The Thesis Committee for Morgan Paige Avera
Certifies that this is the approved version of the following thesis:

Framework for Leveraging Data from Autonomous Trucks to Improve State Maintenance Operations

APPROVED BY
SUPERVISING COMMITTEE:

C. Michael Walton, Supervisor

Zhanmin Zhang

Framework for Leveraging Data from Autonomous Trucks to Improve State Maintenance Operations

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Morgan Paige Avera

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Framework for Leveraging Data from Autonomous Trucks to Improve State Maintenance Operations

Morgan Paige Avera, M.S.E.

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Supervisor: C. Michael Walton

Freight is key in fueling the economy and trucks are a vital connector which moved approximately 30,000 tons of cargo per day in 2018 [92]. Technology is improving, a shortage of drivers continues to expand, and fatalities occur on highways each day. An urgent need to move goods safely and efficiently has propelled the development of autonomous trucks (ATs). Using a combination of technologies, computing can replace a human driver for long, monotonous stretches of highway driving. As ATs hit the road, they are collecting massive amounts of information which could be valuable to those managing and maintaining roadways. Simultaneously, state agencies lack the resources needed to maintain the roadways which provide vital connectivity. Routine maintenance addresses day to day concerns which are often the hardest to track considering the lack of predictability. While it is simple to replace a fallen sign, it is hard to know when a sign has fallen. States have worked to develop systems for sourcing feedback from those who travel on their roadways, but there would be distinct value in adding another source of information. The data being collected by newly deployed ATs can be leveraged to assist in identifying routine maintenance concerns, so they can be addressed quickly which keeps roads in a better condition.

This study lays out how state agencies can implement a data-sharing framework to leverage the operation of ATs on their roadways. Working together, a platform can be built into existing systems that allows AT companies to report maintenance events they spot during operation on state-owned highways. These reports would have higher veracity than typical reporting mechanisms because ATs are equipped with high-quality cameras. Using data provided by Kodiak Robotics, a prototype mapping module was created to showcase how this system would work. Input was provided by private sector and public sector representatives. Both groups agree that there is valuable data available which could be leveraged by the state. Since the data involved in reporting maintenance events is not critical to AT operation, this could provide a starting point for state agencies to work with autonomous technology developers without navigating complex data-sharing agreements.

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CHAPTER 1
INTRODUCTION

America's 128 million households and nearly 8 million business locations rely on a robust and efficient freight network [92]. The interstate highway enables goods movement across the country strengthening the economy and pushing growth. Trucks are the primary mode for moving goods once they have entered the country. In 2018, 11 million tons of goods were moved by trucks which far exceeds the secondary mode, pipeline, moving 3 million tons [92]. The trucking industry is facing a driver shortage that continues to grow as carriers struggle to find qualified applicants. As of 2018, there was a shortage of over 60,000 drivers which is only predicted to grow in the coming years as the workforce retires [20]. In tandem, the rising demand for trucks to move goods and the growing shortage of drivers available has propelled the development of autonomous trucks (ATs).

Deployment of ATs has quickly exceeded that of other autonomous vehicles (AVs). AVs serving passengers primarily operate in urban environments where the surroundings are more complex. ATs must travel at a higher speed to operate on highways, but there is less to look out for than on a city street being used by cyclists, pedestrians, and other vehicles. Additionally, the business model for delivering goods with ATs has been proven out whereas the business model for passenger AVs must be developed. Several AT companies are already actively making deliveries using public roadways and this number is expected to grow quickly in the next few years. While safety drivers remain present in the vehicle, they are often not controlling the truck and, instead, let an on-board computer navigate the roadway environment. ATs understand their surroundings through a suite of sensing technologies, including several high-quality cameras directed at the road. During operation, these cameras take in vast amounts of

information – to the point that it is impractical to collect all the data being generated. Despite the value of this data being collected, it is not being leveraged except to further the development of the autonomous driving system (ADS).

At the same time, maintenance operations continue to rely on traditional systems and have been slow to leverage technological improvements. The American Society of Civil Engineers (ASCE) gave America's road network a grade of D in their most recent analysis [4]. A significant portion of roads are not in a state of good repair and, with current funding levels, more sections of road will fall into disrepair [14, 23]. Maintaining a state of good repair is important for driver comfort, but also driver safety. For example, potholes are not only uncomfortable to pass over, they can cause damage to a vehicle or a collision. While autonomous technologies are advanced, they still operate best on a road which is well maintained. Both human drivers and some AVs rely on striping to define the extent of each lane. Faded and missing pavement markings leads to confusion when driving at night or during adverse weather [47]. As the state department of transportation (DOT) struggles to find funds to keep up with maintenance needs, they do not have the resources to survey each road on a frequent basis. There are methods in place to determine where routine maintenance concerns are arising, but this system has gaps and would benefit from additional data.

There is distinct value in utilizing the cameras on ATs to identify and report routine maintenance events that occur on state-owned highways. The AT companies can report these events to the state DOT to support a timely repair which creates a safer roadway environment for their vehicle. This mutually beneficial reporting framework is feasible to implement because it meshes well with existing practices. AT companies already have cameras pointed at the road and they stand to benefit from routine maintenance events being addressed quickly. State DOTs can take in reports of routine

maintenance events, so they might be addressed more quickly. Working together would bring benefits to both participants and other roadway users. This study outlines a framework for connecting AT companies with state DOTs to provide reports on routine maintenance events occurring on roadways. Event submissions contain coordinates, a description of the maintenance concern, and an image of the maintenance concern. This system must work across state lines and across AT companies in the long term or it will not be sustainable. Developing data standards early on will set precedents which can be maintained in future data-sharing endeavors. Creating this connection will provide state DOTs with a valuable new data source, encourage a good relationship between AT companies and state agencies, and support better roadway conditions for all vehicles travelling on the state-owned highway network.

CHAPTER 2
BACKGROUND

The transportation industry is in a period of rapid innovation where new solutions are being developed that can address critical problems. Public agencies must keep up with these changes and adapt their own practices so they can make use of the limited funds which are available. Multiple states have AV operations in some capacity, but the data they collect is not yet being captured and leveraged by public agencies. By utilizing the presence of ATs on roadways, DOTs can begin to modernize a practice which currently does not utilize emerging technology. While it may be infeasible to send out maintenance workers to inspect each lane-mile owned by the DOT, it is easier to digest reports of routine maintenance concerns and continue to do inspections of a smaller portion of road segments. Additionally, this data feed presents a good place to begin developing a data-sharing relationship with AT companies. Reports of routine maintenance events do not require companies to share proprietary data. State agencies cannot sign a non-disclosure agreement (NDA) because they are subject to Freedom of Information Act requests. However, this application of data-sharing can be enabled without development of complex data-sharing agreements. Once the relationship has been established, DOTs can consider how they might utilize the vast quantity of high-quality data that ATs collect regarding traffic conditions, pavement quality, and more.

2.1 Autonomous Freight Industry

Autonomous vehicles (AVs) are no longer theoretical, instead, there are multiple operational deployments showcasing the technology. Some simpler forms of vehicular autonomy such as adaptive cruise control and lane-keep assist are already available in consumer vehicles. In the freight industry, there are several companies making deliveries

using an autonomous driving system (ADS) to operate their trucks. These vehicles understand their surroundings through a suite of sensor technologies that are constantly collecting data. As AVs scan the roadways, they pick up information that could help support routine maintenance operations. Operating along highways, ATs regularly come across potholes, faded lane striping, and other routine maintenance events. The missing link is a framework for these companies to collect information on routine maintenance events and report it to the relevant public agency. This study proposes a system that could provide this link and provide state DOTs access to a new data source. Creation of this connection will allow data that is already being collected to be leveraged for the good of the travelling public.

The development of AV technology has rapidly accelerated in recent years. The Society of Automotive Engineers (SAE) established levels of driving autonomy which range from Level 0 to Level 5 (Fig. 1). Levels 0 to 2 are often referred to as low-level automation where a human driver is required to execute almost all the driving task, but some assistance is provided by vehicle technology. Levels 3 to 5 are considered high-level automation where the vehicle can drive itself. Level 3 AVs require driver intervention when a task is encountered that the vehicle is not capable of navigating. Level 4 AVs must be capable of navigating defined environments with no human intervention. Level 5 AVs refer to a theoretical future where an AV could navigate any roadway environment without human intervention [72]. The work presented in this thesis focuses on Level 4 automation where a vehicle can navigate designated routes without human intervention.

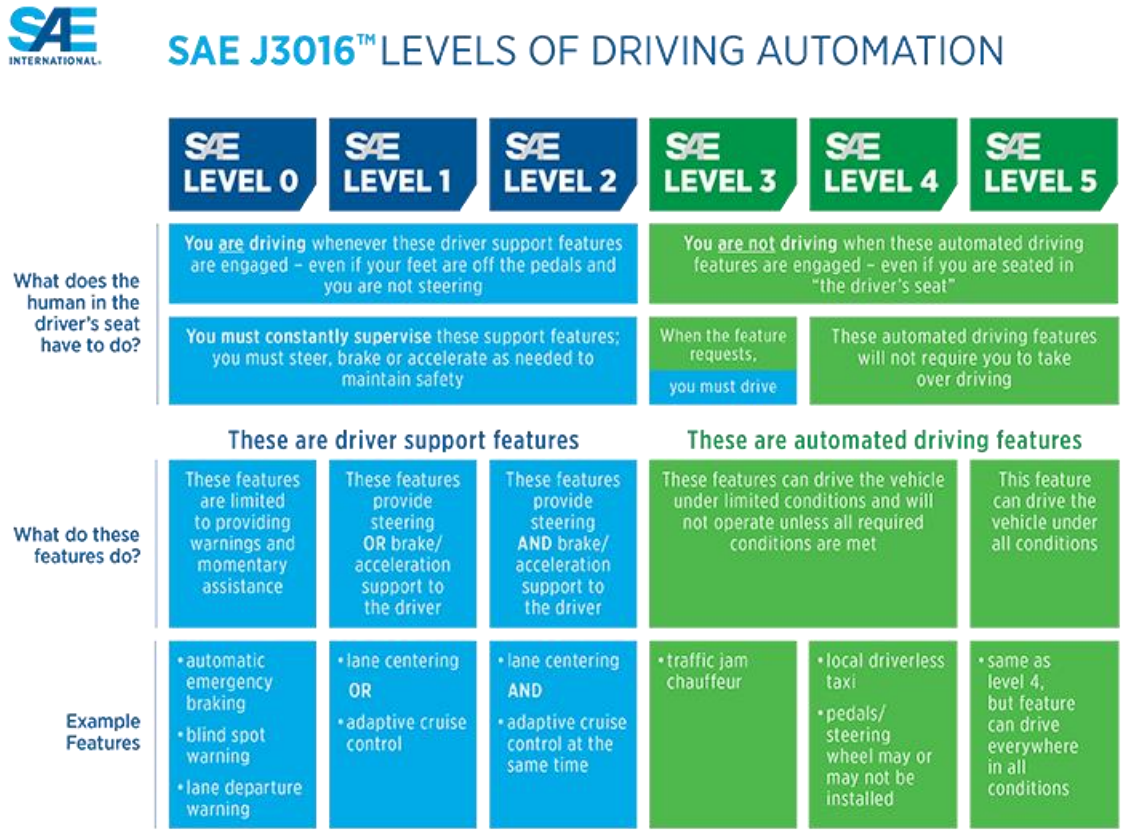


Figure 1: SAE Levels of Automation [67]

AVs operate like humans when executing the dynamic driving task (DDT), but every step must be spelled out explicitly. The process consists of sensing the surroundings, determining appropriate behavior to achieve a goal, and executing the decision [68]. The first step of perceive surroundings is executed using a suite of sensor technologies. This suite of sensors often includes cameras, radio detection and ranging (radar), light detection and ranging (lidar), global positioning system (GPS), and inertial navigation system (INS). In tandem, these technologies provide a high-quality view of the roadway environment which is used for decision making. As an example, an AT might sense that there is an object in their lane ahead. In the next step, the ADS analyzes

the surroundings and must decide how to navigate the upcoming roadway [68]. Continuing the example, the AT may decide to change lanes to avoid the object which was detected. Based on the decision made, the AV then executes the planned path. In this example, this step would be composed of turning on the blinker and navigating into the adjacent lane. As the vehicle continues to move it will repeat the process of sense, perceive, and execute [80, 86]. How an ADS performs each of these steps is what sets apart various AVs from each other.

Humans have the benefit of many years learning how to use context clues in classifying objects, but computers cannot easily make inferences. When a human driver encounters an object in the street, they instinctually make judgements about what the object is and quickly plans if and how they will need to adjust their driving in response. However, an ADS must be explicitly told how to interpret objects and what risks are acceptable which is a complex process [30]. This is particularly relevant to navigating urban streets where surroundings are more complex than those of an interstate highway. The likelihood of anyone walking across a multi-lane highway is significantly lower than the likelihood of someone doing this on a city street. This means that, in a sense, ATs have less to worry about. The lower complexity of highway surroundings and strong economic incentives have driven the rapid development of Level 4 ATs.

2.1.1 Technology Behind Autonomous Trucks

The technology powering ATs includes an on-board computer which processes information supplied by a suite of sensing technology. The on-board computer is responsible for taking information from sensors, determining the appropriate reaction, and executing this action. ATs primarily rely on a combination of technologies consisting of camera, lidar, and radar. Each technology can provide valuable information, but

limitations prevent any one technology from completing the DDT on its own. Instead, the technologies work in tandem to provide a comprehensive vision of the surrounding road environment. In the realm of ATs, it is particularly important to have short-range and long-range sensing capability.

The most familiar sensors enabling autonomous operations are cameras which are efficient at capturing a detailed view of the surroundings. Cameras are placed strategically on the vehicle to provide a clear view of what is ahead, next to, and behind the vehicle. Camera placement is more complex for ATs than passenger AVs because the presence of a trailer can obscure many views available from the cab. Realistically, cameras cannot be placed on trailers as they would need to be attached to a new trailer with each delivery. Cameras must be carefully calibrated to provide a cohesive view of the surroundings [86]. Cameras are the least expensive of the three sensing technologies which increases their appeal. However, the view available from cameras is easily obscured by harsh weather conditions and processing footage is computationally expensive [44]. Cameras have the important ability to recognize colors which helps to identify traffic signals, emergency vehicles, and construction zones [3, 30]. Cameras provide vital textural information which can supplement radar and lidar information to effectively identify objects. ATs can use short-range and long-range cameras to provide a detailed view of the immediate surroundings while keeping an awareness of what is further ahead [42]. Cameras are useful AT sensors as they are relatively inexpensive, widely available, and capable of capturing detailed information. Cameras are restricted by the computational cost of processing footage, the ease with which the view is obscured, and the reduced functionality in nighttime conditions.

The next technology, radar, is adept at detecting the location and speed of objects regardless of weather conditions. The implementation of radar technology allows an AT

to send out radio waves and understand its surroundings based on how these waves come back to the sensor. Short-range radar has a wide field of view (typically 150 degrees) which can detect the presence of an object and its speed using the Doppler effect. The Doppler effect allows a radar to detect speed of an object in a single measurement instead of needing to compare multiple measurements [41]. Long-range radar can easily extend the vision of a vehicle out to around 300 to 500 meters, but this is insufficient forward vision for standard ATs. AT companies have worked hard to acquire radar technology which can perceive objects up to 1000 meters away [48]. As the field of vision is extended outward, the resolution of the image lowers in compensation which means that at a long distance the radar is only capable of providing a rough image. Even with lower resolution, the extended field of view is essential to ATs because they require more time to slow down or stop. The ability to function in weather which is challenging for lidar and cameras makes radar essential to autonomous operations. Radar is limited by its inability to provide a detailed representation an object which makes it difficult to understand what an object is.

Lidar is the most expensive and least mature technology being used by autonomous vehicles. There has been debate around the necessity of lidar with a few companies trying to build ATs without it [48, 79]. Lidar works similarly to radar using laser bursts in replacement of radio waves. Along the same line, lidar and radar both have various ranges which they can operate that to provide different perspectives [86]. The lidar unit spins to create a full 360-degree view which generates a detailed map of the surroundings as shown in Figure 2. The benefit of an image created by lidar compared to footage from a camera is the reduced computational cost of analysis. This technology relies on its own light to operate which means it is more effective at night than cameras [42]. However, lidar does not function well amidst rain, snow, dust, and other

challenging weather conditions. The presence of snowflakes or dust particles absorb the light which allows lidar to function [9]. Lidar is not capable of perceiving color or texture which can make it more difficult to effectively categorize objects. Lidar units have seen price reductions in recent years, but low-cost models are not effective for the needs of ATs. According to industry experts, it is more common for a company to spend upwards of $50,000 to acquire a unit which can provide the resolution and field-of-view necessary. On its own, lidar would be an expensive way to perform the sensing task and it is unreliable in challenging weather. While lidar provides a valuable view of surroundings with more detail than radar and less computational cost than cameras, it is not a comprehensive solution to understand the ATs surroundings.

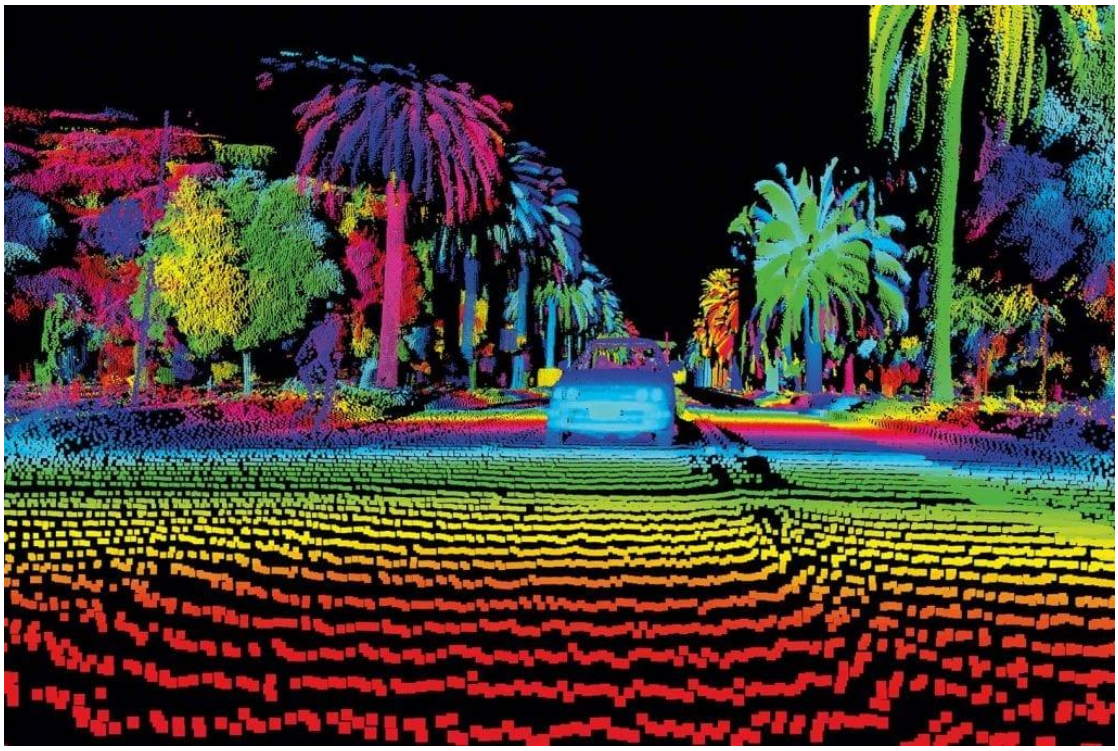


Figure 2: Example Lidar Scan [69]

Sensor fusion brings together lidar, radar, cameras, and supplemental sensor information to provide a cohesive view of the world around an AT. The term sensor fusion refers to the process of blending the different views provided by each sensor which provides a better view of the surroundings than any individual technology is capable of [41]. This process allows ATs to leverage the proficiencies of each technology while reducing their weak points. In addition to the three primary technologies discussed, GPS and INS are used to localize the vehicle and understand its position on the road [42, 81]. Before ATs are able to operate on a new route, the route must be driven to develop a high-definition (HD) map. The vehicle uses this as another input to help it understand what can be expected along the drive. Beyond this, some ATs use audio input to detect emergency vehicles and some AT companies are exploring the value of thermal sensors [86, 81]. In general, ATs use supplemental technologies to provide texture and context to the surroundings but will listen to the three primary sensors where there is conflicting input. ATs cannot rely on static information, such as previously constructed maps, because the highway environment changes relatively rapidly [42]. ATs operate by blending together the images created by the suite of sensors and using the available information to make navigational decisions.

2.1.2 Leaders in Development

The primary competitors in the AT space are TuSimple (Fig. 3), Kodiak Robotics (Fig. 4), Waymo, and Embark. Each of these companies have trucks which have run delivery routes and/or continue to run delivery routes using autonomous operation. Aurora is a company which aims to develop passenger vehicle autonomy and freight vehicle autonomy. The company recently announced a plan to bring their trucks to Texas roadways which will add to the field [36]. Starsky Robotics was amongst these

competitors and did the first driverless test run on a public road in Florida, but ran into funding issues and the company has shutdown [37]. Uber acquired the company Otto as part of their self-driving vehicle division and ran several deliveries on public roadways. However, Uber decided to shut down this program in 2018 to focus resources on their self-driving passenger car [44]. Tesla recently introduced the Semi which is a fully electric truck that has advanced autopilot capabilities that the company is well known for. The notable thread connecting these companies is the focus on the highway environment. While passenger vehicles and last-mile delivery vehicles focus on local streets, these larger vehicles are taking on a more straightforward roadway environment. This project focuses in on ATs instead of tackling the entire AV industry because ATs are operating on state owned roadways and will continue to cover longer stretches of roadway than other AVs.

Figure 3: TuSimple Truck [81]

Figure 4: Kodiak Robotics Truck [42]

There are a few notable technologies that are not long-haul ATs which are relevant to understanding where the industry may be headed in the future. Nuro is a company which focuses on autonomous door-to-door delivery services for a variety of goods. What merits discussion is the fact that Nuro attained a waiver from the National Highway Traffic Safety Administration (NHTSA) to operate their vehicle (Fig. 5) on public roadways even though it lacks a steering wheel and brake pedals which are considered essential safety features [60]. While the Nuro vehicle is small and operates at a maximum speed of 25 mph, this waiver shows that NHTSA is willing to allow vehicles onto roadways which do not have features which are standard in traditional vehicles. In the future, it is possible driverless operations will be considered more trustworthy and larger ATs will be able to develop a cab that does not consider the need for a human presence. Volvo's AT named Vera (Fig. 6) gives a glimpse into what this might look like. Vera currently operates in Sweden running goods from a logistics hub to a port terminal. The vehicle is battery-electric and has no space for a driver. Vera is targeted towards ports and logistics hubs where freight needs to be moved repetitively over short distances

[25]. Looking at these two companies, a vision for the future of autonomous freight movements begins to come together, but it will take many years to arrive. For the time being, the focus should be on operations that are already being stood up and developing an ecosystem where ATs can thrive amongst traditional commercial vehicles.

Figure 5: Nuro Delivery Vehicle [28]

Figure 6: Volvo's Vera Truck [49]

The feasibility of ATs is being explored abroad as countries like Sweden and China begin to enable operation. In 2016, the Netherlands issued a Truck Platooning Challenge to industry leaders. In this challenge, the lead truck had a human driver while those following had safety drivers and autonomous systems. Platooning is a way for one driver to move more goods and this challenge showed that there could be fuel economy benefits too [61, 23]. FABU, an artificial intelligence (AI) company, has been working with China Post and Deppon Express to deploy Level 4 ATs. During a test period, the ATs drove over 2,200 miles and delivered more than 60,000 packages [26]. In Sweden, Einride is deploying autonomous trucks that rely on teleoperators to step in when the AT encounters any issues. Many AT companies like the idea of teleoperations because they can assign an operator to more than one AT at the same time [12]. Efforts abroad reinforce the idea that ATs are likely to be a major technology in the coming years.

2.1.3 Regulatory Activity and State Support

ATs are being developed by private companies, but their success relies on support from federal, state, and local government. Recently, ATRI published a report which focuses in on the lack of support that ATs have received at a federal level and what consequences this may have [57]. In the absence of comprehensive federal rulemaking, states have been forced to create their own rules which results in a patchwork system that is challenging for companies to navigate. This tension is somewhat more tenable for autonomous passenger travel, which is largely intrastate, but interstate commerce could be stifled by conflicting rules across state lines. In recent years, there has been some progress in policy and regulation which includes the decision that all regulations which refer to an operator do not prevent autonomous driving made by the NHTSA. Additionally, NHTSA has stated that the organization is willing consider revision of any

regulations that do not make sense for autonomous operation. FMCSA and NHTSA each had a public comment period for proposed rulemaking on several issues surrounding AVs. These rules will help clarify the procedures for testing the capabilities of an AT and any changes to hours of service (HOS) for operators of ATs [28]. Both at the state and federal level, there has been avoidance surrounding the issue of certification. Currently, all AVs are self-certified without a uniform procedure. While this allows for innovation and the development of technology, it is unlikely to be a permanent solution. State or federal government will need to take responsibility for some component of review, but it is hard to define a review process for a technology that is still in development. Steven Shaldover of Partners for Advanced Transportation Technology said in an interview, "No single test can determine the safety of self-driving cars" [38]. Government agencies are unsure how they could test the capabilities of any AV enough to feel confident in providing an endorsement. Policymakers must address many complex questions to allow for safe and effective integration of fully autonomous vehicles into the existing transportation system.

Technically, ATs can operate in any state without the permission of state government, but a supportive environment is appealing for companies when selecting a deployment location. In terms of state level support and active deployments, some leaders have been Texas, Pennsylvania, Arizona, and Florida. Each state has hosted at least one deployment of AT technology and all continue to support the further development of ATs. Texas created the Connected and Autonomous Vehicle (CAV) Task Force in 2019 which was commissioned by Governor Abbott to "ensure that the Lone Star State remains at the forefront of innovation" (TxDOT) [74]. This Task Force builds on the efforts of the Texas Technology Task Force (TTTF) and the Texas Innovation Alliance (TIA) which both focus on encouraging the exploration of new mobility technologies

which could benefit the state. The Florida Chamber of Commerce developed Autonomous Florida to clearly publicize their business-friendly regulatory environment, quality infrastructure, and their willingness to partner with the private sector [29]. Pennsylvania created the AV Task Force in 2016 and held their first annual Automated Vehicle Summit in 2017. Along with Pennsylvania Turnpike Commission (PTC), Ohio Department of Transportation (DOT), the Ohio Turnpike, and Michigan DOT, PennDOT formed the Smart Belt Coalition which focuses on bringing multiple states together to plan CAV initiatives. The Coalition hopes to encourage testing, deployment, and research across the three states to allow them all to learn more about how CAVs fit into the transportation system broadly. Governor Ducey signed an executive order encouraging support of self-driving technologies which led Arizona to develop their Self-Driving Vehicle Oversight Committee to advise Arizona DOT and Department of Public Safety (DPS) on ways to advance the operation of self-driving technologies on Arizona roadways [7, 8]. While most of these efforts have not specifically targeted ATs, the general support of AVs is attractive to companies who are looking for a place to prove out their technology.

2.2 Roadway Maintenance

Travelers and freight carriers alike expect the roadway infrastructure to be built and maintained in a way that ensures safety and efficiency of movement while minimizing costs. However, the most recent grade of road conditions on the United States' report card given by the American Society of Civil Engineers (ASCE) was a D, as roads are chronically underfunded and frequently overcrowded [4]. As infrastructure ages and travel demand continues to rise, the nation has begun to recognize the long-term cost of inadequate maintenance funds [50]. A study done by Cambridge Systematics on

Mississippi owned roads forecasted the cost incurred by users of increased fuel consumption, increased maintenance and repair, and increased tire wear in two scenarios: (1) expected funding levels and (2) adequate funding levels. The study estimated that spending approximately $14 million more annually on maintaining roadways, across 2015 to 2040, would result in total transportation cost savings of $62.5 billion for system users. Whereas, maintaining expected funding levels is predicted to result in $42.7 billion of transportation costs [14]. This study captures the massive return on investment provided by adequate road maintenance and rehabilitation. Finding the additional funding needed to adequately address Mississippi's maintenance needs is a challenge. States across the country must develop innovative methods for stretching the dollars that they are allocated annually. If current decay continues, more road segments will degrade to poor quality and will become even costlier to repair [10, 71].

2.2.1 Maintenance Responsibilities

The Department of Transportation (DOT) of each state is responsible for constructing, operating, and maintaining state-owned roadways. This broad scope makes it challenging for any DOT to effectively execute these responsibilities from a centralized location. For this reason, each state is divided up into districts that can focus on the local issues and priorities. Figure 7 shows how the Texas DOT (TxDOT) has broken up the state into 25 districts that plan, design, build, operate, and maintain their own respective roadways. Management of roadways within a district is still complex as the Houston district alone was managing over 10,000 lane-miles in 2017 with annual expenditures on construction and maintenance exceeding $1 billion [76]. Maintenance activities must be broken down by category and managed according to relevant needs.

Figure 7: TxDOT District Map [81]

2.2.2 Types of Maintenance Activity

Maintenance of roadways can be group into three categories which are routine maintenance, preventative maintenance, and corrective maintenance. The general purpose of maintenance is to establish and sustain a state of good repair, any work done to improve the initial condition state of a roadway falls outside of maintenance (i.e. adding a lane) [13]. Corrective maintenance, also known as reactive maintenance, is executed in response to road quality degradation with a goal of returning the roadway to a good state of repair. Corrective maintenance can often be planned for ahead of time, as degradation is often predictable, but there are situations which require a rapid response. For instance, a heavy rainstorm may cause a landslide that blocks the road which needs to be remedied immediately and was not foreseen. Preventative maintenance consists of work done to preserve the condition of infrastructure by slowing decay [45]. An example would be applying a chip seal to fill minor cracks and address deterioration of the roadway surface.

As the cost savings of preventative maintenance have been proven, it has become a higher priority across the nation [85]. Routine maintenance is the simplest work done which seeks to address day-to-day concerns that arise. Common routine maintenance concerns include potholes and faded or missing striping. In addition to the roadway, any department of transportation (DOT) is responsible for maintaining the roadside and signs [34]. This work consists of anything from filling a pothole to replacing a sign which has fallen. Maintenance activities are split amongst these three categories for planning and funding purposes.

2.2.3 Routine Maintenance Operations

Most states have similar practices for managing routine maintenance concerns which rely on roadway assessments and reporting of concerns. Since the data for this project was gathered from Texas roadways, their system for addressing day-to-day maintenance needs will be the focus [73, 75]. In the case of routine maintenance, identifying and monitoring maintenance needs is an important component which is why TxDOT has developed several tools. On the homepage of their website, TxDOT has a mechanism called Report Road Conditions where road users can provide information on issues they encountered while driving. The tool has two mechanisms: (1) inform TxDOT of an issue without submitting a formal complaint and (2) issue a formal complain to TxDOT regarding road conditions which requires a follow-up explaining how the issue is remedied. Similarly, drivers can call 5-1-1 to report any damage to the roadway. Since there are no published reports, it is unclear how many incidents are submitted using these mechanisms. TxDOT maintains several internal tools that are not available for public access that are more robust: (1) Pavement Management Information System (PMIS), (2) Texas Traffic Assessment Program (TxTAP), (3) Texas Maintenance Assessment

Program (TxMAP), and Texas Condition Assessment Program (TxCAP). PMIS is an "automated system for storing, retrieving, analyzing, and reporting pavement condition information" that is used to record the percent of lane-miles in good or better condition [31]. TxTAP is a targeted effort to evaluate the traffic operations technology deployed along the roadside. TxMAP is an intensive effort which monitors the condition of TxDOT owned roads, in fiscal year (FY) 2009 over 4,000 one-mile segments of road were inspected. During these inspections, the road conditions are assessed across the categories: pavement, operations, and roadside. TxCAP combines the information available across PMIS, TxTAP, and TxMAP to develop a comprehensive image of the state of Texas roadways [31]. Brought together, this information paints an idea of the day-to-day state of TxDOT roadways. While the system has been built to be adept at managing information, it is still challenging to collect the information. The TxMAP inspections require staff to visit a location to assess the conditions. This should not be eliminated, but it could be supplemented by using the information gathered by ATs travelling on state roads.

Common Routine Maintenance Issues

Routine maintenance addresses damage to the road which is more minor than that addressed by corrective maintenance, but it is still important that these issues are remedied in a timely manner. Pothole formation is a frequent occurrence which can be caused by heavy loading, water damage, failure of the sub-material, and more [64]. Some states can provide reimbursement for damage caused by potholes, but it does not occur frequently. In Oklahoma, citizens can be reimbursed for vehicle damage caused by a pothole given the DOT knew of the damage and had time to address it [62]. More often, the cost of pothole damage falls to the driver. A 2016 study done by AAA revealed that

drivers across the country collectively spend around $3 billion on pothole repairs each year. The average cost of repair was roughly $300 with upwards of 5 million drivers experiencing damage from potholes each year [91]. Some potholes do not pose a risk of vehicle damage from driving over them, but drivers still make dangerous maneuvers to avoid them as shown in [89]. Potholes are such a common challenge that multiple studies have worked to develop systems which use cellphones and other low-cost solutions to detect their presence on roads [11, 52, 54]. A study which is still in progress in Colorado is looking at the ability of GPS loggers, accelerometers, noise recorders, and cameras to report roadway conditions with the hope of eventually expanding this work to create an automated process for understanding pavement conditions [1]. DOTs can only address routine maintenance concerns which they are aware of.

Pavement markings are used to help drivers orient themselves and stay within set boundaries to avoid collisions, but faded or missing striping makes driving at night and during adverse weather more dangerous. ATs aim to be capable of operating without lane striping, but the presence of good striping is never a hinderance of smooth operations. Early on, pavement markings were painted on without an analysis of their performance in different conditions. A national study completed in 1993 was able to show that each $1 spent on striping yields roughly $60 in benefit which powerfully supported the need for consistent lane markings [55]. The Manual on Uniform Traffic Control Devices (MUTCD) from FHWA establishes minimum retroreflectivity standards for critical pavement markings such as center lines and edge lines on high volume roadways [MUTCD]. [47] looked at understanding which pavement markings are effective at orienting drivers during night driving and found that a combination of bright centerline and edgeline markings scored the best. In addition to implementing bright lane markings, they must be properly maintained over time. In 2014, [16] laid out national standards for

inspecting lane markings and ensuring minimum retroreflectivity levels are maintained. Even as the country gets better at maintaining striping, fatal crashes still peaked at 6-9 p.m. in 2018 [59]. While ATs may not be a viable replacement for official inspections, they can identify locations where lane striping has significantly deteriorated so that DOTs can address this damage.

Other routine maintenance concerns pose less of a threat to the safety of the traveling public, but still need to be addressed. While a mattress on the shoulder is not an imminent threat, it must be removed and the DOT must know about the mattress to send someone to remove it. In 2017, TxDOT alone had to repair 870 guardrails which were damaged. When possible, the cost of guardrail damage is covered by insurance of whomever is responsible for the damage. However, only $300,000 of the roughly $1.3 million spent on guardrail repair in 2017 came from drivers' insurance [2]. An analysis of the routine maintenance spending by TxDOT between 2008-2010 revealed that pavement was the largest category of routine maintenance expenditures. The amount spent on leveling and overlays far exceeds any other single expenditure at nearly $170 million over the course of 2008 through 2010. Still, almost $20 million was spent on guardrail repairs, $47 million was spent on fixing signage, and $30 million was spent on high performance striping [34]. With expenditures on this magnitude, it is important that problems are identified and addressed early on before they become more costly to repair.

2.3 Data-Sharing from Private Company to Public Agency

In an increasingly connected world, public agencies are learning how to take advantage of data being collected for planning and governance. The phrase "data is the new oil" aptly captures the idea that data is a valuable resource which is powerful once refined. [52] emphasizes the importance of public-private data sharing to support flexible

planning for the future. As data becomes more complex, public-private partnerships will need to expand beyond the act of sharing data into the realm of exploring what value can be extracted from a dataset. As advanced technologies begin operating on public roads, state DOTs are trying to understand how to make use of the vast quantities of data being collected while respecting privacy and allowing companies to keep a competitive edge. To leverage the data collected by ATs operating on highways, there must be some trust between the state DOT and the AT companies. In developing this framework, the AT company needs to feel confident that their business model is not threatened by participation. Asking for a low risk data type provides an opportunity to cultivate a data-sharing partnership without concerns of sensitive information being made public. There are valuable case studies which have already occurred that provide insight to effective data-sharing endeavors.

2.3.1 National Freight Data-Sharing Efforts

An excellent example of effective data sharing is the Freight Performance Measures program maintained by the American Trucking Research Institute (ATRI) working with the Federal Highway Administration (FHWA). Since 2002, ATRI has partnered with industry to collect, anonymize, and store data from over 500,000 commercial vehicles across the country [6]. The data on time, position, and speed has been used internally and shared out to support freight research. ATRI works with trucking companies to protect their interests and ensure that use of the data which they share is tightly defined. ATRI's ownership of the data puts them in a position where they can help valuable data from the freight industry be leveraged for research while allowing companies to feel safe in sharing valuable information. Since ATRI is not a government organization, they are not subject to Freedom of Information Act (FOIA) requests. They

can anonymize data before sharing out to public agencies to allow the data to be leveraged without threatening the companies which support the database.

In Minnesota, data from ATRI was validated using local data and then used to generate key performance measures. While the region had access to data from weigh-in motion sensors and loop detectors, ATRI data provided a more comprehensive view of the freight network. The data was used to develop measures for mobility, travel time reliability, daily delay, and the cost of delay [49]. This reflects the value of this database in supporting freight planning efforts, but it cannot meet the needs addressed in this work. The database focuses on traditional trucks which are not equipped with cameras, so it is not built to provide the complex feedback needed to identify routine maintenance concerns. To leverage the data collected by ATs, photos are needed to validate reports and provide context to maintenance workers.

As the importance of data sharing became more understood, the National Cooperative Freight Research Program (NCFRP) developed a data sharing guidebook. The most relevant guidance for this work is the suggestion to restrict use of the data [58]. While AT companies are willing to provide images to improve routine maintenance activities, it would be important to ensure that these images could not be used against the company. Maintaining a long-term connection with the AT companies will help support informal data-sharing agreements. Texas has worked as a state to develop positive industry relationships which will be useful in navigating the development of a data-sharing framework which can support routine maintenance operations.

2.3.2 International Activity

Internationally, there is important progress being made that can be used to guide efforts in the United States. Studies across the world and across sectors have shown the

power of data in addressing long-standing issues. A study in the Netherlands explored how the regular collection of standardized data can be used to identify bottlenecks which negatively impact travel time reliability [84]. Another study looked at understanding the loss of cargo at a port in Taiwan. Through analysis of historic data, patterns in cargo loss could be identified and recommendations to avoid large losses were put forward [87].

In Australia, the government committed over $14.3 million to create the National Energy Analytics Research (NEAR) program to compile information on electricity consumption and grid impacts. The NEAR program maintains a publicly available data repository which contains data on energy consumption behaviors and predictions of future trends. However, the program has found that the industry is not always willing to provide information needed which leads to inconsistent data sources. As in transportation, it is difficult to gather granular household-level information without threatening the privacy of residents [39]. In Belgium, on-board units (OBUs) were used to measure GPS trajectories of heavy-duty vehicles. As part of a dynamic pricing scheme, the trucks were required to install an OBU which could then be leveraged. Data collected through this method can be aggregated to understand patterns in behavior, such as looking at how freight volumes vary during the day [35]. As data processing capabilities advance, huge efforts can be undertaken. A study done in Europe used the Transport Technology and Mobility Assessment (TEMA) platform to analyze GPS data from sixteen databases capturing travel behavior in different provinces. The platform was enabled comparison of the commercial vehicle mix, peak hour behavior, and carbon dioxide emissions across the provinces [63].

It is clear that data can be leveraged to support the improvement of systems, but it is not easy to gain access to data owned by the private sector. This study in Denmark [40] developed a framework for public agencies when approaching freight planning needs

which require private data. The study suggests identifying stakeholders, holding interviews, and negotiating terms of a data-sharing agreement. The work highlighted the importance of identifying where data from the freight sector could be used and making the steps to acquire the data.

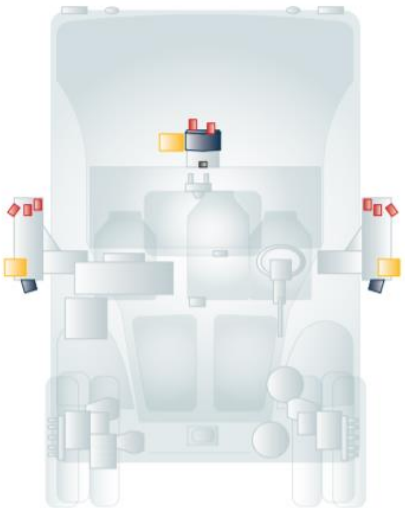
CHAPTER 3
METHODOLOGY

3.1 Dataset Acquisition

Data was gathered by Kodiak Robotics using their AT which uses the sensor suite shown in Figure 8. The data collected for this study came from runs between Houston and Dallas on Interstate Highway 45 (IH-45). The truck had a safety driver and an engineer on board. The safety driver is responsible for being alert and ready to take over the driving task should the AT disengage. The engineer monitors the operation of the AT from a technical standpoint. For this data collection, the engineer was tasked with capturing an image anytime they noticed a maintenance issue on the road or roadside. The staff were not informed of priority routine maintenance concerns for TxDOT, so there is the chance of captures that are not relevant to TxDOT maintenance or missing captures that are relevant. This method was not meant to provide a comprehensive assessment of the road condition. Instead, this data can supplement typical routine maintenance operations. Since the AT is equipped with a front-facing camera, an image of the incident can be captured to provide helpful context for processing. Since all ATs are equipped with GPS, an incident report can include an image, the date of capture, and the latitude and longitude of the location. Figure 9 shows an example where the AT captured the location of a pothole. When being put into practice, there should be defined incident categories which are of value to the state agency. This will help prevent collection of data which is not pertinent to the state DOT and allow the AT company to know what the state DOT is looking for.

» **Cameras** allow the truck to detect visible objects and identify lane markings. Camera data, when processed through advanced algorithms, are best able to differentiate what an object actually is, and give the Kodiak Driver a rich understanding of the world around the truck.

» **LiDAR** (Light Detection and Ranging) sensors bounce short laser bursts off objects to create 3D-maps of the environment around the vehicle. LiDAR sensors create detailed short- to medium-range 3D scans, and have an unparalleled ability to detect the presence of an object in a particular area. Since LiDAR sensors use their own light, they also work great in low-light conditions, but are less effective in rain, snow, and fog.



» **Radar** sensors bounce radio waves off nearby objects to determine their location and velocity. Radar is very useful for determining the location and speed of objects in conditions such as road-spray, fog, or our new friend, Texas thunderstorms. Radar generally gives a lower-resolution view of the world than cameras or LiDAR.

» The **Inertial Navigation System** (INS) uses a combination of sensors, including GPS, to help the truck determine its position and orientation. The INS is critical for helping the Kodiak Driver localize itself on the road and on the map.

Figure 8: Kodiak Truck Sensor Suite [42]

Figure 9: Example Image Capture from AT

3.2 Data Processing

The raw data received for this study was in a GoogleDoc which contained text and images. Each report had an image, the longitude, and the latitude with most reports also containing a brief description of the event. An example event entry is shown in Figure 10, where the AT came across a road sign which was broken and no longer visible to drivers. The GPS information was provided in decimal degrees, as opposed to degrees, minutes, and seconds, which is helpful for the upcoming mapping process. Decimal degrees is the standard GPS unit when mapping, so this did not need to be converted. If an event report provided GPS in degrees, minutes, and seconds, this could easily be converted to decimal degrees. Broadly, it is important to know which coordinate system the AT is using or the coordinates will not align properly when mapped. The most common coordinate system in use today is the World Geodetic System (WGS84) and is the coordinate system used by Kodiak trucks. To be used in a mapping software, the information provided via word document must be transferred to a spreadsheet.

Lat/Lng: 32.203152,-96.475517
Broken road sign

Figure 10: Example Report (Pre-Processing)

OBJ-ID	LONGITUDE	LATITUDE	CATEGORY	DESCRIPTION	IMG_FILE
1	-95.779539	30.897421	PAVEMENT	Seam across lanes	EV_1

Figure 11: Post-Processing Event Reports

For mapping purposes, the text entries were transferred into an Excel spreadsheet which was saved as a comma-separated values (CSV) file. CSV is the simplest file format which is most often accepted by mapping software. The example entry, shown in Figure 11, contains an ID number, longitude, latitude, category, description, and image file name for each event reported. The categories were developed as part of the larger framework to help make it easier for TxDOT to map events and quickly understand what time of repair is needed. The description provides an ability to provide more clarity, so

that qualifiers (such as faded or missing in the case of lane striping reports) can be added to events. The image file entry provides the file name where the associated image is stored. The main purpose of this field is to that it can be seen once an event is selected on the map. From there, it is easy to pull up the associated image and assess what exact repair is needed. The image can also be provided out to maintenance workers, so they have a reference of what they are addressing. With the images saved out to separate files and the event reports transferred to a spreadsheet, the data is now in a format where it can be input to the mapping tool used for this study, ArcGIS.

3.4 ArcGIS Online

The mapping prototype for this study was developed in ArcGIS Online to allow easy access and sharing of results. While ArcMAP was considered early on, it is not well-suited to the needs of this project. ArcGIS Online has the capacity to share a link to any map developed on the site. This map allows visitors to view the map and access information without needing to own an ArcGIS license. ArcMap is a powerful tool, but geared towards analysis and static data summaries. After comparing the two programs, work was shifted to the ArcGIS Online platform. Both tools are powered by ESRI, so functionally the maps generated are the same. Once the decision on a mapping tool was made, the CSV file could be added as a new layer of data.

The CSV file is uploaded by adding a layer from file and setting it as XY data. Within ArcGIS, coordinate data is referred to as XY data. Identifying our event reports as XY data, longitude is used as the X values and latitude is used as the Y values. Now the data is shown on the map as a series of points which are overlaid onto the basemap being used. In this study, the Streets basemap was used because it has the name of interstate highways labelled which makes it easier to understand where an event has occurred.

Another powerful function of ArcGIS Online is the predictive Style tool. Based on the type of data being added to the map, a handful of suggestions are supplied for how to display the information. For this study, events are color-coded based on the event category. This displays how often each type of event is occurring without having to look to the spreadsheet data. The TxDOT Open Data Portal is a well-maintained source for geographic information system (GIS) data. From the Boundaries category and Roads category, respectively, the shape file for TxDOT district outlines and freight network roads were pulled for use in the in this study. Each of these provide useful context for understanding where an event has occurred. The district outlines can be used to define who is responsible for an event, since routine maintenance is managed at the district level. Once all the data is added to the map, any other work was fine-tuning to make the map easier to engage with as a visitor. The pop-up function was disabled for the freight road network, so that information about a road segment would not be shown when trying to click on an incident. With the mapping tool built, developing a prototype for the reporting side of the framework became the focus.

3.5 Event Reporting Tool

The event reporting tool must capture information that is needed to support the map developed without being arduous for the company submitting events. For this reason, a couple of different methods were explored during the prototyping process. In development, a system which is efficient while providing the needed information was the goal. One decision was whether a company submits each incident separately or whether incidents are batched for submission. Broadly, the benefit of individual submission is that the form can be rigid and leave less room for inaccurate reporting and the cost is the repetition required when multiple events are being reported. For batched reporting, the

process can be faster on a per event basis, but there is a higher risk of inaccurate reporting without the guidance that can be built into webform.

To explore both options, a prototype for each was developed and discussed with both stakeholder groups to get an understanding of what fits in with existing practices. For individual submission, a Qualtrics webform was developed that allows the respondent to select the type of incident, input the coordinates, and upload an image. A distinct benefit of the survey method would be the ability to have a multiple-choice selection for categorization of incidents. This helps streamline the processing for the state agency receiving event reports. Qualtrics could output data in CSV format which would make it easy for the state agency to ingest information from the webform to their system. For batched reporting, the simplest method would be similar to how data was reported for this project with a bit of fine tuning. The AT company would compile a spreadsheet with coordinates, description of the event, and the image file name. A folder would be emailed or shared via cloud storage service which contains the spreadsheet and the associated image files. The receiving agency would need to refine the provided descriptions into appropriate categories as a part of data processing. Both reporting methods would be effective and have their own drawbacks, so it came down to input from industry experts to determine which method should be employed. Until the deployment of ATs expands greatly, either method will take little time to maintain once implemented.

3.6 Interviews with Industry Experts

A small handful of individuals were interviewed as part of the process to develop the framework. Kodiak made information available as needed to support this work and was not formally interviewed. To provide perspective on how this would be incorporated to state agency operation, four TxDOT district staff members from Austin and Fort

Worth were interviewed. The other AT company operating in Texas, TuSimple, provided some insight to how this would fit into their company. Finally, an expert from ATRI was able to provide guidance on the national context and how this effort would expand beyond Texas. Currently, ATs operate in Texas, New Mexico, and Arizona but this is expected to expand rapidly over the next few years. The interviews were held after an initial prototype was developed, so that those providing input could understand what the framework would entail. All interviews were held using video conferencing software, Zoom, so that presentation slides could be shared during discussion. These discussions were focused on understanding what would make the framework feasible, what barriers would need to be navigated, and what value does the data have. Developing a tool without considering the realities of systems that are already in place and the available capacity of all participants is less valuable.

CHAPTER 4
DISCUSSION & RESULTS

4.1 Framework Overview

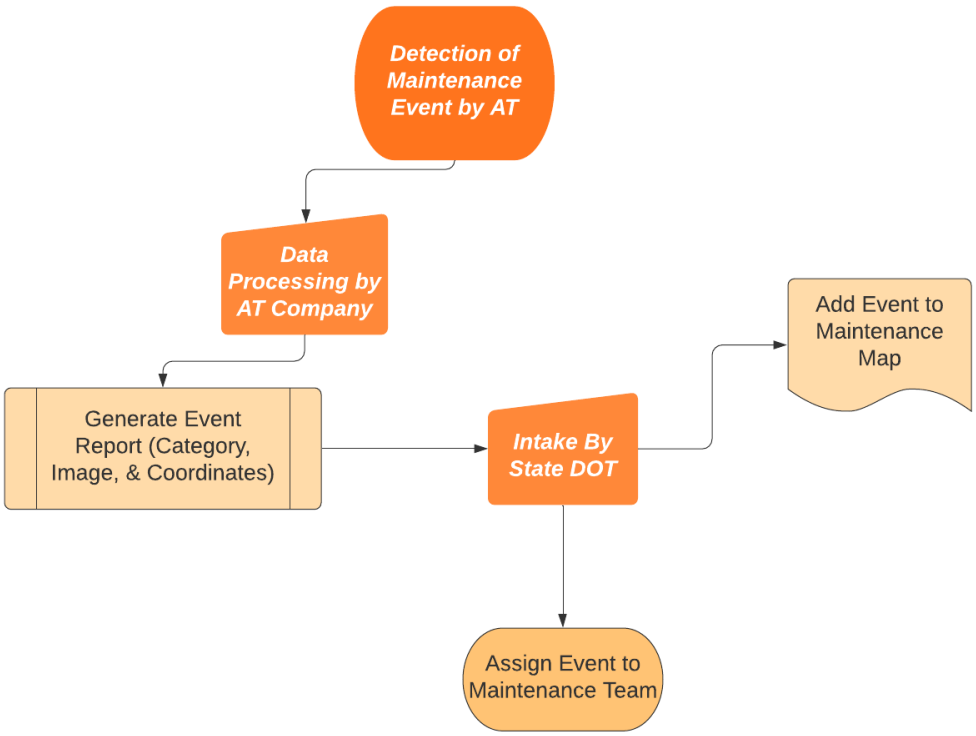


Figure 12: Framework Flowchart

The framework for leveraging data from ATs to support routine maintenance consists of five steps laid out in Figure 12. Each event report will originate from detection by an AT during operation. The AT company will develop a process for routing events from detection to submission. In this step, the company will pull together the relevant information needed by the state DOT and push the new event report. The state DOT will review the event report submissions and add them to a map with other events. From here,

the event is allocated to a maintenance team to be addressed. The maintenance team can access the map and report to understand the issue which requires resolution. Using the image and coordinates, the maintenance team deployed to the location will have better awareness of what concern they are addressing. The event detection procedure, data processing procedure, and maintenance response will be dictated by the organizations performing them. Procedures for the points of connections, submitting events and mapping events, are outlined in the following sections.

4.2 Mapping Prototype

The map prototype is active on the ArcGIS Online platform (accessible via: link) with 17 routine maintenance events reported. Table 1 summarizes all the event reports generated as part of this study. As shown in Figure 13, the map is overlaid with markers for each maintenance event, lines of the freight network roadways, and outlines of the TxDOT district boundaries. Figure 12 displays an example of the pop-up which appears when any event is selected. The dialogue box provides the exact latitude and longitude, the category for the event, the description, and the image file name. The events are color-coded by category to make the number of occurrences readily accessible. Most state DOTs have an internal tool for tracking events which will likely be used in place of ArcGIS, but this provides a tool for visualizing the data provided.

Table 1: Event Reports

OBJ-ID	LONG	LATITUDE	CATEGORY	DESCRIPTION	IMG_FILE
1	-95.7795	30.89742	PAVEMENT	Seam across lanes	EV_1
2	-95.5605	30.70457	PAVEMENT	Seam across lanes	EV_2
3	-95.5463	30.69032	PAVEMENT	Seam across lanes	EV_3
4	-96.7624	32.65272	POTHOLE	On the right shoulder	EV_4
5	-96.6415	32.3708	OBJECT	Shoulder, abandoned truck	EV_5
6	-96.4755	32.20315	SIGN	Fallen sign	EV_6
7	-96.4464	32.04048	OBJECT	In road, pop dots in lane	EV_7
8	-96.47	32.16828	OBJECT	Roadside, construction barrel in ditch	EV_8
9	-96.4833	32.21834	SIGN	Fallen sign	EV_9
10	-96.5786	32.30183	SIGN	Knocked down temporary sign	EV_10
11	-96.6658	32.56507	OBJECT	Roadside, construction barrel	EV_11
12	-96.6661	32.564	POTHOLE	Located on exit divider	EV_12
13	-96.7439	32.65654	LANE_STRIPING	Faded, far right	EV_13
14	-96.7244	32.66079	POTHOLE	Located on exit divider	EV_14
15	-96.7223	32.65856	POTHOLE	Located on left side of Exit 473C	EV_15
16	-96.7676	32.65128	LANE_STRIPING	Missing	EV_16
17	-96.7566	32.65418	LANE_STRIPING	Missing	EV_17

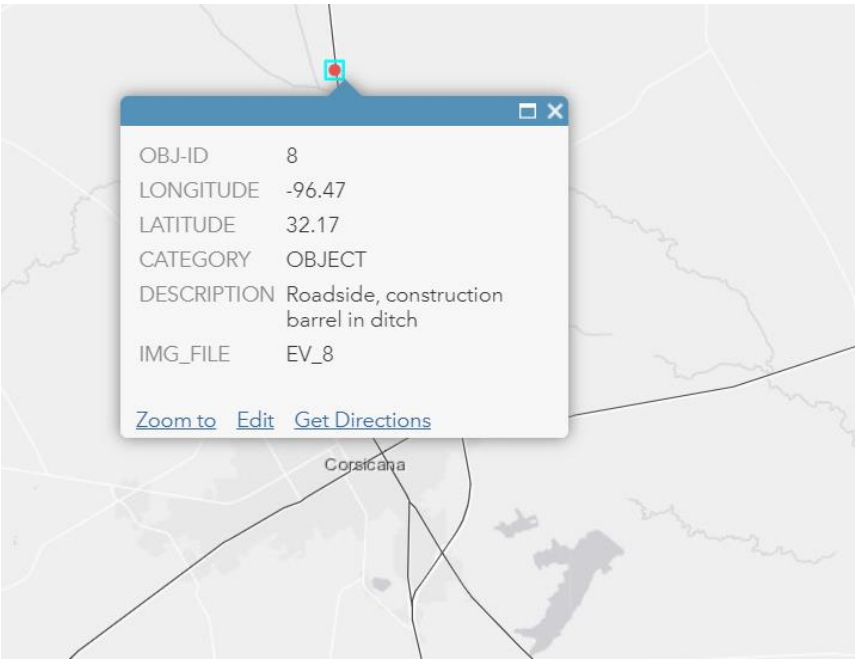


Figure 13: Example OBJECT Event Details

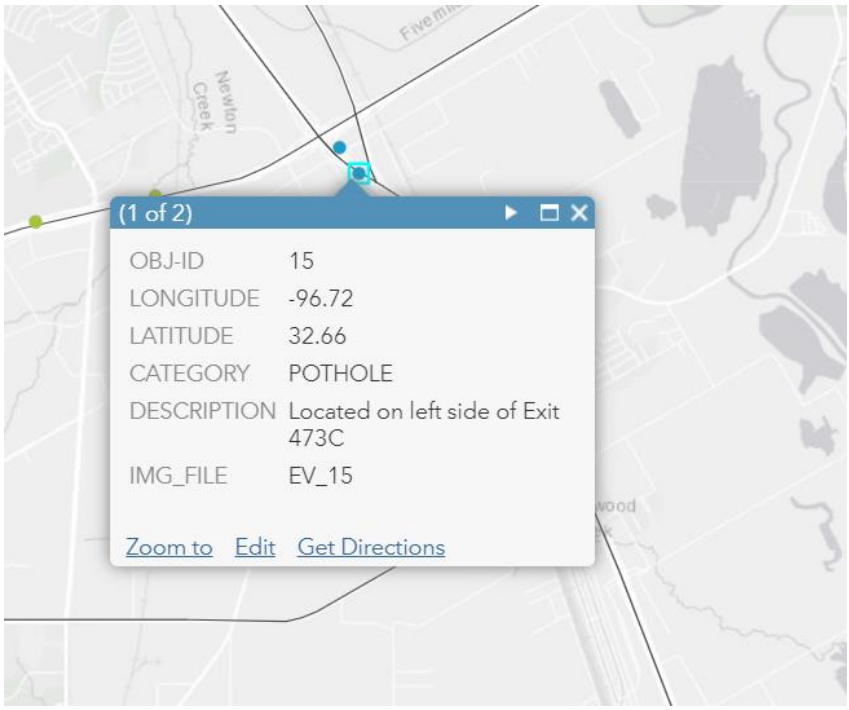


Figure 14: Example POTHOLE Event Details

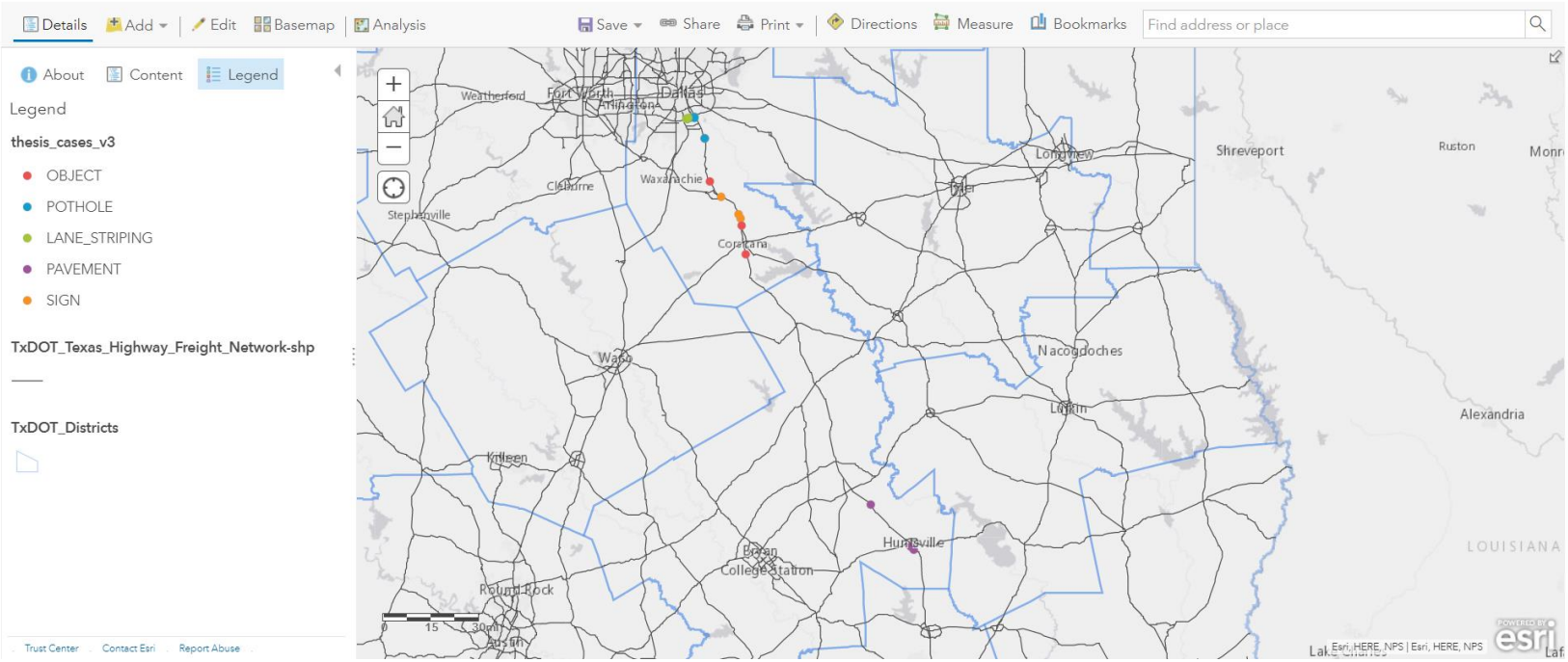


Figure 15: ArcGIS Online Map Prototype

The preliminary data provided for this study was collected during January 2020 across several runs of the Kodiak AT. The data collected provides a useful insight to the type of routine maintenance events occurring along I-45 between Houston and Dallas. Most events were within the Dallas district with a few occurring in the Bryan district. Figure 17 shows a cluster of pothole and lane striping events reported on a section of Interstate Highway 20 (IH-20) which connects to IH-45. Clustered pothole and lane striping events may indicate that this segment of roadway is aging and may need to be inspected for other maintenance issues before it falls into a state of disrepair. Figure 18 shows a string of object and sign event reports along IH-45 near Corsicana. Sign damage and abandoned objects have less relation to the overall state of the road, so this string of events says less about the condition of the road. Figure 19 shows a string of events in the pavement category which are interesting. These three events occurred in the Bryan District near Huntsville. These pavement seams would not traditionally be considered a maintenance problem as they have not visibly failed, but it is interesting that AT operators have flagged them. It may mean that these lateral lines cutting across the road are confusing for the AT to navigate.

Figure 16: Clustered Events on I-20

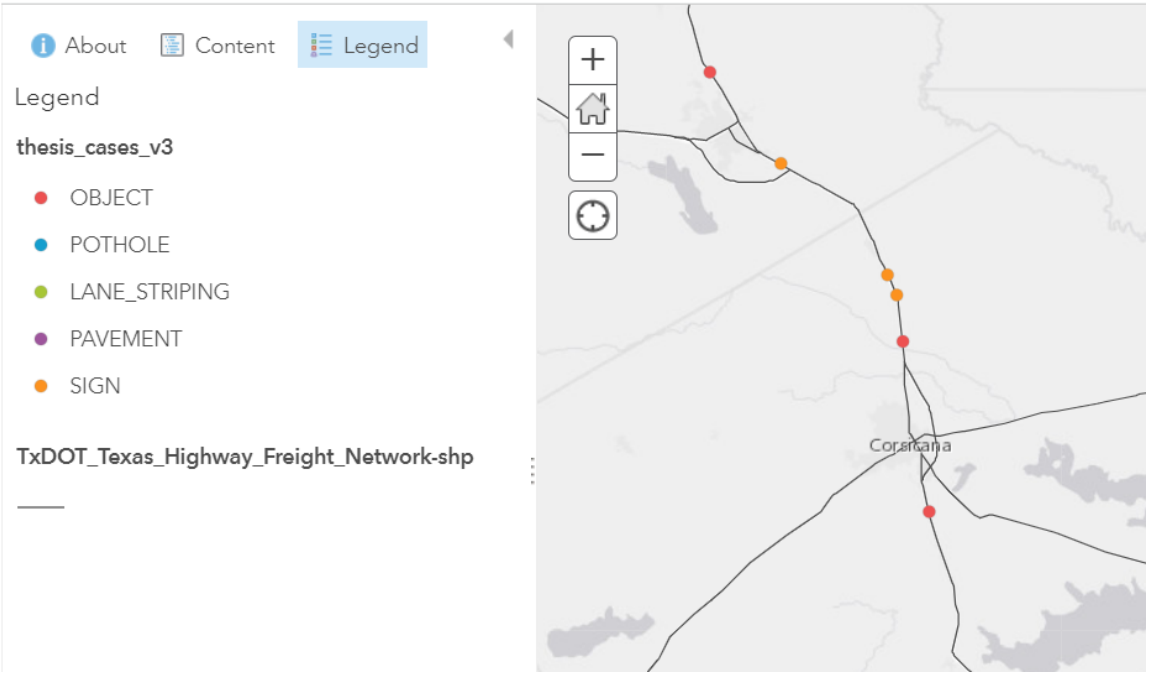


Figure 17: String of Events on IH-45

Figure 18: String of PAVEMENT Events on IH-45

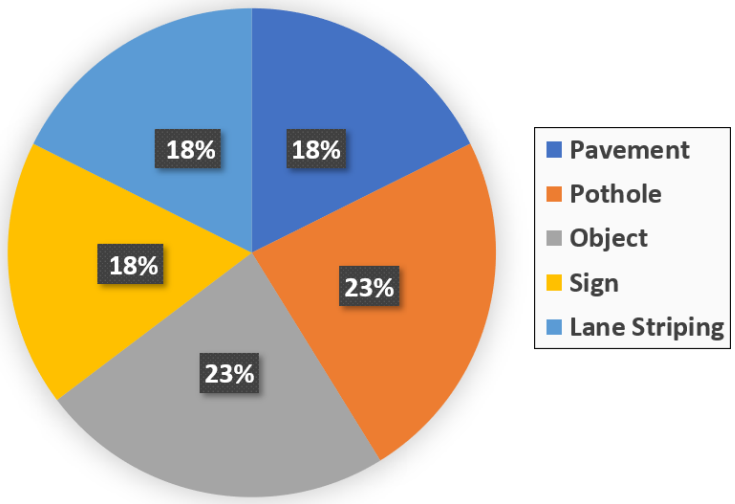


Figure 19: Breakdown of Event Categories

From consulting with state agency personnel, it seems that potholes, lane striping, and sign damage are the most relevant issues being captured. The pie chart in Figure 19 shows the distribution of event types. No single category stands out as a prominent issue, but potholes and out-of-place objects were slightly more common in this dataset. One category which was not captured that would be of significant value is guardrail damage. State agencies must address guardrail damage quickly, as it presents safety and liability concerns should a collision occur. The pavement category captures locations where the road has lateral pavement seams which are darker than the rest of the roadway and difficult for the truck to understand. However, this is not a flaw in the roadway and, therefore, not a maintenance concern. Objects lying in the road or on the shoulder are of interest, but they are often reported by citizen complaints. None of the objects reported in this data would be of particularly high interest. There is one exception, the abandoned truck identified in one report could be valuable information as most regions endeavor to keep the shoulder clear and pay special attention to larger obstructions. Reports of potholes and damaged pavement markings are of particular interest to state agencies

because they often go unreported by the general public. In a full deployment, the object and pavement categories would likely be omitted and a category for guardrail damage would be added.

States currently rely on citizen complaints and employee reports to identify routine maintenance concerns. These systems provide a lot of valuable information to the state, but they lack the veracity which comes with adding a photo and coordinates to a report. The citizen complaint system works well for urgent or obtrusive problems, such as a mattress lying across a lane or a traffic collision, but is less effective for more subtle concerns. There is a problem with location accuracy, as it takes some time for the driver to pick up their phone and contact the agency. When travelling on the highway, less than a minute between recognizing a maintenance concern and providing a location can result in a mile of inaccuracy which makes the task of locating the concern more challenging for maintenance workers. In Texas, the Highway Emergency Response Operator (HERO) program which can deploy a truck to assist in clearing minor collisions, help fix a flat tire, and other small issues. These operators are tasked with looking for maintenance concerns as they are driving along the Texas highways to provide another source of input. While these two systems capture many occurrences, they do not provide photos or exact coordinates for the incident. The veracity of information is higher for the AT event reports and the ATs are concerned with the condition of the roadway to ensure their vehicle can operate effectively. While AT companies can work around faded striping and missing signs, it is easier to operate when the infrastructure is in good condition. The mapping process should be relatively simple to maintain as long as the event reporting system is put together well.

4.3 Event Reporting System

The main component of this framework is the system for reporting events to the state DOT, so they can be mapped and addressed. This process will likely go through phases of complexity because the ideal system requires a point of integration which may not be feasible as a starting point. This system can be rather flexible which is helpful in moving from a pilot program to a broader architecture. In the long run, this system could be utilized nationwide, but it would be valuable to pilot it at a smaller level before moving to large scale action. As Texas has the most AT activity currently and a supportive environment for AT deployments, it would be a good place to test out the impacts of providing routine maintenance event reports to the state DOT. In the initial system, a simpler reporting tool can be utilized while navigating the intricacies of developing a data feed from AT companies to the state DOT.

The simplest starting place for the system is a manual reporting tool where AT companies input incidents on a regular basis. While state DOTs would like information as quickly as possible, it will take time to develop the data feed system and this simpler model can be used to prove out the value of the data source. The two primary options explored were a webform survey and a spreadsheet file. Both options require manual input from the AT company, but within a route there are likely to be a limited number of routine maintenance occurrences. In this system, the AT company should not be punished for reporting irrelevant events as it is easy for the DOT to discard irrelevant reports. If there was a penalty for over-reporting, there would likely be maintenance concerns which are missed. However, any inconsistencies in the format of reporting should be addressed to avoid confusion and excessive data processing needs. The DOT must provide ample

context regarding what maintenance concerns are most important to capture, so that the AT operators have a sense of direction when looking for events to report.

In the case of a survey webform, the primary benefit is an ability to reduce the chance of mistakes in reporting events and the primary cost is slowing down the process of generating a report. Many online survey creation tools exist already, such as Google Forms, Qualtrics, Survey Monkey, and others. Generally, any of these services will work if they allow some restriction of who accesses the survey and a file can be uploaded as part of the survey. Free solutions will have the most limited capacity for restricting access, so state agencies should try to use tools with more robust capabilities. As an example, the Qualtrics tool allows for a survey to be protected by a password. Password protection would significantly reduce the chances of the submission platform being overwhelmed with fake reports. At the same time, password protection allows the AT companies to share access to the reporting tool internally without having to specifically designate which employees have the ability to make a report. Since AT companies would prefer to maintain privacy of their submissions, the survey tool used must have reasonably high cybersecurity protocols in place. Qualtrics has thorough cybersecurity standards which include annual penetration testing by an independent third-party and authorization by the Federal Risk and Authorization Management Program (FedRAMP) [62]. Survey design is flexible but should be kept simple to avoid confusion for those filling out event reports. Since AT companies will often have multiple events to report, it would be wise to include multiple iterations of the reporting questions without requiring a respondent to exit the form. For the same reason, respondent should not be prevented from making multiple submissions to the survey. The survey data collection tool can be used as a backup for the data collected. If downloaded data is lost or damaged, the online service will retain a clean copy of the information submitted. The prototype developed

for this study remains active as a reference for development of a tool during a deployment (accessible via link). Collecting event reports via the survey method provides a means for submissions to be anonymized away from the company and would be simple to maintain. However, it is slightly more time consuming for the company when reporting a larger number of events.

The second submission form which was explored was a file sharing method using a spreadsheet and image files. The concept being that a spreadsheet would be used to track the critical information for each event (coordinates, category, description, and image file name) and the image files would be sent alongside the spreadsheet. An easy way to compile these would be through a zipped folder. This method does not provide anonymity, but the lack of data sensitivity means companies are likely to be willing to participate in a transparent way. When summarizing data or providing to maintenance teams, the company should not be associated with an event report to avoid publicly associating specific submissions with any one company. To support this method, each company which participates would be sent a template spreadsheet which lays out the various entries required for each event report. The accompanying materials would need to specify the categories for events to avoid confusion in processing reports. This would be easier for the company to fill out because there is no limitation for how many events can be put into a spreadsheet. This method would only be as secure as the landing space for the submissions. In the case of small folder size, email could theoretically be used but it would be impractical. It would be difficult to provide access to the information to new staff and the email would need to change when staff changes. A better fit is the use of an online file storage system similar to Dropbox or GoogleDrive. TxDOT uses a platform built by Microsoft called SharePoint which can be accessed both by internal and external personnel. Microsoft, as a company, is dedicated to robust cybersecurity protocols which

makes SharePoint a good solution for the data sharing component. The site even retains past versions of files which can quickly be restored to minimize the threat of data loss or corruption [56] . In this system, AT companies can be given permission to submit files without the ability to access other files or download files they did not upload. This would protect the security amongst peers, taking away risk that submissions would be identifiably associated with the submitting company. TxDOT employees already maintain a SharePoint account, so there is not the added vulnerability which comes with creating an account on a new service. While there is neither method is far and away superior to the other, reporting events using uploads to a cloud storage system is more efficient and can provide comparable security if the appropriate service is used.

CHAPTER 5
CONCLUSION

The economy is powered by a strong freight sector which continues to evolve and make use of new technologies. State DOTs that keep up with these advancements can find ways to leverage innovative activities occurring within their state. As AT development continues, it seems likely that ATs will become prevalent in the next couple years. State DOTs can act early to work with the companies operating ATs to understand how they can ingest information about roadway conditions. For a system to succeed, it must be cohesive across state lines and across companies. Many AT companies will operate within a state and some of these AT companies will be operating in more than one state for their long-haul transport. The broad introduction of AVs onto roadways may change the nature of how maintenance is tracked and how issues are reported. As more vehicles on the road have cameras, the presence of this technology could be leveraged so that road users may provide the road operator with more information about the current state of the roadway.

In this study, a preliminary dataset was provided by an AT company, Kodiak, which is actively running freight on public highways. It is easier for an AV to operate on infrastructure which is in a state of good repair. However, many highways across the country are not in a state of good repair. The presence of camera-equipped ATs on these roadways can be leveraged to identify routine maintenance concerns. Detection of potholes, damaged striping, and damaged guardrails helps an AT operate smoothly, but also increases safety for the travelling public. While state DOTs can get reports of these maintenance issues from citizen complaints and maintenance workers, it does not provide a comprehensive look into the state of the roadways and the AT data stream would be the first to provide images of the maintenance concern being reported.

To leverage the data being collected from ATs operating on public roads for routine maintenance purposes, there must be a framework put into place which establishes roles and submission standards. From looking at preliminary data and engaging with both public and private stakeholders, an initial framework concept has been developed. Event reports begin with detection by an AT which captures a snapshot of the event to be converted to an official report back at the company hub. The company submits any new maintenance events found during a run using the reporting tool run by the state DOT. From there, the state DOT processes the submissions and adds them to a map of current maintenance events. From here, maintenance workers are tasked with addressing the issue and can use the event report as a reference while in the field. Elements of this structure will likely be fine-tuned in a pilot to maximize efficiency of the process, but the framework will remain intact. Special attention must be paid to the point of connection between the state DOT and the AT company. The process of reporting maintenance events should not be onerous for the AT company, since they are providing this information on a voluntary basis. Finding a way to automate the process of detecting and reporting a maintenance event would be valuable as AT operations scale and companies operate on a dynamic road network. For the event reports to be of significant value to state DOTs, any form of reporting should sustain the inclusion of an image and coordinates of the event.

This work is limited by the fact that the framework has not yet been actionably implemented. Therefore, comments on the feasibility of the framework are speculative. The value presented comes from proving out the value in this data and the willingness of both parties to participate in such a framework. State DOTs want access to better information regarding the condition of their roadways. AT companies want the state DOTs to have this information, so that roads will be in a better state of repair which

makes their operations easier. There is still more to be done, but this concept provides insight into how state agencies can leverage data collection to improve operations.

In the near term, this framework should be tested in a real-world pilot which engages at least one AT company. For an initial effort, it would be logical to prove out the concept in a smaller region within one to two districts which have higher AT traffic. A deployment of this concept would allow the framework to be refined before expanding to a broader landscape. On a slightly longer horizon, Texas may consider a statewide deployment if the density of AT operations remains high within the state. It is difficult to predict the timeline for AT development and difficult to understand how quickly companies will be able to scale their operations. The final vision for this framework would ultimately be a national level system. Since ATs are likely to operate across state lines, it would be best to have a system maintained by a federal agency to enforce a common data structure. Efforts could be repeated across multiple states, but this would be a less efficient allocation of resources and companies would likely be more hesitant to engage with numerous database systems. It is important that this system is cohesive to encourage AT companies to participate.

Across any of these implementations, there are places where refinement would strengthen the framework and make it easier as the framework expands. In terms of detecting events, the preliminary data relies on a system operator to monitor the road and manually tag any maintenance concerns. This is fine while companies have someone tasked with this role, but eventually this role will not be necessary for the operation of the AT. A feasible alternative would be using the error codes to flag anomalies within the road environment. For example, when striping is too faded for the truck to read, ATs often rely on models and maps to determine where the striping should be. When the AT is forced to make this transition, the system could flag this and generate a report

automatically. The other change would be in the event report submission process. This process similarly will benefit greatly from being converted from a manual task to an automated process. For this, a standardized transmission format must be agreed upon. During a pilot, these two challenges should be explored by the AT companies and DOT to find a way to structure a framework that can continue operate as AT deployments continue to expand. A similar framework could be used for passenger AVs to report road maintenance concerns. These activities along with regulations and policy can help develop a conducive environment for AV deployments.

APPENDIX

A. Images from Event Reports

Event 1: Pavement Seam

Event 2: Pavement Seam

Event 3: Pavement Seam

Event 4: Pothole

Event 5: Abandoned Truck

Event 6: Fallen Sign

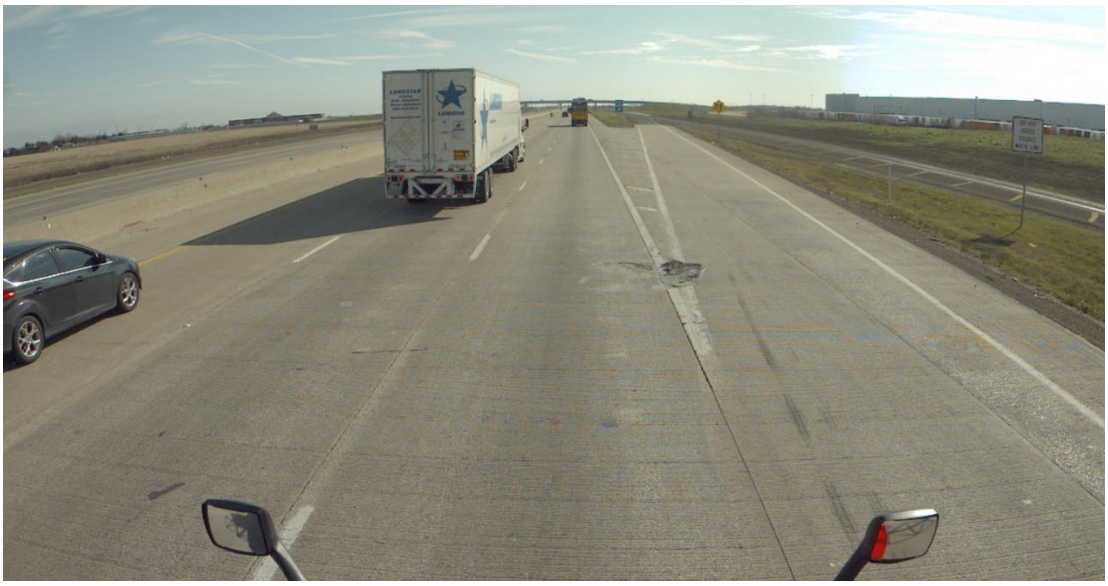
Event 7: Pop dots in middle of left lane

Event 8: Construction barrel in ditch

Event 9: Fallen Sign

Event 10: Damaged temporary sign

Event 11: Construction barrel on shoulder



Event 12: Pothole

Event 13: Faded striping

Event 14: Pothole

Event 15: Pothole

Event 16: Missing striping

Event 17: Missing striping

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