various implementations. Within this task, the team will test their functionality, fine tune their operations and validate their performance. One of the emphasis of this task would be on the use of dynamic and temporary video sensors and their application to specific conditions, such as work zones, incidents and special events.

Within this task, the team will develop and use microsimulation models for various facilities in Wyoming, and integrate the computer vision algorithms with the models. This would provide additional tools for traffic operations optimization, management and analysis.

Task 5: Development and Testing of Traffic Management Applications (Sep 2024 – Mar 2025)

The computer vision algorithms are expected to provide a large amount of information on real time traffic conditions. This information will be used to optimize traffic operations and make management decisions in real time (e.g. variable speed limits in work zone areas). The application developed in this task is expected to assist traffic management personnel with implementing optimal decisions based on the given inputs.

Task 6: Assessing the Capabilities of DAS Applications (Jan 2025 – Apr 2025)

The capabilities of the recommended DAS applications in Wyoming will be explored with respect to traffic monitoring, considering the challenging traffic, roadway geometry and environmental conditions. Selected locations will be replicated in traffic simulation, with DAS operations simulated through Applications Programming Interface (API). The simulation analysis would provide further insights into the benefits of DAS installations, and assist in pinpointing the most beneficial locations.

Task 7: Benefit-Cost Analysis and Installation Schedule (Apr – May 2025)

The research team will analyze various locations within the State, and determine where the application of the proposed systems would have the greatest benefits. The computer vision system costs might include updating some of the traffic cameras, or obtaining new ones for dynamic implementations. The team will assess the costs of the new hardware, as well as the implementation costs of the system. The DAS system implementation costs would include acoustic interrogators and accompanying technology, software, installation and training. The final cost will depend on the number of proposed installation locations. Finally, the benefit-cost analysis will be performed to estimate the optimal schedule of implementing the proposed computer vision and DAS systems.

Task 8: Reporting (throughout the study, Final Report Jun 2025)

The research team will provide constant updates to WYDOT throughout the study. Progress reports will be sent in predetermined intervals. A draft final report will be submitted toward the end of the study in June of 2025. The team will allow the WYDOT personnel and other stakeholders to comment on the findings, and those comments and recommendations will be included in the final report. In addition, the research team will work on journal publications and conference presentations to disseminate the results of the research.

8. Budget and Matching Funds

The total cost of this study will be **$191,143** for the 18-month performance period. The UW team budget amount totals $105,764, while the UC team total budget accumulates to $85,379. The breakdown of the study costs is given in Table 1, including detailed budget items of the UW team. In addition, the subcontract cost breakdown for the UC team is shown in Table 2. The UW research team will provide matching funds from the College of Engineering and Physical Sciences (CEPS) Engineering Initiative funds of **$25,000**, which are already in place.

Table 1: Total Study Budget and UW Cost Breakdown

WYDOT CV/DAS proposal (18 months)		
CATEGORY	**Budgeted Amount**	**Explanatory Notes**
Faculty Salaries	$20,000	
Grad Student Salaries	$26,757	PhD student 3 semesters
Fringe Benefits	$8,662	40.9 percent faculty, 1.8 percent students
Total Salaries and Benefits	**$55,419**	
Subcontract UC	$85,379	
Domestic Travel	$3,000	Conference and meeting travel
Other Direct Costs	$15,488	PhD student T&F+ins 3 semesters
Total Other Direct Costs	**$103,867**	
F&A (Indirect) Costs @ 20 percent	$31,857	WYDOT 20 percent all included
TOTAL WYDOT COSTS	**$191,143**	
Matching funds	**$25,000**	CEPS EI fund

Table 2: Itemized UC Subcontract Budget

UC subcontract breakdown (18 months)		
CATEGORY	**Budgeted Amount**	**Explanatory Notes**
Faculty Salaries	$28,950	
Grad Student Salaries	$14,283	PhD student
Fringe Benefits	$9,823	
Total Salaries and Benefits	**$53,056**	
Domestic Travel	$4,000	Conference and meeting travel
Other Direct Costs	$12,229	PhD student T&F+ins
Total Other Direct Costs	**$16,229**	
Indirect Costs	$15,094	Not applied to student T&F
TOTAL SUBCONTRACT	**$85,379**	

9. Implementation

This study will develop computer vision-based system for traffic and weather monitoring, and management and operations optimizations. In most part, the proposed system will

use the existing cameras, and be added onto the existing traffic management systems within WYDOT and partnering agencies, who will be mainly responsible for implementation. For specific purposes, it might require installations of new fixed or dynamic video cameras. The implementation process will include several steps.

First, the system will need to be implemented in the optimal order to bring the most benefits. The research team will perform a benefit-cost analysis for installation locations, and provide an optimal roadmap of installations, based on the available funds. The hardware from existing traffic cameras is already set up, the data are being transmitted to WYDOT, and the part of the data are available to the general public. The system will consist of codes written in Python, and could be added to the existing traffic management stations, or installed on separate machines. In the case that the new camera installations are recommended, they will need to be installed and connected to the systems. If dynamic cameras are needed (e.g. work zones or incidents), wireless transmission might be used to share the video feeds. In essence, the proposed computer vision system will be able to work with any videos it can access, so the transmission technology will not have any impacts. The proposed system can be integrated with the existing ones, or run as separate applications to assist with the currently used systems.

After the implementation, the systems will need to be checked, tested and validated as necessary. The research team will provide the required documentation and user guides to assist with this process. Furthermore, the research team will provide all necessary hands-on trainings on how to use the applications. As the system is being used by the WYDOT and other authorized personnel, the research team will welcome any feedback on its operations, so that it can be updated as needed in the future.

Furthermore, the research will assess the feasibility of installing DAS applications along Wyoming's transportation facilities. The outcomes of this assessment would be the recommended locations for installation, necessary hardware, technology, software and expertise requirements, costs of installation, and benefits of the system. As a result, the team will recommend to WYDOT how many installations would be optimal, where to install them, and how to integrate them with the existing systems.

10. Technology Transfer

The findings and recommendations from this study will be shared with WYDOT throughout the research. The research team also has extensive experience of disseminating research results to the wider audience through publications and presentations. Potential venues where the research will be presented include the Transportation Research Board (TRB) annual meeting, the Institute of Transportation Engineers (ITE) meetings, and the Institute of Electrical and Electronics Engineers (IEEE) conferences conference. The research team will seek input from other interested parties to improve upon the study design and methodology. The findings of this study

can also be included in current and future university courses in transportation engineering.

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