Tornado Path Prediction Using Data Driven Techniques

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THESIS

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Abstract

Each year around 800-1400 tornadoes occur in the United States. Although a very small number of these tornadoes result in injuries and fatalities, the destruction caused by these events can be catastrophic. Despite having advance warning mechanisms and alert systems, the entire prevention of tornado casualties is still quite challenging (1). Studies have indicated that the rate of tornado-related fatalities and injuries are higher when effective warnings are not issued and people do not have access to suitable storm shelters (2). Tornado warnings are issued based upon the atmospheric disturbances being detected on Doppler radars. This system, however, provides the national average lead time of 13 minutes which is insufficient when families are expected to evacuate the areas under danger (3). The National Oceanic and Atmospheric Administration (NOAA) is currently working on developing a warn-on-forecast system to potentially improve the lead time for warnings before the formation of tornadoes (4). Upon studying numerous tornadoes, however, it became evident that the issues pertaining to tornado casualties could not simply be improved by extending warning times. The lack of communication between individuals and officials creates confusion about appropriate actions that individuals must take. Officials believe that by generating the warnings they have performed their job and the responsibility to take appropriate actions were then on the individuals. Individuals, on the other hand, seek to obtain more information regarding the arrival of a tornado, rather than simply relying on current warning mechanisms such as sirens and warnings broadcasted on television and radio. This communication dilemma results in preventable casualties (5).

For the present model, the tornado path was predicted for El-Reno, Oklahoma tornado that had occurred on May 31, 2013. For Model 1, the exact locations were determined by calculating the latitude and longitude points based upon the previously predicted locations. The data was divided into one and two-minute intervals. For Model 2, the same locations were predicted based

on the previous original locations that would be provided by the radar in the actual scenario. Results showed that the distance between the predicted and the original locations were reduced significantly when the locations were predicted from the prior original locations in Model 2. Furthermore, the predicted path of the tornado was divided into different circles of diameter equal to the width of tornadoes which are usually around 0.17 miles to 0.28 miles (6). Results indicated that 90% of the locations were predicted successfully when the diameter/width of the tornado was around 0.3 miles.

To improve the communication gap between officials and individuals when providing warnings to people in a tornado's path, the usage of UAVs (unmanned aerial vehicles) is proposed. UAVs equipped with cameras and Global Positioning Systems (GPS) can continuously map the land features of the area stricken by the disaster and provide updates on the evolution of tornado. Moreover, with UAVs, emergency relief-teams can have real-time access to areas under a tornado warning and can closely monitor victims, hence, ensuring the evacuation of houses and businesses in a tornado's path. This will eliminate the need for the emergency personnel to visit disaster locations for evacuation purposes. UAVs can also replace telecommunication structures which can be impacted by server weather hazards (7). UAVs can be connected to Doppler radars and receive updates regarding previously hit tornado locations. By using current and exact locations, UAVs will be able to use the prediction model to predict the next location of a tornado and can warn residents that are in a tornado's path.

The prediction of tornado path along with warning individuals by UAVs will be helpful for emergency managers in allocating their services as well. When tornadoes or other natural disasters occur, it is the responsibility of emergency relief-teams to provide affected individuals with immediate relief. To provide such services, they are in constant need of up to date information pertaining to the disaster location (7). Due to time limitations, however, a team of UAVs will be required to serve the purpose of providing warnings and leading individuals to tornado shelters. Tuna et al. suggested the using a formation control system to control the position of multiple UAVs relative to each other. The use of such a system will ensure that multiple UAVs will not warn the same location and can potentially prevent collisions among UAVs (8).

Lastly, UAVs can be extremely helpful in a post-tornado scenario. A detailed information regarding the damaged infrastructures can be determined from UAV photogrammetry. To assess the damage incurred by a tornado, it is essential to collect necessary data about the damaged locations. However, due to blocked roads by fallen trees or other debris, these areas are not accessible. The images collected by UAVs will be useful in conducting a post-event survey (9). Another issue is to rescue people that are still alive but stuck under the rubbles. By attaching the infrared cameras to UAVs, it will be able to detect any human or animals that are stuck under the damaged infrastructure. Finally, due to the small size and light weight of UAVs, they could be easily damaged by the heavy winds of tornadoes. Hence, it is recommended that UAVs do not go near the eye of the tornado. Upon receiving information regarding the houses and businesses in a tornado's path, they must travel away from the tornado and providing warnings to the houses and businesses.

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LIST OF ABBREVIATIONS

NWS	National Weather Service
NOAA	National Oceanic and Atmospheric Administration
POD	Probability of Detection
FAR	False Alarm Ratio
SPC	Storm Prediction Center

1. Introduction

1.1 General

A tornado can be defined as a column of air that rotates violently and has an appearance of a condensation funnel. The funnel, however, sometimes is not visible as the tornado can be hidden underneath a pile of clouds. This pile of clouds is known as a cumuliform cloud, the tornado can extend simply to or from this cloud. A tornado vortex is a whirling mass of air that touches the ground by extending to and from the cumulus cloud. The visual effects of tornadoes include rotating dust or some structural ground-based damage to vegetation fields (10). Majority of tornadoes are developed over sparsely populated areas and despite their violent destructive nature, only 1-10% of these tornadoes inflict intense damages. On some rare occasions, however, upon hitting the densely populated area, tornadoes can cause intense damage and take many lives (11). The United States experience the high number of tornadoes as compared to other countries in the world. Although tornadoes can touchdown at any location, the south-central part of the US has relatively high frequency of tornadoes and is called a tornado alley. This region comprised of Texas, Nebraska, Oklahoma, Kansas, Iowa and Ohio (12).

The Enhanced Fujita Tornado Intensity Scale is used to estimate the intensity of tornadoes. The scale ranges from EF-0 to EF-5 intensity and determines the speed of tornado winds based upon the damages that tornado incurs on fields and infrastructures (13). In the United States, about 77% of tornadoes are of EF-0 and EF-1 intensity and hence, do not cause significant destructions. Out of all the tornadoes that touchdown, 95% are below EF-3 intensity. The remaining 5% are considered violent tornadoes and they incur severe damages. Although the percentage of violent tornadoes does not seem very significant, given a high frequency of tornadoes in the United States which is currently 1,000 tornadoes every year, this small percentage can result in massive devastations and casualties (12).

1.2 Current Methods for Predicting Tornadoes

Once the tornado is detected on the radar or spotted by the trained storm spotters, the National Weather Service (NWS) start to generate tornado warnings. The current lead time provided by the National Oceanic and Atmospheric Administration (NOAA) is 13 minutes (3). Hence, the individuals have only 13 minutes to seek shelter. People living in permanent structures are advised to seek shelter inside their basements, while, the residents of mobile homes have no choice but to evacuate their residence. In many cases, however, violent tornadoes have completely destroyed the permanent homes as well.

Most of the research regarding tornado fatalities mainly focus on the technology aspect of the warnings, not much attention has been given to the process of warning communication and human perception (2). Officials think that they had done their part by alerting the public with severe weather warnings, whereas, studies have shown that these warnings are either disregarded or disbelieved. Sirens, for instance, is of the least trusted warning mechanisms despite being widely used in tornadic situations to alert public. Sirens are not able to provide the information regarding the severity of the event. There can be the same tone of sirens for both the severe thunderstorms or the high-intensity tornadoes and people simply cannot distinguish the severity of the potential danger (14).

Although consistent tornado warnings along with the tornado track are broadcasted on television and radio but in the event of damaged power lines and loss of electricity they cannot help much. Currently tornadoes are predicted by radars and satellite and their path is generated before their arrival. Nevertheless, given the unpredictably of tornadoes, they can certainly deviate from their predicted path. Therefore, it is essential to predict the exact location of a tornado along with the entire path, and in the event where tornadoes do change their path, the predicted locations should be updated as well. Although Doppler radars scan the atmospheric conditions of tornadoes every 5-10 minutes, environment conditions such as biological contamination, velocity data and ground clutter can provide errors in determining the path of tornado (15). Furthermore, tornadoes often to do not travel in a straight path, they can loop in circles, take turns or backtrack. The weather can also change drastically during these outbreaks of tornadoes, people might leave the shelter after the dissipation of tornado and encounter a new tornado along the escape route. By not knowing the exact location and movement of tornadoes, it is extremely difficult to protect people from its destruction.

1.3 Objective of Study

The goal of the proposed model is to predict the path of the tornado and save resident's lives by providing them with the immediate evacuation warnings. Doppler radars will be used to determine the original location of a tornado along with its linear speed and direction. Based on this data, the next location of the tornado will be predicted with the time interval of either one or two-minute and residents will be provided with warnings to immediately take appropriate actions. Moreover, the prediction path will be used by emergency personnel to allocate their services in the areas that require immediate attention. The emergency team provides their services immediately after the tornado pass through the damaged areas to clean up the rubbles and debris and to find people that are stuck under bricks and stones. These tasks can be extremely hazardous and if the tornado changes its position or backtrack then their lives could be in danger as well. By using this prediction model, emergency-response supervisors will not send their team to the hazardous location until the tornado dissipates from that area completely.

Furthermore, the false alarm ratio (FAR) is a critical issue when it comes to issuing tornado warnings. The weather services sometimes increase the radius of areas that are under warnings to ensure the safety of the residents in cases of tornadoes increase in their intensity. Hence, by knowing the exact locations, the number of towns and counties that are being warned unnecessarily can be reduced which will consequently reduce the false alarm ratio.

To serve the purpose of effectively communicating tornado warnings to people in the path of the tornado, the use of unmanned aerial vehicle (UAVs) can be beneficial. Nowadays, UAVs have shown vital importance in many military and civilian applications. Numerous tasks including irrigation control, traffic control, fire monitoring, post-disaster survey, etc. have been performed efficiently by UAVs (16). In the present scenario, UAVs will constantly receive data from the prediction model to determine the updated location of the tornado. In addition, these UAVs will be connected to radar and satellite as well. By receiving updates on the original location and incorporating those into the prediction model, UAVs can generate more accurate predicted locations.

Once the locations are determined, the next step would be to provide warnings to people in tornado’s path. Instead of sending the emergency relief team to the areas under tornado warnings, UAVs can serve as first responders. These UAVs can be operated by emergency personnel who can have a real-time access to these locations. They provide warnings to each and every house or business in tornado’s path. Depending on the housing type, UAVs can guide people to either take shelter in their basement or leave the house to seek sturdy shelter. In the event of approaching tornado, people try to leave their houses in vehicles towards shelter which can be extremely dangerous. A thunderstorm before the arrival of a tornado along with heavy rain, large hail, and strong winds can make it impossible to see where they are heading and substantially decrease the speed of the car. Beyond the potential threat of tornadoes, flooded roads and fallen trees on the way to a shelter can pose a life threating situations. With the help of cameras and GPS installed inside UAVs, emergency personnel can guide people to take safer routes to the shelter. Due to the time limitations, this job needs to be conducted by a team of UAVs. Some military applications have been found to use multiple small relay UAVs to communicate information in an obstructed line-of-sight environment. To help people in the path of the tornado, multiple small UAVs can provide the consistent wireless communication link between the emergency relief-team and the individuals (16).

In addition to providing tornado warnings, UAVs can be used post disaster for recovery purposes as well. Emergency relief-team is responsible for rescue operations immediately after the dissipation of tornado. To efficiently plan these operations, however, it is essential to have reliable a communication system that delivers the continuous updates about the destructive areas. Due to the breakdown of power lines, antennas, and other communication mechanisms, it is cumbersome for emergency management facilities to communicate with other. Therefore, UAVs would be useful to conduct search and rescue operations along with getting information about casualties so immediate services are provided to severely injured people (8). Furthermore, in a post-tornado scenario, data pertaining to damage is collected by operators to expedite the process of rebuilding the infrastructure. Going to these devastated areas and taking images of broken buildings and other properties can pose a potential danger to the officials. Many of these areas cannot be accessible due to flooded roads. UAVs, on the other hand, can perform the job efficiently and provide the high-resolution images of the affected areas (9).

1.4 Limitation of Study

The current prediction model was only applied to predict the path of El Reno, Oklahoma tornado as the tornado database provided by the Storm Prediction Center (SPC) does not include the minute to minute data regarding the movement of other tornadoes. The database usually contains the start and the end locations of the tornado and to predict the path of the entire tornado, more information pertaining to actual locations is required. Furthermore, the prediction model can be used to predict the path of tornadoes that are within 10-15 miles. Long track tornadoes that could cover areas up to 50 miles or more will not be predicted by this model as these tornadoes can give rise to many other small tornadoes which will be hard to keep track of.

Moreover, although UAVs would be an ideal option for providing warnings to the residents in tornado's path, their usages have some limitations due to their relatively small size and lightweight. In the event of tornadoes that could reach a high intensity of winds up to 200-300 mph, the use of UAVs is not recommended.

2. Literature Review

2.1 Overview of Tornadoes

2.1.1 Development of Tornadoes

A tornado is a form of a storm that rotates violently, it contains a narrow column of air which extends from the thunderstorm to the ground. The rotation of tornado gives it an appearance of condensation funnel or a swirling cloud of dust that is being risen from the ground. The diameter of the column of the air is somewhere about 100m which can increase or decrease in the size depending upon the intensity of the storm. The most violent tornadoes can have the average wind speed from 125 m/s to 140 m/s. The rotation of the condensation funnel with high wind speed can cause severe damage on the ground, even in the event of funnel not completely reaching the ground (18).

Tornadoes are visible as a funnel cloud when the pressure inside them is very low, due to the low pressure the condensation of water vapor occurs which results in the formation of cloud particles. In some cases, where the pressure is high due to air being too dry, the condensation funnel either does not form or extents to the ground. In this scenario, a tornado can be seen as rotating dust or debris column. In cases, where the pressure of the air is very high that no particles can loft, the tornadoes are completely invisible. The most complicated form of form to spot are the rain wrapped ones, these in are completely covered in precipitation and therefore they are either not visible at all or may be visible from a restricted viewing angle. The time that tornadoes remain on the ground can last somewhere from few seconds to hours, however, on average most tornadoes last only 10 minutes. Although tornadoes can occur anywhere in the world, the Great Plains of the US have seen the highest number of tornadoes. Majority of these tornadoes touch down to the east during the spring season. The base of these tornadoes are thunderstorms, the moist air from the

Gulf of Mexico combines with the cool and dry air from Canada and aggravate these storms. These two different masses air upon combining create an instability in the atmosphere which results in the formation of a tornadic supercell with strong rotation (19).

The rotating column of wind that extends from the base of cumulus cloud but does not reach the ground or water surface is called the funnel cloud. Upon touching the ground, however, this funnel cloud becomes a tornado. Many tornadoes initiate as a funnel cloud, but not all funnel cloud give rise to tornadoes. Moreover, tornadoes do not always rely on the funnel cloud to form, very strong cyclonic winds are sufficient to trigger the formation of relatively violent tornadoes (10).

2.1.2 Tornado Regions:

When the tornado touchdown on the ground, it comprised of different air flow regions. These regions are surrounded by a tornado and divided into five separate regions. The region Ia is called the outer flow region and is separated from the core of the tornado itself. This outer flow region surrounds the core and comprised of air that builds and approaches towards the core. The central axis of the tornado give rise to the core of the tornado, the core usually extends upward and outward towards the radius of the winds. In an idealized tornado, the radius of the core can extend up to tens to hundreds of meters. The air inside the core consists of the air that has entered through the boundary region II, III and IV. Region II considered a boundary layer and provides an inflow of air that is resulted by the frictional interaction of the air with the surface of the earth. This interaction tends to flow the air towards the center and strengthen the core region of the tornado and give rise to the wind speed as well. Furthermore, the air that enters from the boundary layer (region II) to the core of the tornado (region Ib) must pass through another boundary layer (region III). This region is extremely critical in the formation and the movement of the tornado. Inside this region, the horizontal flow of the air turns into the vertical upward flow. The areas that come in contact with this region can suffer the most damage. In addition to high wind speed, borne missiles and debris are also generated in this particular region. Lastly, the upper flow of the tornado (region IV) comprised of the rotating updraft of the parent thunderstorm (20).

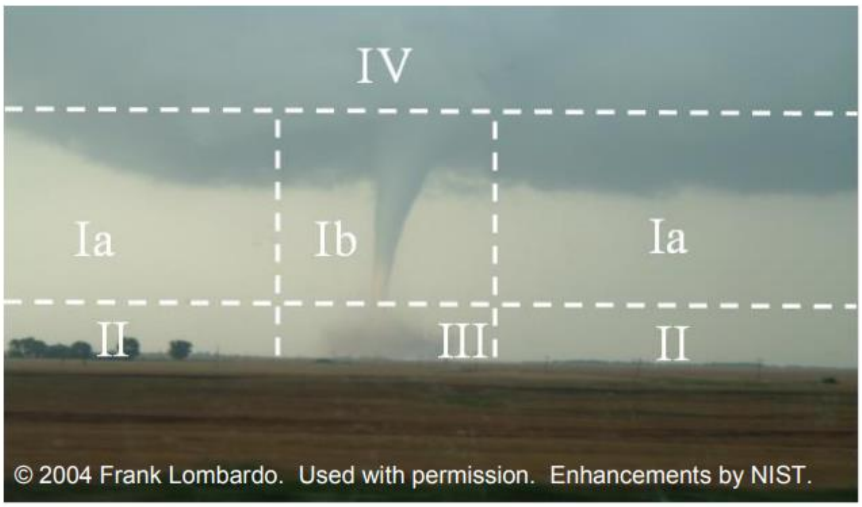

Figure 1: Flow Regions of tornado [20]

2.1.3 Types of tornadoes:

The tornadoes can be divided into two types: supercell and non-supercell tornadoes. The supercell tornado forms within a mesocyclone which would be a very large scale circulation. The isolated supercell storm, large and violent tornadoes, or supercell within a thunderstorm fall into supercell category of tornadoes (18). These supercell tornadoes develop from the winds that rotate updraft, these rotations get stronger with high wind speed. A supercell form when the wind above the ground levels can blow at a different speed and in different directions. For instance, in case of tornado alley, winds come from the southwest at 5 mph, however, at about 5000 ft above the same location, the winds are blowing from the southeast at the speed of 25 mph. This difference in the wind speed and direction gives rise to the invisible tube of air that beings to rotate horizontally. In addition to these horizontal winds, the air inside the thunderstorm tilts the horizontal air to the vertical which result in the formation of an updraft wind rotation. A tornado occurs when these rotating updraft winds get the warm and moist air flow at the ground level. [3] The non-supercell tornadoes form by the vertical air on the ground that caused by the combination of both warm and cold winds. These tornadoes are smaller and less devastating as compared to the supercell tornadoes. In addition, non-supercell tornadoes occur mostly in sparsely populated areas. Non-supercell tornadoes are further divided into three different tornadoes which include gustnado, landspout and waterspouts tornadoes. Gustnado does not involve any condensation funnel, it is simply a rotation of dust or debris on the ground. The landspout tornado forms within a thunderstorm cloud and looks like a narrow or rope-like condensation funnel. Finally, the waterspout tornadoes form over water and have the same appearance as the landspout tornadoes (21).

2.2 Detecting and Forecasting Tornadoes

The accuracy of the tornado detection is essential to provide forecasts and warnings to the public. Forecasters either use radar to predict tornadoes or analyze certain features of the severe weather which can potentially result in the formation of tornadoes. Trained storm spotters can also identify tornadoes and report to the National Weather Service (NWS) to generate warnings. Additionally, various computer models are used to examine radar images, these models can demonstrate weather condition to predict the hazardous weather. The National Severe Storm Laboratory (NSSL) has developed an algorithm called WSR-88D Mesoscale Detection Algorithm to evaluate data generated by radars. The forecasters usually look for the pattern of rotation in this radar images and concentrate on the criteria such as size, depth, and strength for the development of tornadoes. To determine the areas of high winds and intense rotation, the forecasters look for the Tornado Vortex Signature (TVS) on Doppler radars. The TVS is a velocity pattern shown on the radar as a smaller and tighter rotation before the tornado touches down on the ground. Despite the TVS being shown on the radar, a thunderstorm might not develop into the tornado, however, it definitely increases the probability of the tornado occurrence (22).

2.2.1 Tornado Warnings:

Enhanced tornado warnings are the key to reduce fatalities and injuries that can result from the violent nature of tornadoes. Longer lead times on the warnings can provide opportunities to residents to plan the escape and take further precautions. Simmons et al. examined the relationship between the tornado warnings and the subsequent casualties by using the dataset which comprised of tornado data from 1986 and 2002. The results corroborate with the fact that the warnings had a substantial effect on the casualties of the tornado. By simply warning people in advance the rate of injuries was reduced by 40%. In addition, fatalities were also seemed to be reduced with an increased lead time of 15 minutes (23).

The effective communication of the severe weather through watches and warnings is delivered by using electronic media such as television and radio. The NWS has also developed a software that interprets the computer codes pertaining to watches and warnings and automatically display that information on television screens to alert public. Furthermore, NOAA Weather Radio All Hazards (NWR) is operated and maintained by NWS to generate weather forecasts and severe weather alerts (2). The radio has considered to be a direct warning system between the official and residents and have been operational for over 50 years. To determine the effectiveness of NWR usage, a study had been conducted in west Tennessee. The results revealed that only 24.6% of the households own the NWR receivers out of those 8.1% regularly monitor the services provided by NWS (24).

Stokoe et al. conducted a case study where they attempted to understand the human behavior when it comes to perceiving tornado warnings. It was concluded that white men, compared to other demographics, tended to ignore the warnings, hence, were more vulnerable to tornado destructions. Another vulnerable population consisted of Hispanics, the elderly and those who had already experienced a tornado in their lives. This group either ignored, distrusted or did not understand the warnings at all. As this population is expected to increase, the death rate will increase with it regardless of the advancement in warning mechanisms (14). To further explore the human perception, Sims et al. focused on identifying the differences in psychology of people living in different regions of the United States. For this study they seek to evaluate the difference between people living in the South (Alabama) and the Midwest (Illinois) pertaining to tornado warnings. The data indicated that about 42% of Illinois residents would take actions upon receiving warnings through technology such as radio or television, while, on the other hand, only 4% of Alabama residents reported the use of such mechanism to take further actions to seek shelters in the event of tornado arrival. Moreover, 33% of the Alabama residents reported to use their own judgement such as determine the shape or darkness of the clouds prior to seeking shelter compared to 9% of Illinois residents (15).

2.2.2 Warn-on-detection

Unlike hurricanes that can be tracked from miles away, tornadoes are intense and short lived hazardous events that can evolve rapidly and cause devastating destructions over the course of few minutes. Currently, tornado warnings follow a paradigm called warn-on-detection (4). According to this method, warnings are issued on the basis of tornadoes being detected on the

Doppler radar. Trained spotters can also detect tornadoes and communicate their observations to the weather forecast offices upon which the officer conducts his own investigation regarding the funnel cloud and storm in their warning areas before generating a warning. Severe weather reports from National Weather Service (NWS), airborne surveys and any information from the state or local emergency management can also be helpful to generate warnings. An example of a reliable report to generate warnings would include a distinctly visible tornado vortex in contact with the ground with a condensation funnel. In addition, a rotating debris or dust that is overlaid by a condensation funnel can also signify the touchdown of a tornado. This phenomenon, however, can get complicated when tornadoes or funnel clouds are hidden by dust, darkness or precipitation. Therefore, tornadoes that touchdown late at night can cause significant destruction as the duration between warnings and touchdown gets shorter due to darkness or not being observed by public or spotters (10).

2.2.3 Warn-on-Forecast

Currently, tornado warnings are issued based upon radar detection or visual observations which can leave public with less time to take immediate actions to save their lives. On the other hand, hurricane tracks are generated way in advance by forecasters by using numerical weather prediction models. By using such models, hurricane warning is issued when tropical disturbances are observed due to the increase in wind speed up to 74 mph. This may provide plenty of time to the individuals to evacuate danger zones. To increase the lead time for tornadoes, flash floods and thunderstorms, National Oceanic and Atmospheric Administration (NOAA) is working toward developing a convective-scale warn-on-forecast system. According to this system, the high resolution numerical weather prediction models will provide the information regarding both the internal structure and the evolution of the storm which result in increasing warning lead times (4).

The warn-on-forecast researchers will analyze the conditions of the storm by combining the data from satellite, radar and high-resolution surfaces. This set of analysis will then use to initiate the ultra-high resolution computer models. The researchers claim that these model will be able to predict the hazardous weather 30-60 minutes before their formation (25).

2.2.4 Path Length and Width of Tornadoes:

The path length of the tornado is recorded in miles and tenths of miles and path width is recorded in yards. These parameters can be used to indicate one large tornado or in some cases, multi-segmented tornadoes as well. In the storm prediction center database, the length and width indicate the segment of the tornado in the particular county. In the event of multi-segment tornadoes, however, the latitude and longitude of the start and the endpoint can be used to determine the full length of the tornado. During the entire length of the tornado, the maximum width is recorded as the actual width of the tornado.

2.2.5 Tornado path and direction:

The studies regarding tornado hazards mitigation and risk-assessment tend to focus primarily on its length, width, and EF-scale, while the information regarding the path direction is often neglected. The current tornado data on NOAA website provides the being and end direction of tornadoes, however, directions at each and every point of a tornado are missing. The path direction would be extremely beneficial for the local emergency department as they can better facilitate the resources in the event of severe weather conditions. By determining the direction of tornado every few minutes, the evacuation process will also become less difficult. Moreover, tornado path direction will also help official making warning decisions.

Studies and tornado records indicate that most tornadoes travel from the southwest direction toward the northeast. However, given the unpredictability of tornadoes, this perception cannot be applied to all tornadoes. Once they are on the ground they can change their direction anytime. Suckling et al. studied the path direction of 6,194 tornadoes occurred during 1980-2002 and found that although the majority of tornadoes do originate from the southwestern quadrant, there are some seasonal and regional variations involved. These variations are more evident in the late spring season, where more tornadoes predominantly generate from the west instead of southwest component. In addition, more summer tornadoes originate from westerly to the northwesterly component. Therefore, to improve tornado hazard mitigation, it is essential to incorporate these seasonal variations (26).

2.2.6 Weather Surveillance Radar-1988 Doppler (WSR-88D)

Radars are used by forecasters to predict severe weather, the effectiveness of these predictions can help emergency personnel to warn people in a timely manner. Simmons et al. examined the quality of the warnings and causalities of tornadoes after the installation of Weather Surveillance Radar-1988 Doppler (WSR-88D). According to their analysis, it was evident that warnings of tornadoes were increased from 35% to 60% after the installation of WSR-88D radars at National Weather Service Weather Forecast Offices. The mean lead time of the warnings of tornadoes was also increased from 5.3 minutes to 9.5 minutes along with the reduction in the false alarm ratio. Furthermore, after conducting the regression analysis of the casualties of tornadoes, it was observed that both the fatalities and the injuries were 45 and 40 percent lower than expected (27).

2.2.7 Doppler on Wheels (DOW) mobile radar

To predict tornadoes efficiently it is important to study their behaviors along with the parent storms that spawned them. Doppler radars have been used to serve this purpose, they are portable and can be mounted on the mobile platform to perceive how tornadoes develop and move in certain directions. The benefit of these Doppler on wheel radars is that they can be brought relatively close to tornadoes, this enhances the ability of radar to provide precise spatial resolution. Moreover, the development of the storm can be monitored closely and accurate warnings can be generated pertaining to the movement of the tornado. It also aids in mapping the wind field near the ground which provides the idea of destruction that tornadoes can bring about (28).

2.3 Vulnerable Housing Stock

Upon conducting the research on the locations which tend to have the high percentage of tornado-related fatalities, it was observed that the weak housing stocks such as mobile homes are the most unsafe places. The locations where tornado fatalities tend to occur were determined from tornado data provided from 1985 -2005, it was revealed that over 70% of these fatalities have taken place inside the housing structures while 10% occurred inside vehicles or on boats (17). Furthermore, out of the housing-related fatalities during 1985-2005, 44% of those occurred within mobile homes. In another research conducted during 2001-2005, it was noted that the percentage of these fatalities inside the mobile home has further increased to 57% compared to 37% from 1986-1990 (1). The dramatic increase in the death rate pertaining to mobile home residents is explored in data collected for the tornado occurred in Oklahoma City on May 3, 1999. The data indicated that with the destruction of less than 100 mobile homes, eleven mobile home residents lost their lives (38). The number of fatalities among mobile home residents in different regions of the United States was determined and it was noted that the South region had the highest number of these fatalities. For instance, the region comprised of Arkansas, Alabama, Georgia, Mississippi, and Tennessee had 52.1% of fatalities in mobile homes during 1985-2005. Moreover, the deep and interior South region also had the higher percentage of mobile home related fatalities in the event of tornadoes. The southeast United States encompasses the highest percentage of mobile homes as compared to any other region. Furthermore, the mobile home stock is above 20% in many of the counties in this region. Hence, the unreliable housing type in the southern United States poses a potential danger to the vulnerable population of this area from tornadic events (1).

According to the National Severe Storms Laboratory (NSSL), research has shown that the risk of people killed by a tornado in mobile home is 15 – 20 times greater than the people inside a permanent structure. Although only 7% of US population live in mobile homes, 50% of tornado fatalities occurred in these mobile homes. These homes not attached to the ground and only violent winds are sufficient to rip them apart. One of the examples of mobile home tornado-related fatalities was occurred in Newton, Georgia on March 1, 2007, where six people were killed from taking sheltering inside mobile home (5). Although tragic event like tornadoes cannot be prevented, proper warnings and immediate evacuation of unsafe places can make a substantial difference in saving vulnerable lives. In the above-mentioned examples, maps generated by the radars must have shown these mobile homes in tornado's path. The fatalities could have been prevented by providing immediate warnings and ensuring the evacuation of the houses.

2.4 Examples of some violent Tornadoes

2.4.1 Alabama Georgia Tornado

This tornado had occurred on March 1, 2007, in southern Alabama and Georgia and took 19 lives which include 8 high school students. These students were seeking shelter inside the school and a concrete wall collapsed on them. The students were kept inside the school for three hours due to tornado warnings. The school building could have been evacuated if an accurate tornado path direction was known. Parents of students were waiting outside the school when the wall had collapsed due to strong and intense winds. Additionally, the school was in the path of three severe tornadoes and they might have thought that letting the students out would endanger their lives. Later the National Weather Service (NWS) team had found that the school area was unnecessarily warned by 58% and accurate storm-based warning would have reduced the area under the warning (5).

2.4.2 Moore Oklahoma Tornado

On May 20, 2013, a violent EF-5 tornado had touched down in Moore, Oklahoma. A mother along with her four-month-old son died while taking the shelter inside a bathroom of 7-Eleven. The mother, who was also an employee at the 7-Eleven took shelter inside the bathroom along with other employees, her son and three customers upon hearing the sirens of a tornado warning. The tornado was of EF 5 intensity and tore the entire building of the 7-Eleven into piles of bricks and twisted metal pieces (29).

There could be many things that had gone wrong in this particular scenario. The fatalities could have been avoided had the people were being located at the safer location. In these type of events, a live coverage from TV is the only option to actually know where the tornado is heading. However, in the event of severe storms, power lines can be down, hence, the victims have no way of knowing whether they are in the path of tornado or not.

2.4.3 Mother's Day Tornado

This tornado had occurred on May 10, 2008 in Oklahoma and Missouri. The tornado was given a rating of EF4 intensity and it took 21 valuable lives. Upon conducting a survey, National Weather Service (NWS) found that all the fatalities that had occurred during this tornado were covered by warnings and the mean lead time between the warnings was found to be 18 minutes. Hence, this was the matter of people not responding to the warning and taking appropriate actions pertaining to reach safer locations. Another interesting finding revealed that half of those fatalities had occurred inside the mobile homes. In fact, one of the families tried to take shelter inside the closet of a mobile home, but the tornado ripped apart the house and the residents were thrown in different directions. The father and the child survived, however, the mother died. Another fatality occurred when a person tried to take a shelter on the second floor of his house, hiding in the basement or at least on the first floor might have saved his life. Upon interviewing the survivors, NWS discovered that these residents have seen numerous warnings and watches with the siren activations in the path, however, never experienced a tornado, hence, they were more likely desensitized to the warnings. Most of these people ignored the warnings and stayed inside their homes and this violent tornado had taken 21 precious lives (30). These fatalities could have been avoided by simply evacuating the houses in the path of tornado, NWS issued watches 6 hours before the tornado actually touched down which would give plenty of time to residents to seek shelter.

2.2.4 Woodward, Oklahoma Tornado

The tornado had touched down at 11:50 pm on April 14th 2012 and dissipated at 12:27 am and resulted in 6 fatalities and 29 injuries. After conducted the survey, the NWS Norman, Oklahoma forecast office gave this tornado an EF-3 rating. Soon after the touch down, tornado incur some minor damages in the rural portions of Woodward County which resulted in downed trees, poles and power lines. At 12:12 am, approximately after 22 minutes of touch down, the tornado hit two mobile homes which resulted in 3 fatalities. As the tornado travels towards the north side of Woodward, it struck more mobile homes and killed 3 more people. Upon analyzing the issues pertaining to tornado fatalities, it was determined that the Woodward county had been given two tornado warnings on April 14th at 3:20 pm and 4:59pm. Nevertheless, before generating tornado warning on 12:00 am when the tornado was about to hit the city of Woodward, the weather radio had alarmed 22 times. From April 14-15, the entire Woodward County was in tornado watch for about 15 hours and 15 minutes. On the afternoon of April 14, 2012 those tornado watch had been changed to severe thunderstorm or tornado warning for about 4 hours and 14 minutes before the arrival of tornado (31).

Reflecting upon the scenario of Woodward, OK tornado it became evident that tornado warnings and watches were definitely had not been the issue that resulted in fatalities. Residents were provided with ample time to evacuate their homes before the formation of tornado. However, despite early warnings and watches, mobile home residents lost their lives. There was 22 – 28 minutes of time duration between the tornado being touched down and hitting mobile homes. The images from radar and satellite show the tornado passing through the Woodward County, however, the path showing the exact location of tornado was not provided. Since this tornado had touched down in Arnett, OK and the generated path from radar and satellite must have indicated its route to Woodward, OK, the mobile homes in Woodward should have been evacuated. In such situations, emergency relief-team could ensure the evacuation of the homes in the path of tornadoes, however, due to flooded roads, fallen trees and down poles and power lines, it is nearly impossible for them to conduct these tasks. Hence, to ensure the safety of emergency personnel and residents, the use of unmanned aerial vehicles (UAVs) is suggested. A team of UAVs can be deployed to warn people in the path of tornado and by having the real-time access to these locations, emergency and safety managers can ensure the evacuation of danger zones. Moreover, by using the current model, the exact locations of the tornado can be predicted after receiving the original location information from radars and satellite. The next location of tornado will be predicted after every one or two-minute and warnings to evacuate houses are issued to residents. In addition, UAVs will also assist them with reaching safe shelter.

3. Materials and Methodology

3.1 Study Area

The present study seeks to predict the tornado movement by determining its exact locations. By knowing the location of tornado, people in its path can be warned before the arrival of a tornado which can save lives of the residents. Currently, tornado warnings are issued by the NWS when tornadoes are detected on radars (4). The problem with the issuance of warning primarily based upon Doppler radar observation is that these warnings are mainly focused on the parent thunderstorm that may or may not spawn a tornado. The National Weather Service forecasters relied upon the principle that it is safer to warn the public for severe weather events than to have casualties from not providing advance warnings. This phenomena can result in increased false alarm rate which is currently 75% of tornado nationally (32). Due to increased false alarm rate, people become desensitize to tornado warnings, however, when the tornadoes do touch down they become completely clue less about the actions they need to take. By using the present model, a tornado path is generated and the exact locations are determined.

3.2 Experimental Model

3.2.1Original Path

Data from National Weather Service (NWS) for the tornado that had touched down in El Reno, Oklahoma on May 31, 2013 are used to predict the tornado path. The minute by minute location of tornado is provided along with linear speed that it was travelling with by the NWS (33). The linear movement of the tornado represents its translation speed. This translation speed along with the translation direction is used to calculate the translation velocity of tornadoes (20). The tornado had touched down at 6:03 pm and dissipated at 6:43 pm and killed eight people. Among the deceased, three people were severe storm researchers who thought they were not in the path of the tornado, however, this particular tornado had deviated from its usual path and took a significant left turn and these three storm chasers were caught inside of the tornado. Other people were killed while trying to escape the tornado in their vehicles. This tornado was given an EF3 rating on the Fujita scale. EF3 tornadoes have the rotational speed between 136-165 mph, however, for this tornado, both the Doppler on Wheels and the RaXPol radar indicated the speed more than 200 mph. Furthermore, the wind speed close to the surface around the core of tornado was found to be about 295 mph from RaXPol radar. Despite these high winds, this tornado was not given a rating higher than EF3 as the surveyors did not find any damage on the ground that would exceed the EF3 rating (33). Hence, to conduct the ratings of tornadoes, the radar winds speeds are not used simply because the radar indicated the speed in the air on elevation from the ground and EF scale represents the ground-based damage conditions (10). This tornado had remained on the ground for about 40 minutes and covered the total distance of 16.2 miles. In addition to the long-track, this tornado was found to be extraordinarily wide and covered the width of 2.6 miles. The tornado had developed southwest of El Reno and rapidly changed both its speed and direction. This tornado destroyed some businesses and homes near El Reno along with the destruction of crops in several fields (33).

The data was provided for all the locations from 6:03pm – 6:43pm and comprised of 39 points on the map. To generate the predicted path, the points were used for both one and two-minute intervals. The addresses of these locations were provided by the NWS. Furthermore, the latitude and the longitude points were determined from these addresses to acquire the exact locations of the tornado. The average linear speed of this tornado, according to the NWS data was found to be 24.3 mph. To obtain the accuracy of the present model, however, it was necessary to determine the speed at each and every location. Hence, the speed provided by the radar for each location in miles per hour was used to calculate the distance by using the following kinematics formula.

$$\text{Distance} = \text{Velocity x Time} \qquad (1)$$

The tangent inverse formula was used to calculate the angel between each location.

$$\theta = \text{inverse tangent} \left(\frac{y2 - y1}{x2 - x1}\right) \qquad (2)$$

Where x_1 = longitude location at point 1

y_1 = latitude location at point 1

x_2 = longitude location at point 2

y_2 = latitude location at point 2

3.2.2 Predicted Path

In order to predict the same tornado, the first step was to determine the angle between each location. For this purpose, the tornado path provided by the NWS was downloaded on the paint application and the tangent inverse formula in equation (2) was used to calculate the angel between each point. The NWS data had also provided the speed of the tornado at each and every location, therefore, that speed was used to calculate the distance between each location. The speed of the tornado was converted from miles per hours to kilometers per hour. Both one and two-minute intervals were used to predict the next point on the map. The distance between the latitude points and the longitude points were calculated using the following formulas;

$$x = V.\cos\theta\, t \qquad (3)$$

$$y = V.\sin\theta\, t \qquad (4)$$

The next step was to add the calculated distance in kilometers from equations (3) and (4) to the original latitude and the longitude points to predict the next location of tornadoes. As the latitude and longitude points are represented in degrees, the kilometer distance had to be converted into degrees before adding to the original points. The following estimation formulas were used to covert distance in km to degrees.

$$1° \text{ Latitude } = 111 \text{ km} \quad (5)$$

$$1° \text{ Longitude } = 88.9 \text{ km} \quad (6)$$

The point estimation value was then added to the previous latitude and longitude points to obtain the next point. All the points were calculated and plotted on the map to obtain the tornado track. Alongside the predicted track, the original track was also plotted.

3.3 Original and Predicted Angle

To determine the accuracy of the model, the error between the angles of the predicted and the original data was calculated by using the following formula,

$$\% \text{ Error } = |(\frac{\text{predicted angle} - \text{original angle}}{360°})| * 100 \quad (7)$$

In the above equation, instead of dividing the difference between the angles to the original angle as done in usual cases, 360° was used. This was due to the fact that these angles represent the direction of tornado on the map. Based on the surface of the Earth, geographically, each point on the Earth had two-dimensional coordinates. The X-coordinates, represent horizontal positions and are called longitude and they run between -180 and +180 degrees. Likewise, they Y-coordinates are called latitude, these vertical points lie between -90 and +90 degrees (34). Hence, to find the error between the predicted and the angle direction, it was essential to use the entire 360° plane that take into account both the latitude and longitude coordinates.

3.4 Original and Predicted Distance

The distance between the original and the predicted locations were calculated to test the accuracy of the model. The NOAA's website was used to determine the distance between the latitude and longitude points of two locations (35). To generate the predicted path, the prior predicted location was used to predict the next location. In the actual tornado scenario, the Doppler radars will provide the information regarding the exact actual locations. To accommodate this scenario in the current model, the original locations were used to predict the subsequent locations and the distance between these locations were calculated and compared with the initial distance. The error between these initial and final distance were calculated to demonstrate the efficiency of the prediction model by the following formula.

$$\text{Error} = \left|\left(\frac{\text{final distance} - \text{initial distance}}{\text{final distance}}\right)\right| \quad (8)$$

3.5 Tornado Width and Predicted Locations

The width of tornadoes is around 0.17 miles to 0.28 miles (6). To check whether the predicted points were within the width of tornadoes, circles of the diameter 0.1, 0.2 and 0.3 miles were drawn along the tornado path of two-minute interval. To draw circles on the map, the distance between the two actual locations was calculated and divided by the diameter of circles to determine the number of circles on the path. If the predicted point was inside the circle then it will count as a success, if not, then failure. The circles were drawn on the separate segments of the two-minute path which include 6:03pm – 6:15pm, 6:17pm – 6:29pm, 6:31pm – 6:43 and the results were included in Table XV.

4. Results and Discussions

4.1 El Reno, Oklahoma Tornado Original Path

The original tornado path provided by the National Weather Service and Storm Prediction Center was used to develop the model for predicting a tornado's path. The latitude and the longitude of the exact addresses where the tornado had touched down were determined and included in Table I for the one-minute interval path and Table II for the two-minute interval path. The arc tangent formula provided in equation (2) was used to determine the angles of each point in the path. The original path of the tornado is provided in Figure 2.

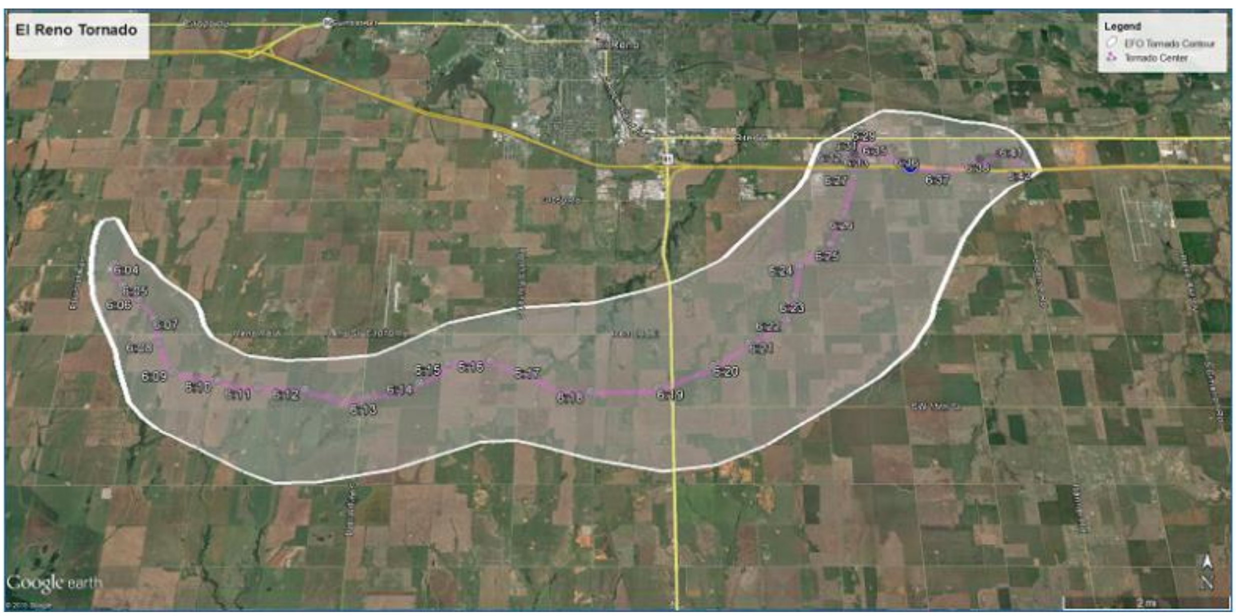

Figure 2. El Reno, Oklahoma Tornado Original Path [33]

TABLE I

EL RENO, OKLAHOMA TORNADO– ONE-MINUTE INTERVAL PATH (ORIGINAL DATA)

Time	Location	Latitude	Longitude	Angle
		North (+ve)	West (-ve)	Degrees
6:04	10803 Reuter Rd W, El Reno, OK 73036	35.478	-98.074	
6:05	10803 Reuter Rd W, El Reno, OK 73036	35.474	-98.069	-25.70
6:06	5103 S Fort Reno Rd, El Reno, OK 73036	35.472	-98.064	-39.34
6:07	S Fort Reno Rd, El Reno, OK 73036	35.468	-98.059	-68.86
6:08	9600 Reno Rd W, El Reno, OK 73036	35.462	-98.057	-45.70
6:09	8300 S Brandley Rd, El Reno, OK 73036	35.456	-98.051	-5.97
6:10	8300 S Brandley Rd, El Reno, OK 73036	35.455	-98.042	-9.95
6:11	5768 15th St SW, El Reno, OK 73036	35.454	-98.033	-4.10
6:12	5768 15th St SW, El Reno, OK 73036	35.453	-98.021	-4.63
6:13	8945 S Airport Rd, El Reno,	35.452	-98.008	12.37
6:14	7650 S Reformatory Rd, El Reno, OK 73036	35.455	-97.995	26.37
6:15	7650 S Reformatory Rd, El Reno, OK 73036	35.458	-97.989	7.02
6:16	7624 S Country Club Rd, El Reno, OK 73036	35.459	-97.979	-19.43
6:17	8010 S Choctaw Ave, El Reno, OK 73036	35.456	-97.970	-14.54
6:18	1400 S Choctaw Ave, El Reno, OK 73036	35.452	-97.956	3.56
6:19	6517 S Frisco Rd, El Reno, OK 73036	35.453	-97.939	20.13
6:20	1300 Rother Rd, Union City, OK 73090	35.458	-97.927	29.08
6:21	Alfadale St, Union City, OK 73090	35.462	-97.919	26.71
6:22	4720 Reno Rd E, El Reno, OK 73036	35.466	-97.911	71.77
6:23	4720 Reno Rd E, El Reno, OK 73036	35.476	-97.907	58.72
6:24	Reuter Rd E, El Reno, OK 73036	35.478	-97.906	35.81
6:25	S Radio Rd, El Reno, OK 73036	35.483	-97.899	65.92
6:26	11519 NW 5th St, El Reno, OK 73036	35.491	-97.896	61.39
6:27	815 SW 25th St, El Reno, OK 73036	35.499	-97.891	64.21
6:28	6100 OK-66, El Reno, OK 73036	35.505	-97.888	70.89
6:29	5158-5342 Rte 66, El Reno, OK 73036	35.508	-97.887	46.30
6:30	4816-5088 Rte 66, El Reno, OK 73036	35.507	-97.888	185.50
6:31	5800 OK-66, El Reno, OK 73036	35.506	-97.892	258.89
6:32	5602 OK-66, El Reno, OK 73036	35.504	-97.892	247.86
6:33	4006 Ewing Ln, El Reno, OK 73036	35.503	-97.893	182.59
6:34	5602 OK-66, El Reno, OK 73036	35.503	-97.890	4.29
6:35	I-40, El Reno, OK 73036	35.504	-97.882	-24.03
6:36	I-40, El Reno, OK 73036	35.501	-97.876	-6.52
6:37	I-40, El Reno, OK 73036	35.500	-97.868	19.63
6:38	2868-2904 Dyer Dr, El Reno, OK 73036	35.502	-97.862	-1.79
6:39	3057 Dyer Dr, El Reno, OK 73036	35.502	-97.859	15.31
6:40	I-40, El Reno, OK 73036	35.504	-97.853	-4.28
6:41	3525-3601 N Banner Rd, El Reno, OK 73036	35.503	-97.850	-41.77
6:42	I-40 & N Banner Rd & US-270, El Reno, OK 73036	35.501	-97.848	-19.94

TABLE II

EL RENO, OKLAHOMA TORNADO – TWO-MINUTE INTERVAL PATH (ORIGINAL DATA)

Time	Location	Latitude	Longitude	Angle
		North (+ve)	West (-ve)	Degrees
6:03	10803 Reuter Rd W, El Reno, OK 73036	35.478	-98.074	
6:05	10803 Reuter Rd W, El Reno, OK 73036	35.474	-98.069	-41.05
6:07	S Fort Reno Rd, El Reno, OK 73036	35.468	-98.059	-32.31
6:09	8300 S Brandley Rd, El Reno, OK 73036	35.456	-98.051	-55.62
6:11	5768 15th St SW, El Reno, OK 73036	35.454	-98.033	-7.95
6:13	8945 S Airport Rd, El Reno,	35.452	-98.008	-4.39
6:15	7650 S Reformatory Rd, El Reno, OK 73036	35.458	-97.989	17.15
6:17	8010 S Choctaw Ave, El Reno, OK 73036	35.456	-97.970	-5.61
6:19	6517 S Frisco Rd, El Reno, OK 73036	35.453	-97.939	-4.74
6:21	Alfadale St, Union City, OK 73090	35.462	-97.919	24.38
6:23	4720 Reno Rd E, El Reno, OK 73036	35.476	-97.907	50.10
6:25	S Radio Rd, El Reno, OK 73036	35.483	-97.899	39.82
6:27	815 SW 25th St, El Reno, OK 73036	35.499	-97.891	63.59
6:29	5158-5342 Rte 66, El Reno, OK 73036	35.508	-97.887	65.93
6:31	5800 OK-66, El Reno, OK 73036	35.506	-97.892	196.47
6:33	4006 Ewing Ln, El Reno, OK 73036	35.503	-97.893	255.15
6:35	I-40, El Reno, OK 73036	35.504	-97.882	3.85
6:37	I-40, El Reno, OK 73036	35.500	-97.868	-14.67
6:39	3057 Dyer Dr, El Reno, OK 73036	35.502	-97.859	11.91
6:41	3525-3601 N Banner Rd, El Reno, OK 73036	35.503	-97.850	8.33
6:43	I-40 & N Banner Rd & US-270, El Reno, OK 73036	35.501	-97.848	-41.77

4.2 El Reno, Oklahoma Tornado Predicted Path

Presently, Doppler radars are used by NWS to predict the path of tornadoes and the warnings are issued for the town and counties that could potentially be in danger zones. Moreover, a list of locations that could possibly be in tornado's path is generated. Warning mechanisms such as TV, radio, sirens are used to alert public. Despite these continuous warnings, however, reducing tornado-related fatalities is still challenging in the event of strong and violent tornadoes. The underlying problem of people not taking enough initiatives to respond to tornado warnings is the tornado false alarm ratio (FAR). The National Weather Service (NWS) issues tornado warnings upon tornadoes being detected on radars. This warning phenomenon consists of two measures called probability of detection (POD) and false alarm ratio (FAR). The probability of detection

(POD) can increase by generating more warnings on severe thunderstorms that can spawn a tornado, however, if these conditions do not result in a tornadic event then this will result in increasing false alarm ratio (FAR) (36). The false alarm ratio can be defined as the ratio of tornado warnings that do not result in the formation of the tornado to the total number of tornado warnings. Brotzge et al. pointed out that during 2008 approximately 75% of warnings generated by NWS were a false alarm. Numbers like these can result in people's mistrust in warning mechanisms and potentially decrease the validity of tornado warnings (32). Additionally, Simmons et al. found a significant increase in fatalities and injuries in the areas that had higher false alarm ratio. According to their findings, a one-standard-deviation increase in the FAR lead to the increase in expected fatalities by 12% and 29% and increase in expected injuries by 14% and 32%. Consequently, decreasing in FAR in those areas reduced fatalities by 4% -11% and injuries by 4-13%. Therefore, reducing FAR can subsequently decrease the rate of casualties (37).

The National Oceanic and Atmospheric Administration's (NOAA) aims to predict the tornado before it is being detected on radar (25). By using such system, they anticipate to increase the lead time up to hours. However, issuing warnings prior to observe severe weather that may or may not result in a tornado can potentially further increase the false alarm ratio (FAR). Therefore, it is essential to reduce the false alarm ratio and only people that are in the path of the tornado are warned. In some scenarios it could be beneficial to issued warnings for areas that may or may not be in the path of the tornado, however, in the long run, this may result in the reduction of the validity of tornado warnings.

In the present model, kinematics formulas are used to predict the exact locations of tornadoes so the warnings are issued to only those houses and businesses that are in tornado's path. The tornado path was predicted for El Reno, Oklahoma tornado that had touched down on May

31, 2013. The National Weather Services provided the linear speed at which the tornado was traveling for the one-minute interval. The speed and the direction were used to predict the exact location of the tornado which comprised of its latitude and longitude points. Both the latitude and the longitude were calculated separately and listed in Table III and IV for the one-minute interval path and Table V and VI for two-minute interval path. The latitude and the longitude points for both the original and the predicted path were plotted on the map as shown in Figure 3 for the one-minute interval path and Figure 4 for two-minute interval path. Upon observing Figure 3 and Figure 4, it was evident that the predicted and the actual locations in the one-minute path interval were much closer to each other as compared to the locations in the two-minute path interval. Hence, updating tornado path every minute or less by radars can generate accurate data regarding the exact locations.

Table III
EL RENO, OKLAHOMA TORNADO – ONE-MINUTE LATITUDE PREDICTION

Time	**Latitude**	**Distance**	**Angle**	**Linear Speed**	**Linear Speed**	**Estimation**
	(North +ve)	km	degree	miles/hr.	km/hr.	
6:04	35.478					
6:05	35.475	-0.36	-63.43	15	24.135	-0.003
6:06	35.472	-0.34	-39.35	20	32.18	-0.003
6:07	35.468	-0.48	-46.04	25	40.225	-0.004
6:08	35.462	-0.64	-72.47	25	40.225	-0.006
6:09	35.457	-0.55	-54.39	25	40.225	-0.005
6:10	35.455	-0.19	-11.4	35	56.315	-0.002
6:11	35.454	-0.15	-9.29	35	56.315	-0.001
6:12	35.454	0.02	1.32	39	62.751	0.000
6:13	35.453	-0.20	-8.79	49	78.841	-0.002
6:14	35.456	0.36	17.13	45	72.405	0.003
6:15	35.461	0.57	37.61	35	56.315	0.005
6:16	35.461	0.04	2.47	37	59.533	0.000
6:17	35.457	-0.46	-20.79	48	77.232	-0.004
6:18	35.454	-0.34	-15.04	49	78.841	-0.003
6:19	35.452	-0.26	-10.2	55	88.495	-0.002
6:20	35.454	0.24	10.47	49	78.841	0.002
6:21	35.457	0.36	20.31	39	62.751	0.003
6:22	35.462	0.56	32.09	39	62.751	0.005
6:23	35.470	0.88	69.52	35	56.315	0.008
6:24	35.477	0.76	78.44	29	46.661	0.007
6:25	35.483	0.65	38.27	39	62.751	0.006
6:26	35.491	0.88	62.73	37	59.533	0.008
6:27	35.499	0.89	72	35	56.315	0.008
6:28	35.506	0.86	65.8	35	56.315	0.008
6:29	35.513	0.75	75.58	29	46.661	0.007
6:30	35.510	-0.31	205.27	27	43.443	-0.003
6:31	35.508	-0.28	223.45	15	24.135	-0.002
6:32	35.506	-0.27	244.65	11	17.699	-0.002
6:33	35.502	-0.37	247.62	15	24.135	-0.003
6:34	35.504	0.21	24.78	19	30.571	0.002
6:35	35.505	0.07	6.34	25	40.225	0.001
6:36	35.502	-0.29	-23.73	27	43.443	-0.003
6:37	35.501	-0.13	-9.35	29	46.661	-0.001
6:38	35.503	0.20	14.74	29	46.661	0.002
6:39	35.504	0.18	14.04	27	43.443	0.002
6:40	35.506	0.17	14.47	25	40.225	0.002
6:41	35.506	-0.01	-1.33	15	24.135	0.000
6:42	35.504	-0.23	-59.3	10	16.09	-0.002

Table IV
EL RENO, OKLAHOMA TORNADO – ONE-MINUTE LONGITUDE PREDICTION

Time	**Longitude**	**Distance**	**Angle**	**Linear Speed**	**Linear Speed**	**Estimation**
	(West -ve)	km	degree	miles/hr.	km/hr.	
6:04	-98.074					
6:05	-98.072	0.18	-63.43	15	24.135	0.002
6:06	-98.067	0.41	-39.35	20	32.18	0.005
6:07	-98.062	0.47	-46.04	25	40.225	0.005
6:08	-98.060	0.20	-72.47	25	40.225	0.002
6:09	-98.055	0.39	-54.39	25	40.225	0.004
6:10	-98.045	0.92	-11.4	35	56.315	0.010
6:11	-98.035	0.93	-9.29	35	56.315	0.010
6:12	-98.023	1.05	1.32	39	62.751	0.012
6:13	-98.008	1.30	-8.79	49	78.841	0.015
6:14	-97.995	1.15	17.13	45	72.405	0.013
6:15	-97.987	0.74	37.61	35	56.315	0.008
6:16	-97.976	0.99	2.47	37	59.533	0.011
6:17	-97.962	1.20	-20.79	48	77.232	0.014
6:18	-97.948	1.27	-15.04	49	78.841	0.014
6:19	-97.932	1.45	-10.2	55	88.495	0.016
6:20	-97.917	1.29	10.47	49	78.841	0.015
6:21	-97.906	0.98	20.31	39	62.751	0.011
6:22	-97.896	0.89	32.09	39	62.751	0.010
6:23	-97.892	0.33	69.52	35	56.315	0.004
6:24	-97.891	0.16	78.44	29	46.661	0.002
6:25	-97.881	0.82	38.27	39	62.751	0.009
6:26	-97.876	0.45	62.73	37	59.533	0.005
6:27	-97.873	0.29	72	35	56.315	0.003
6:28	-97.869	0.38	65.8	35	56.315	0.004
6:29	-97.867	0.19	75.58	29	46.661	0.002
6:30	-97.874	-0.65	205.27	27	43.443	-0.007
6:31	-97.877	-0.29	223.45	15	24.135	-0.003
6:32	-97.879	-0.13	244.65	11	17.699	-0.001
6:33	-97.880	-0.15	247.62	15	24.135	-0.002
6:34	-97.875	0.46	24.78	19	30.571	0.005
6:35	-97.868	0.67	6.34	25	40.225	0.007
6:36	-97.860	0.66	-23.73	27	43.443	0.007
6:37	-97.852	0.77	-9.35	29	46.661	0.009
6:38	-97.843	0.75	14.74	29	46.661	0.008
6:39	-97.835	0.70	14.04	27	43.443	0.008
6:40	-97.828	0.65	14.47	25	40.225	0.007
6:41	-97.823	0.40	-1.33	15	24.135	0.005
6:42	-97.822	0.14	-59.3	10	16.09	0.002

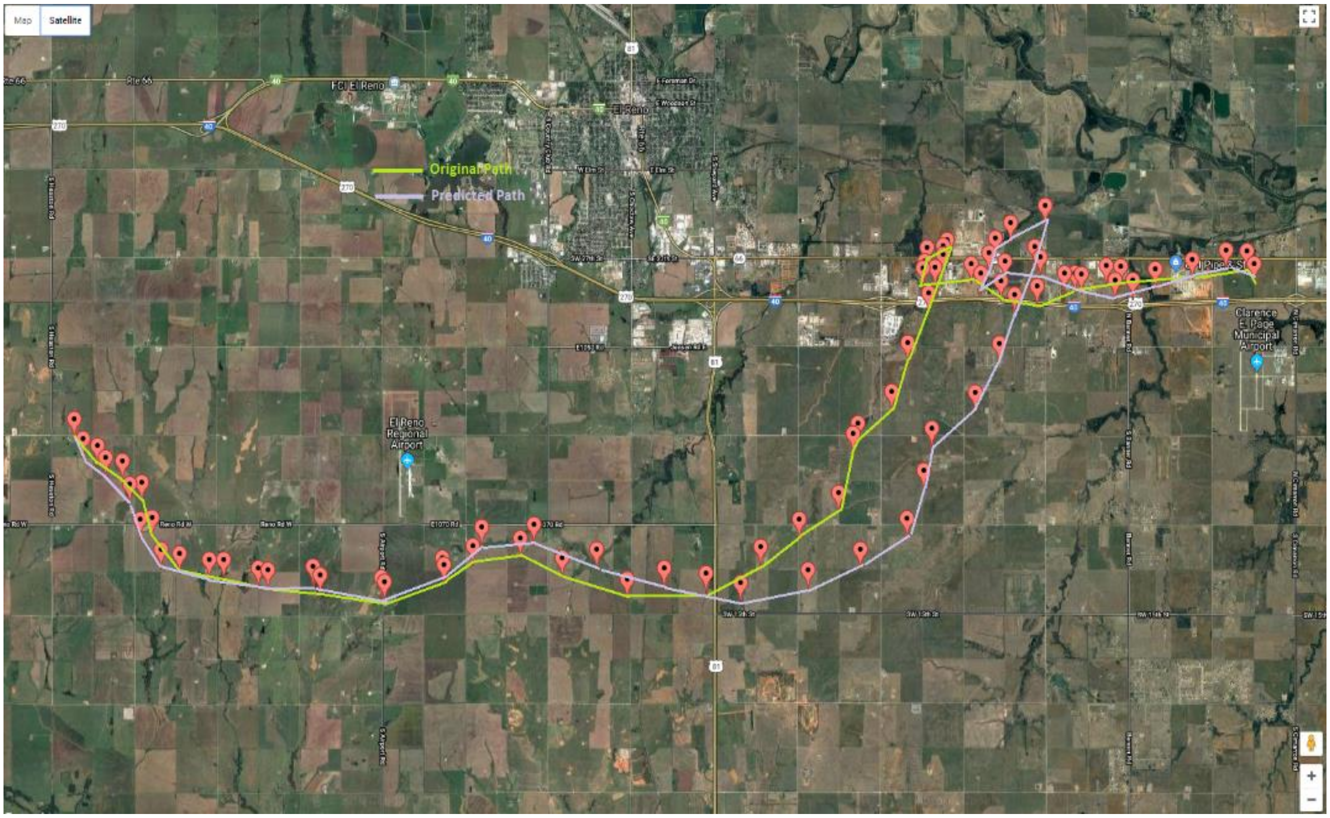

Figure 3: Original and Predicted Path for one-minute interval

Table V
EL RENO, OKLAHOMA TORNADO – TWO-MINUTE LATITUDE PREDICTION

Time	**Latitude**	**Distance**	**Angle**	**Linear Speed**	**Linear Speed**	**Estimation**
	(North +ve)	km	degree	miles/hr.	km/hr.	
6:03	35.478					
6:05	35.470	-0.95	-62.76	20	32.18	-0.009
6:07	35.461	-0.93	-44.12	25	40.23	-0.008
6:09	35.451	-1.18	-61.98	25	40.23	-0.011
6:11	35.448	-0.33	-10.13	35	56.32	-0.003
6:13	35.446	-0.22	-5.78	40	64.36	-0.002
6:15	35.451	0.55	24.09	25	40.23	0.005
6:17	35.448	-0.31	-9.38	35	56.32	-0.003
6:19	35.445	-0.36	-6.94	55	88.50	-0.003
6:21	35.454	1.05	25.92	45	72.41	0.010
6:23	35.464	1.09	30.54	40	64.36	0.010
6:25	35.478	1.57	56.97	35	56.32	0.014
6:27	35.494	1.74	68.15	35	56.32	0.016
6:29	35.505	1.24	68.27	25	40.23	0.011
6:31	35.502	-0.38	208.12	15	24.14	-0.003
6:33	35.498	-0.49	247.28	10	16.09	-0.004
6:35	35.500	0.27	11.83	25	40.23	0.002
6:37	35.497	-0.38	-16.515	25	40.23	-0.003
6:39	35.499	0.26	13.8	20	32.18	0.002
6:41	35.500	0.11	7.91	15	24.14	0.001
6:43	35.496	-0.46	-58.5	10	16.09	-0.004

Table VI

EL RENO, OKLAHOMA TORNADO – TWO-MINUTE LONGITUDE PREDICTION

Time	Longitude	Distance	Angle	Linear Speed	Linear Speed	Estimation
	(West -ve)	km	degree	miles/hr.	km/hr.	
6:03	-98.074					
6:05	-98.068	0.49	-62.76	20	32.18	0.006
6:07	-98.058	0.96	-44.12	25	40.23	0.011
6:09	-98.051	0.63	-61.98	25	40.23	0.007
6:11	-98.030	1.85	-10.13	35	56.32	0.021
6:13	-98.006	2.13	-5.78	40	64.36	0.024
6:15	-97.992	1.22	24.09	25	40.23	0.014
6:17	-97.971	1.85	-9.38	35	56.32	0.021
6:19	-97.938	2.93	-6.94	55	88.50	0.033
6:21	-97.914	2.17	25.92	45	72.41	0.024
6:23	-97.893	1.85	30.54	40	64.36	0.021
6:25	-97.882	1.02	56.97	35	56.32	0.011
6:27	-97.874	0.70	68.15	35	56.32	0.008
6:29	-97.868	0.50	68.27	25	40.23	0.006
6:31	-97.876	-0.71	208.12	15	24.14	-0.008
6:33	-97.879	-0.21	247.28	10	16.09	-0.002
6:35	-97.864	1.31	11.83	25	40.23	0.015
6:37	-97.849	1.28	-16.515	25	40.23	0.014
6:39	-97.838	1.04	13.8	20	32.18	0.012
6:41	-97.829	0.80	7.91	15	24.14	0.009
6:43	-97.826	0.28	-58.5	10	16.09	0.003

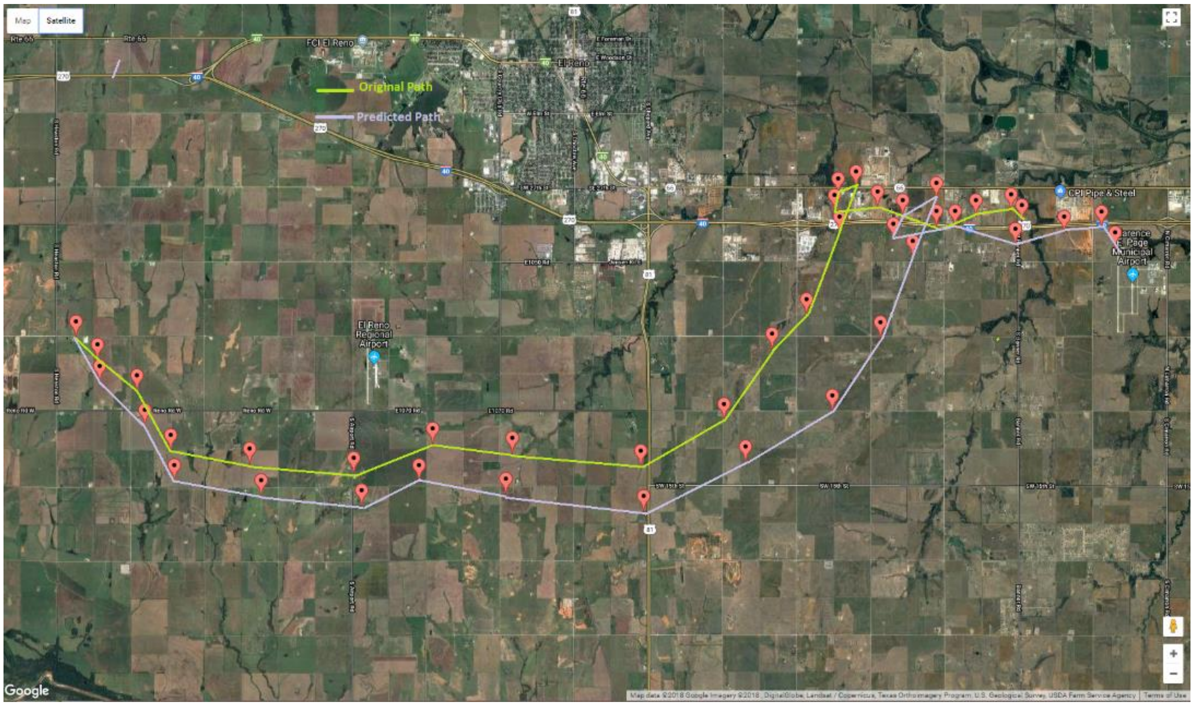

Figure 4: Original and the Predicted Path for two-minute interval

4.3 Distance between the original and the predicted locations

The distance between the original and predicted path was determined by using the latitude and longitude points for both one and two-minute path intervals and the results are listed in Table VII and Table IX. The average distance between the original and the predicted points for one-minute interval data was found to be 0.69 miles and for two-minute path interval 0.81 miles. For the Model 1, the locations are predicted based upon the location where the tornado had first touched down and later added to the previous predicted location, however, in the actual scenario, the direction and the linear speed of the tornado are going to be updated every minute or so by the radars. The point prediction based on the previous location would provide accurate data regarding the actual locations of the tornado. Hence, to test the accuracy of the model, the latitude and longitude points were predicted based upon the previous exact location of the tornado in Model 2. This phenomenon had greatly reduced the distance between the original and the predicted locations of the tornado. (shown in Figures 5-10 for two-minute interval and Figures 11-20 for the one-minute interval). The distance was again calculated between the original and the new predicted locations and the results are listed in Table VIII for one-minute path interval and Table X for two-minute path interval. The average distance between the actual and the predicted locations was reduced to 0.125 miles for the one-minute path and 0.18 miles for the two-minute path.

Next, the error between the initial and the final distance was determined. The results are listed in Table XI for one-minute data and Table XII for the two-minute data. For one minute data, the average error between original and the predicted points was reduced by 5.96 times and 4.53 times for the two-minute interval data. Furthermore, for two-minute interval data, at 6:37 pm and 6:4pm the distance between the original and the predicted point was found to be zero and hence, they these points were not included for the error calculation. Likewise, for one-minute interval data, the predicted locations at 6:08 pm, 6:14 pm, 6:19 pm and 6:35 pm were exactly same as the original locations, hence, were not included in the error calculations.

Table VII
DISTANCE BETWEEN ORIGINAL AND PREDICTED PATH (ONE-MINUTE INTERVAL) – MODEL 1

Time	**Original Latitude**	**Original Longitude**	**Predicted Latitude**	**Predicted Longitude**	**Distance**
	(North +ve)	(West -ve)	(North +ve)	(West -ve)	miles
6:04	35.478	-98.074	35.478	-98.074	
6:05	35.474	-98.069	35.475	-98.072	0.18
6:06	35.472	-98.064	35.472	-98.067	0.17
6:07	35.468	-98.059	35.468	-98.062	0.17
6:08	35.462	-98.057	35.462	-98.060	0.17
6:09	35.456	-98.051	35.457	-98.055	0.24
6:10	35.455	-98.042	35.455	-98.045	0.17
6:11	35.454	-98.033	35.454	-98.035	0.11
6:12	35.453	-98.021	35.454	-98.023	0.13
6:13	35.452	-98.008	35.453	-98.008	0.07
6:14	35.455	-97.995	35.456	-97.995	0.07
6:15	35.458	-97.989	35.461	-97.987	0.24
6:16	35.459	-97.979	35.461	-97.976	0.22
6:17	35.456	-97.970	35.457	-97.962	0.46
6:18	35.452	-97.956	35.454	-97.948	0.47
6:19	35.453	-97.939	35.452	-97.932	0.40
6:20	35.458	-97.927	35.454	-97.917	0.63
6:21	35.462	-97.919	35.457	-97.906	0.81
6:22	35.466	-97.911	35.462	-97.896	0.89
6:23	35.476	-97.907	35.470	-97.892	0.94
6:24	35.478	-97.906	35.477	-97.891	0.85
6:25	35.483	-97.899	35.483	-97.881	1.01
6:26	35.491	-97.896	35.491	-97.876	1.13
6:27	35.499	-97.891	35.499	-97.873	1.01
6:28	35.505	-97.888	35.506	-97.869	1.07
6:29	35.508	-97.887	35.513	-97.867	1.18
6:30	35.507	-97.888	35.510	-97.874	0.81
6:31	35.506	-97.892	35.508	-97.877	0.86
6:32	35.504	-97.892	35.506	-97.879	0.74
6:33	35.503	-97.893	35.502	-97.880	0.73
6:34	35.503	-97.890	35.504	-97.875	0.85
6:35	35.504	-97.882	35.505	-97.868	0.79
6:36	35.501	-97.876	35.502	-97.860	0.90
6:37	35.500	-97.868	35.501	-97.852	0.90
6:38	35.502	-97.862	35.503	-97.843	1.07
6:39	35.502	-97.859	35.504	-97.835	1.36
6:40	35.504	-97.853	35.506	-97.828	1.41
6:41	35.503	-97.850	35.506	-97.823	1.53
6:42	35.501	-97.848	35.504	-97.822	1.48

Table VIII

DISTANCE BETWEEN ORIGINAL AND PREDICTED PATH BASED UPON THE EXACT PREVIOUS LOCATOIN FROM RADARS (ONE-MINUTE INTERVAL) – MODEL 2

Time	**Original Latitude**	**Original Longitude**	**Predicted Latitude**	**Predicted Longitude**	**Distance**
	(North +ve)	(West -ve)	(North +ve)	(West -ve)	miles
6:04	35.478	-98.074	35.478	-98.074	
6:05	35.474	-98.069	35.475	-98.072	0.18
6:06	35.472	-98.064	35.471	-98.064	0.07
6:07	35.468	-98.059	35.467	-98.058	0.09
6:08	35.462	-98.057	35.462	-98.057	0.00
6:09	35.456	-98.051	35.457	-98.053	0.13
6:10	35.455	-98.042	35.455	-98.041	0.06
6:11	35.454	-98.033	35.454	-98.032	0.06
6:12	35.453	-98.021	35.454	-98.021	0.07
6:13	35.452	-98.008	35.451	-98.007	0.09
6:14	35.455	-97.995	35.455	-97.995	0.00
6:15	35.458	-97.989	35.460	-97.987	0.18
6:16	35.459	-97.979	35.458	-97.978	0.09
6:17	35.456	-97.970	35.455	-97.965	0.29
6:18	35.452	-97.956	35.453	-97.955	0.09
6:19	35.453	-97.939	35.453	-97.939	0.00
6:20	35.458	-97.927	35.458	-97.925	0.11
6:21	35.462	-97.919	35.463	-97.918	0.09
6:22	35.466	-97.911	35.467	-97.909	0.13
6:23	35.476	-97.907	35.474	-97.907	0.14
6:24	35.478	-97.906	35.483	-97.906	0.35
6:25	35.483	-97.899	35.484	-97.897	0.13
6:26	35.491	-97.896	35.491	-97.894	0.11
6:27	35.499	-97.891	35.499	-97.893	0.11
6:28	35.505	-97.888	35.507	-97.887	0.15
6:29	35.508	-97.887	35.512	-97.885	0.30
6:30	35.507	-97.888	35.505	-97.895	0.42
6:31	35.506	-97.892	35.504	-97.892	0.14
6:32	35.504	-97.892	35.504	-97.893	0.06
6:33	35.503	-97.893	35.501	-97.894	0.15
6:34	35.503	-97.890	35.505	-97.887	0.22
6:35	35.504	-97.882	35.504	-97.882	0.00
6:36	35.501	-97.876	35.501	-97.875	0.06
6:37	35.500	-97.868	35.500	-97.867	0.06
6:38	35.502	-97.862	35.502	-97.860	0.11
6:39	35.502	-97.859	35.504	-97.854	0.31
6:40	35.504	-97.853	35.504	-97.851	0.11
6:41	35.503	-97.850	35.503	-97.849	0.06
6:42	35.501	-97.848	35.501	-97.849	0.06

Table IX
DISTANCE BETWEEN ORIGINAL AND PREDICTED PATH (TWO-MINUTE INTERVAL) – MODEL 1

Time	**Original Latitude**	**Original Longitude**	**Predicted Latitude**	**Predicted Longitude**	**Distance**
	(North +ve)	(West -ve)	(North +ve)	(West -ve)	miles
6:03	35.478	-98.074	35.478	-98.074	
6:05	35.474	-98.069	35.470	-98.068	0.28
6:07	35.468	-98.059	35.461	-98.058	0.49
6:09	35.456	-98.051	35.451	-98.051	0.35
6:11	35.454	-98.033	35.448	-98.030	0.45
6:13	35.452	-98.008	35.446	-98.006	0.43
6:15	35.458	-97.989	35.451	-97.992	0.51
6:17	35.456	-97.970	35.448	-97.971	0.56
6:19	35.453	-97.939	35.445	-97.938	0.56
6:21	35.462	-97.919	35.454	-97.914	0.62
6:23	35.476	-97.907	35.464	-97.893	1.14
6:25	35.483	-97.899	35.478	-97.882	1.02
6:27	35.499	-97.891	35.494	-97.874	1.02
6:29	35.508	-97.887	35.505	-97.868	1.09
6:31	35.506	-97.892	35.502	-97.876	0.94
6:33	35.503	-97.893	35.498	-97.879	0.86
6:35	35.504	-97.882	35.500	-97.864	1.05
6:37	35.500	-97.868	35.497	-97.849	1.09
6:39	35.502	-97.859	35.499	-97.838	1.20
6:41	35.503	-97.850	35.500	-97.829	1.20
6:43	35.501	-97.848	35.496	-97.826	1.28

Table X

DISTANCE BETWEEN ORIGINAL AND PREDICTED PATH BASED UPON THE EXACT PREVIOUS LOCATOIN FROM RADARS (TWO-MINUTE INTERVAL) – MODEL 2

Time	Original Latitude	Original Longitude	Predicted Latitude	Predicted Longitude	Distance
	(North +ve)	(West -ve)	(North +ve)	(West -ve)	miles
6:03	35.478	-98.074	35.478	-98.074	
6:05	35.474	-98.069	35.470	-98.068	0.28
6:07	35.468	-98.059	35.466	-98.058	0.14
6:09	35.456	-98.051	35.457	-98.052	0.09
6:11	35.454	-98.033	35.453	-98.031	0.13
6:13	35.452	-98.008	35.452	-98.009	0.06
6:15	35.458	-97.989	35.457	-97.994	0.29
6:17	35.456	-97.970	35.455	-97.968	0.13
6:19	35.453	-97.939	35.453	-97.937	0.11
6:21	35.462	-97.919	35.463	-97.915	0.24
6:23	35.476	-97.907	35.472	-97.898	0.58
6:25	35.483	-97.899	35.490	-97.896	0.51
6:27	35.499	-97.891	35.499	-97.892	0.06
6:29	35.508	-97.887	35.510	-97.886	0.15
6:31	35.506	-97.892	35.504	-97.895	0.22
6:33	35.503	-97.893	35.502	-97.894	0.09
6:35	35.504	-97.882	35.506	-97.878	0.26
6:37	35.500	-97.868	35.500	-97.868	0
6:39	35.502	-97.859	35.502	-97.857	0.11
6:41	35.503	-97.850	35.503	-97.850	0
6:43	35.501	-97.848	35.499	-97.847	0.15

Table XI
DISTANCE PREDICTION ERROR (ONE-MINUTE INTERVAL)

Time	**Initial Distance**	**Final Distance**	**Error**	**Error**
	miles	miles		%
6:04				
6:05	0.182	0.182	0.00	0
6:06	0.169	0.069	1.44	144
6:07	0.169	0.089	0.89	89
6:08	0.169	0.000	-	-
6:09	0.235	0.132	0.78	78
6:10	0.169	0.056	2.00	200
6:11	0.113	0.056	1.00	100
6:12	0.132	0.069	0.91	91
6:13	0.069	0.089	0.22	22
6:14	0.069	0.000	-	-
6:15	0.236	0.178	0.32	32
6:16	0.218	0.089	1.45	145
6:17	0.456	0.290	0.57	57
6:18	0.471	0.089	4.29	429
6:19	0.400	0.000	-	-
6:20	0.627	0.113	4.57	457
6:21	0.809	0.089	8.08	808
6:22	0.888	0.132	5.72	572
6:23	0.940	0.138	5.80	580
6:24	0.847	0.345	1.45	145
6:25	1.013	0.132	6.67	667
6:26	1.125	0.113	9.00	900
6:27	1.012	0.113	8.00	800
6:28	1.071	0.149	6.18	618
6:29	1.177	0.298	2.94	294
6:30	0.814	0.417	0.95	95
6:31	0.855	0.138	5.19	519
6:32	0.744	0.056	12.23	1223
6:33	0.734	0.149	3.92	392
6:34	0.846	0.218	2.88	288
6:35	0.790	0.000	-	-
6:36	0.903	0.056	15.05	1505
6:37	0.903	0.056	15.05	1505
6:38	1.071	0.112	8.52	852
6:39	1.357	0.313	3.33	333
6:40	1.413	0.112	11.56	1156
6:41	1.533	0.056	26.25	2625
6:42	1.477	0.056	25.27	2527

Table XII
DISTANCE PREDICTION ERROR (TWO-MINUTE INTERVAL)

Time	**Initial Distance**	**Final Distance**	**Error**	**Error**
	miles	miles		%
6:03				
6:05	0.282	0.282	0.00	0
6:07	0.487	0.138	2.52	252
6:09	0.345	0.089	2.88	288
6:11	0.448	0.132	2.39	239
6:13	0.430	0.056	6.63	663
6:15	0.512	0.290	0.77	77
6:17	0.556	0.132	3.21	321
6:19	0.556	0.113	3.93	393
6:21	0.620	0.235	1.63	163
6:23	1.144	0.577	0.98	98
6:25	1.017	0.512	0.99	99
6:27	1.017	0.056	17.07	1707
6:29	1.089	0.149	6.30	630
6:31	0.941	0.218	3.32	332
6:33	0.860	0.089	8.65	865
6:35	1.049	0.264	2.98	298
6:37	1.089	0.000	-	-
6:39	1.199	0.112	9.66	966
6:41	1.199	0.000	-	-
6:43	1.285	0.149	7.61	761

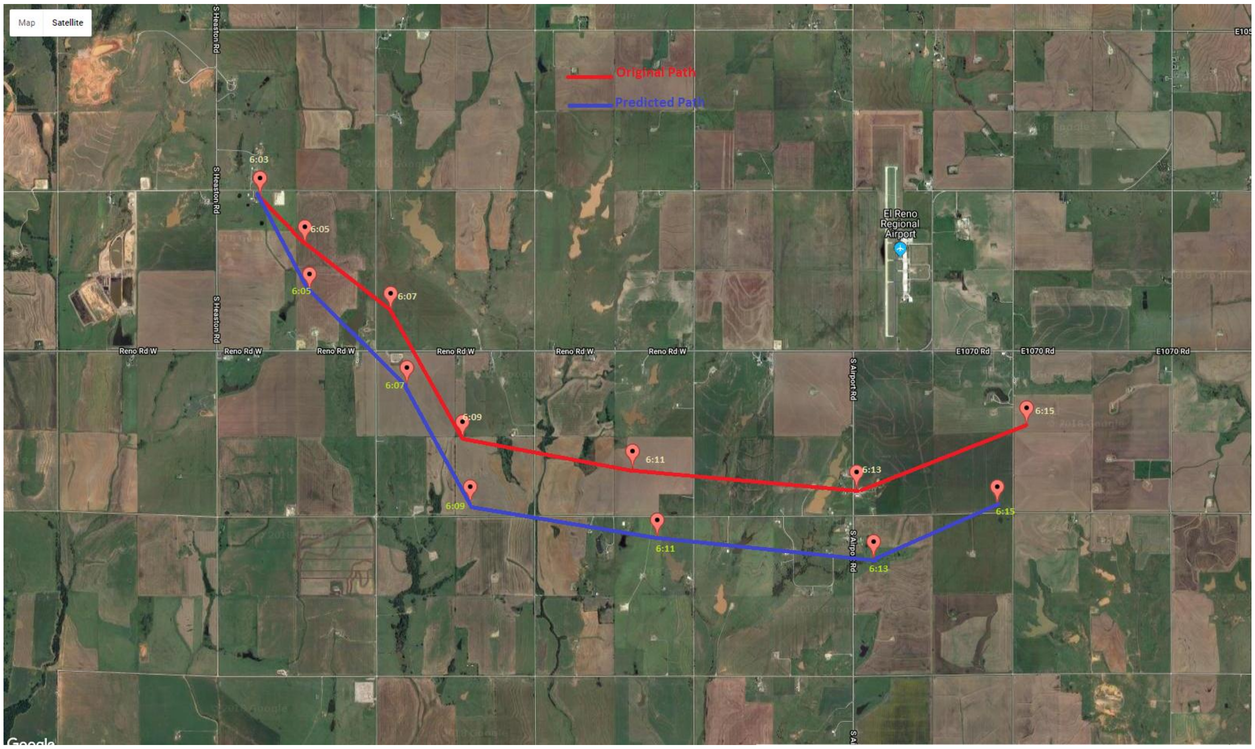

Figure 5: Original and Predicted Path for two-minute data from 6:03pm – 6:15pm

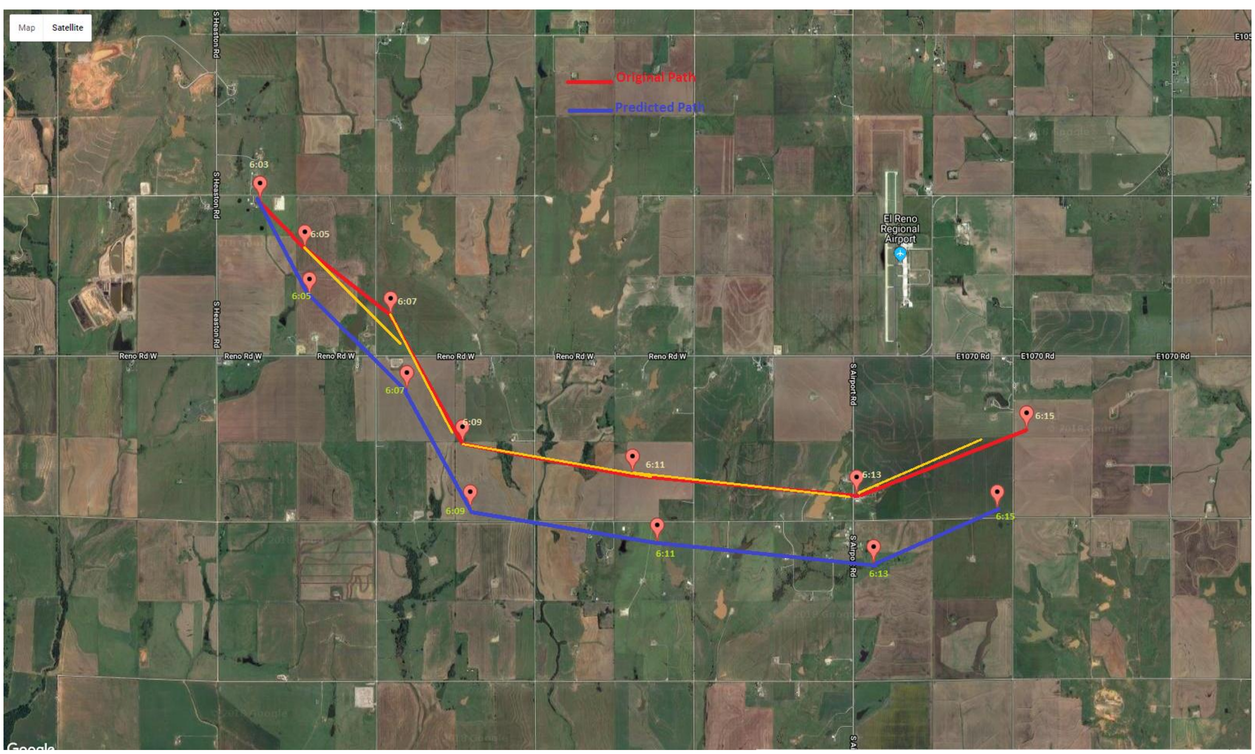

Figure 6: Tornado Path Prediction based upon previous location provided by Doppler radar. Two-minute data from 6:03pm – 6:15pm

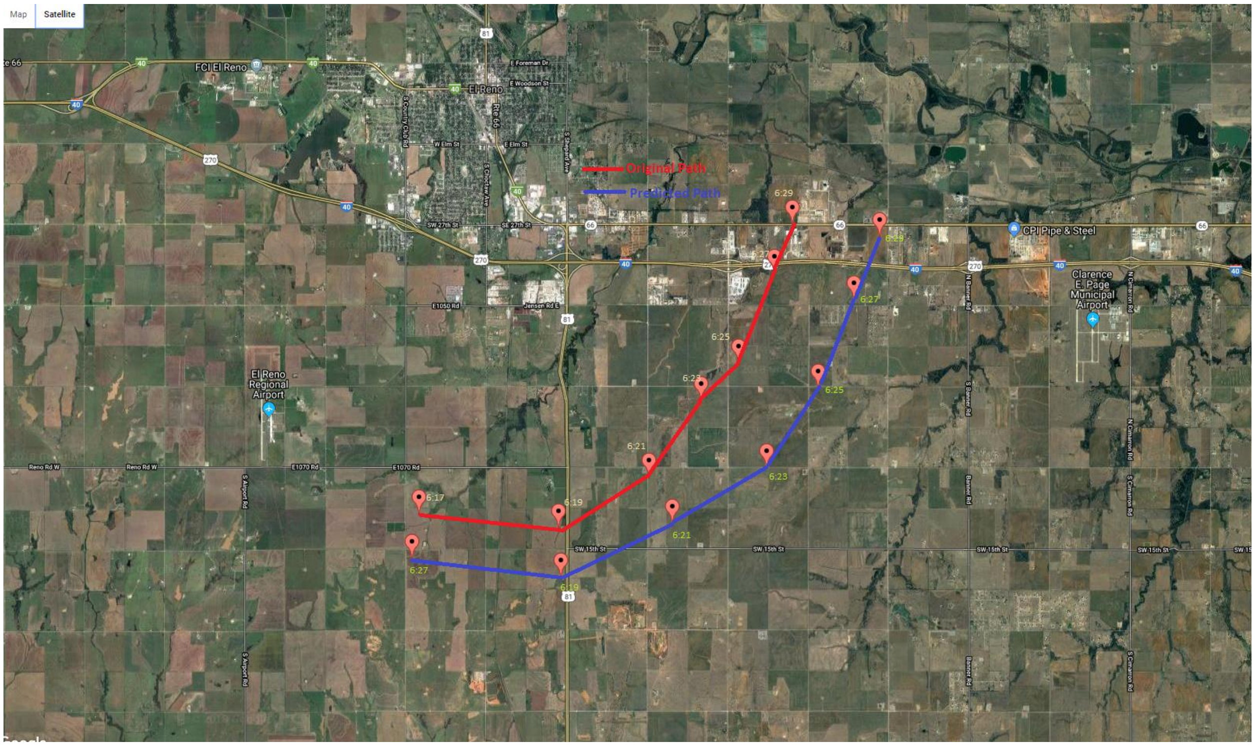

Figure 7: Original and Predicted Path for two-minute data from 6:17pm – 6:29pm

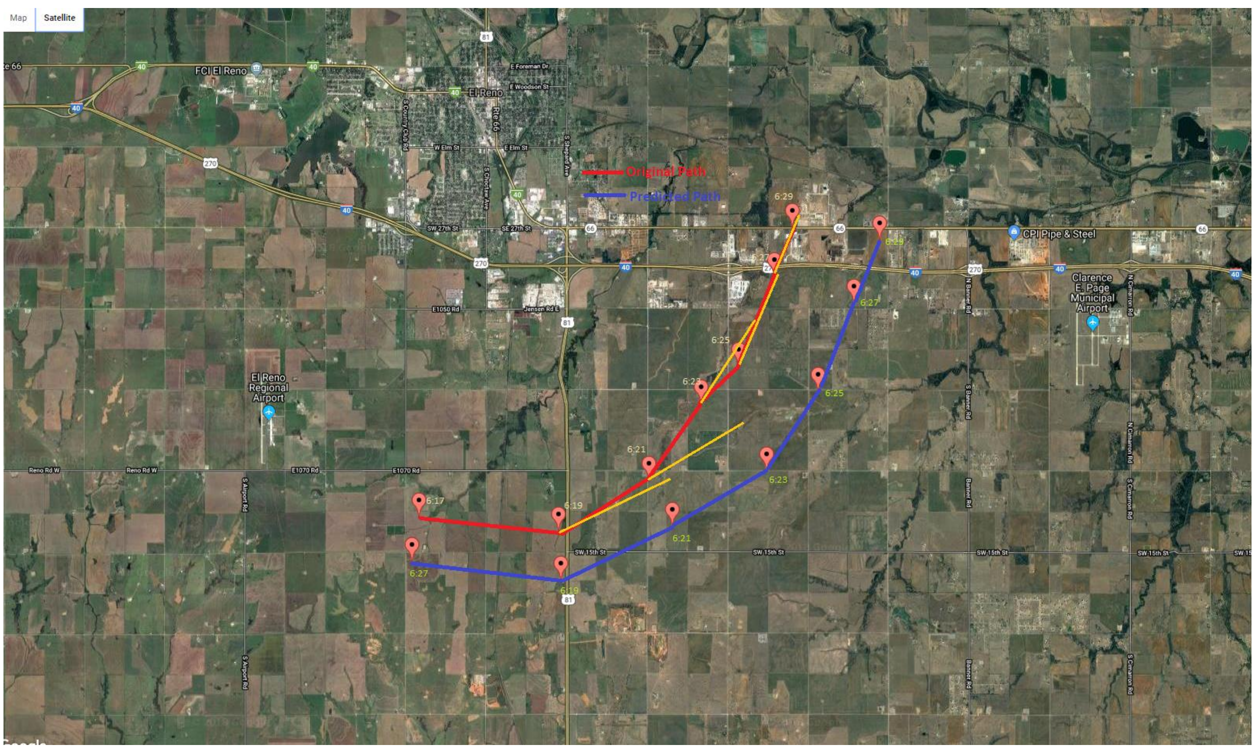

Figure 8: Tornado Path Prediction based upon previous location provided by Doppler radar. Two-minute data from 6:17pm – 6:29pm

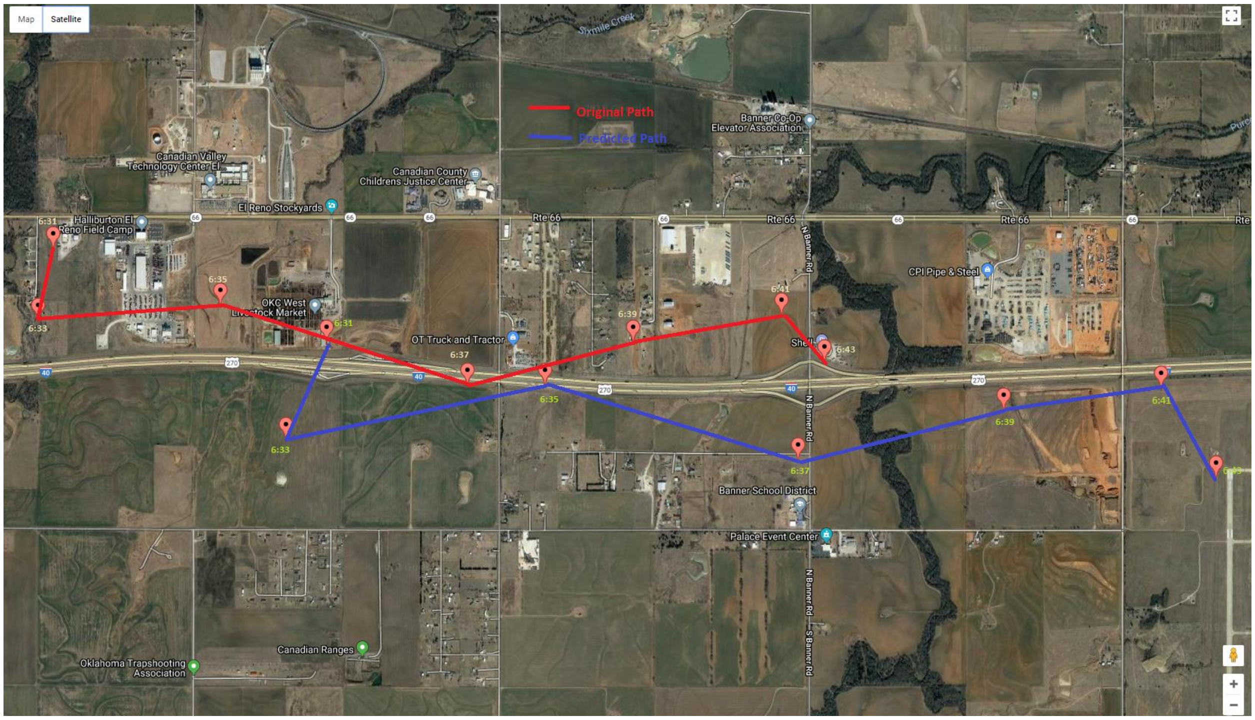

Figure 9: Original and Predicted Path for two-minute data from 6:31pm – 6:43pm

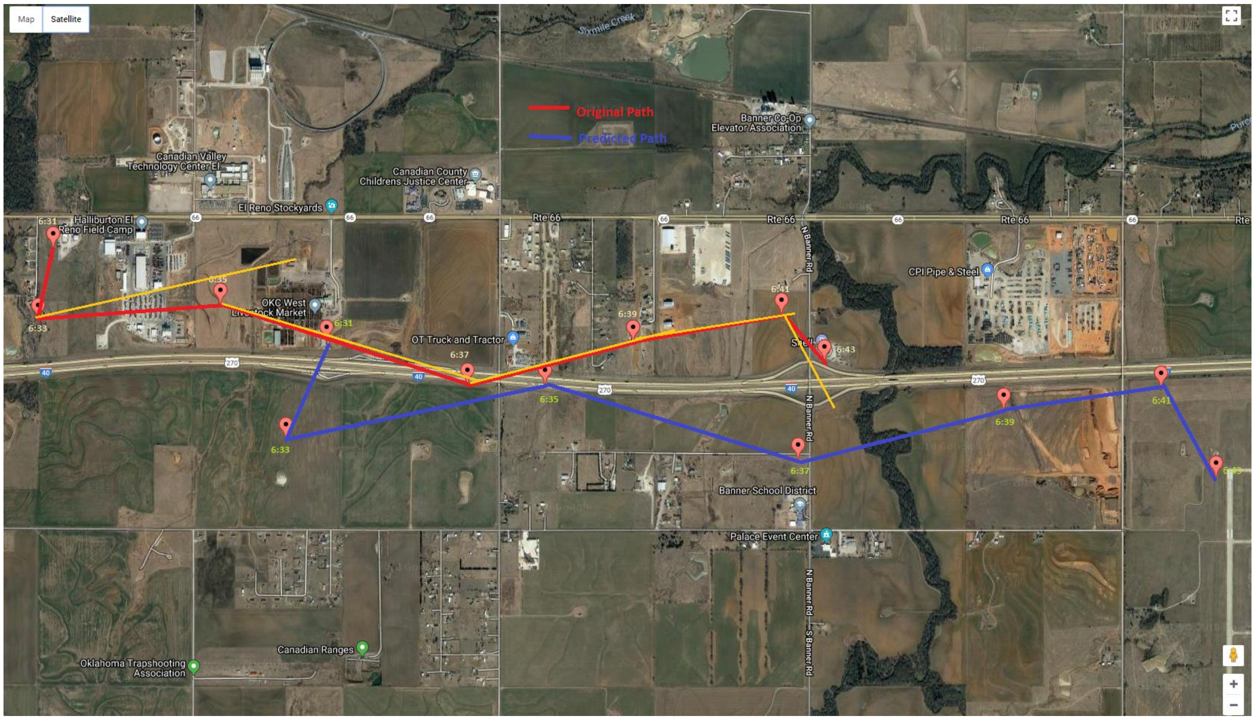

Figure 10: Tornado Path Prediction based upon previous location provided by Doppler radar. Two-minute data from 6:31pm – 6:43pm

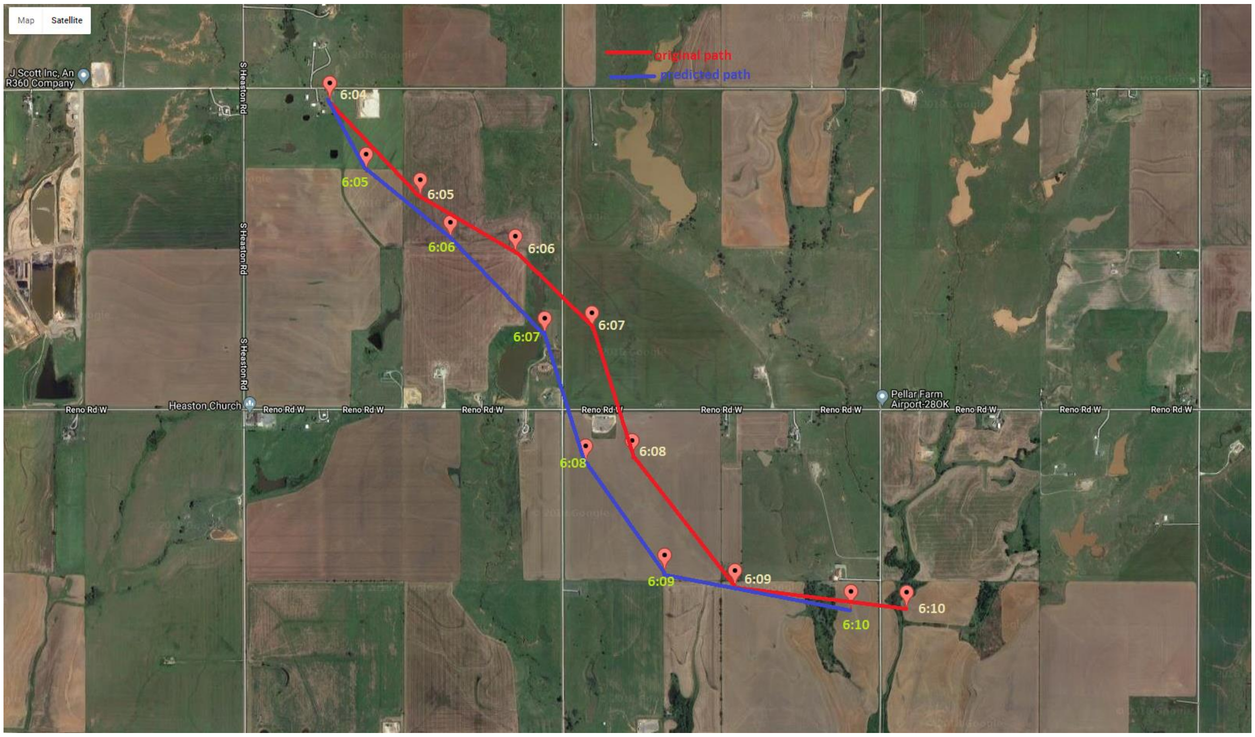

Figure 11: Original and Predicted Path for one-minute data from 6:04pm – 6:10pm

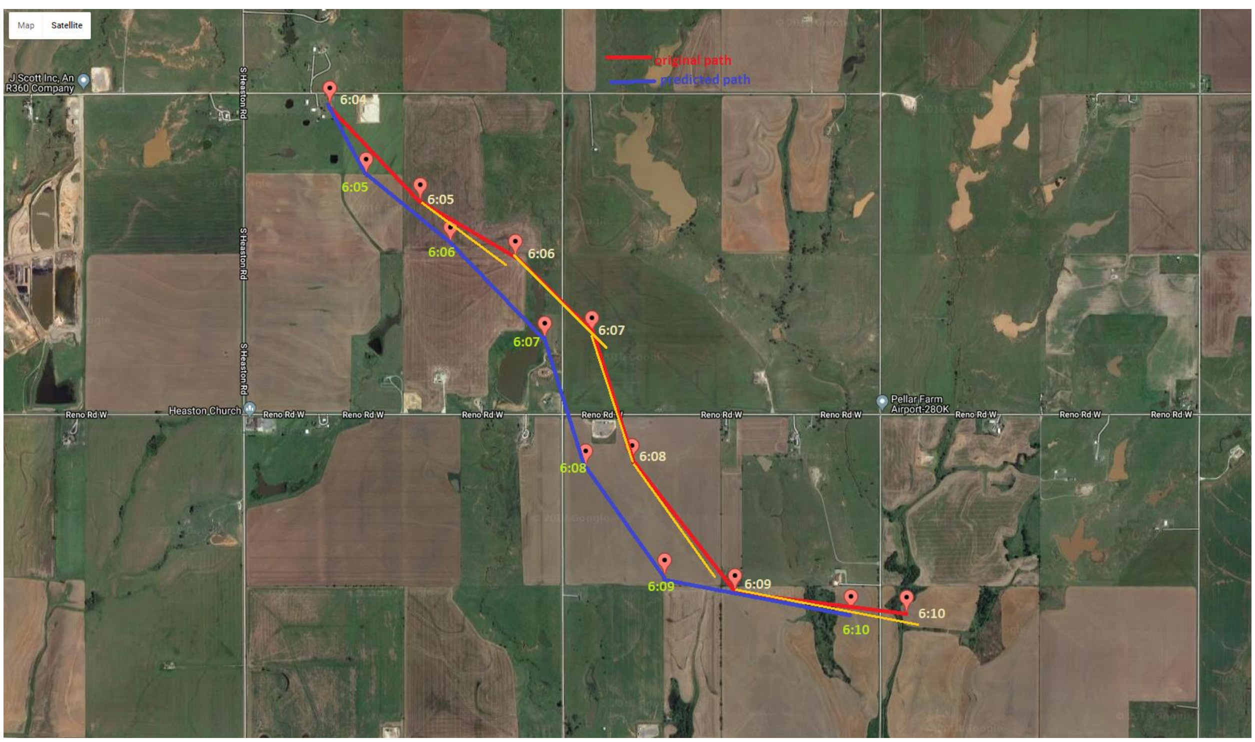

Figure 12: Tornado Path Prediction based upon previous location provided by Doppler radar. One-minute data from 6:04pm – 6:10pm

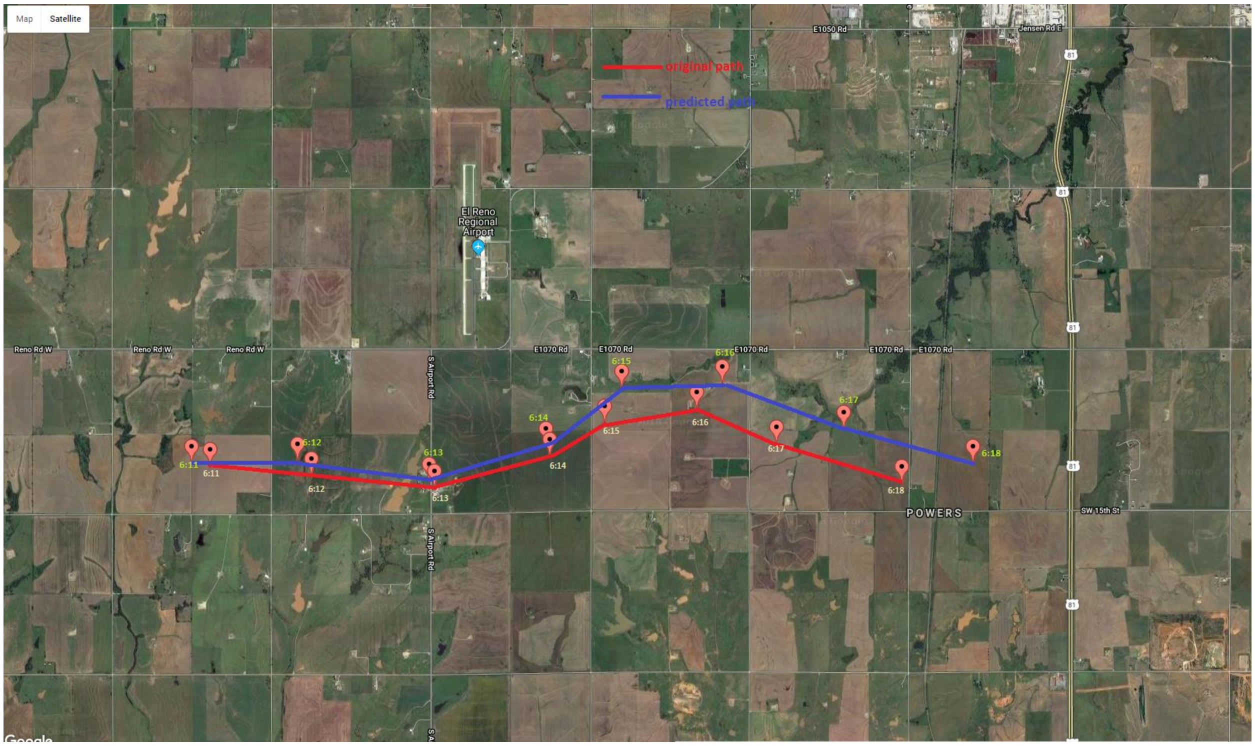

Figure 13: Original and Predicted Path for one-minute data from 6:11pm – 6:18pm

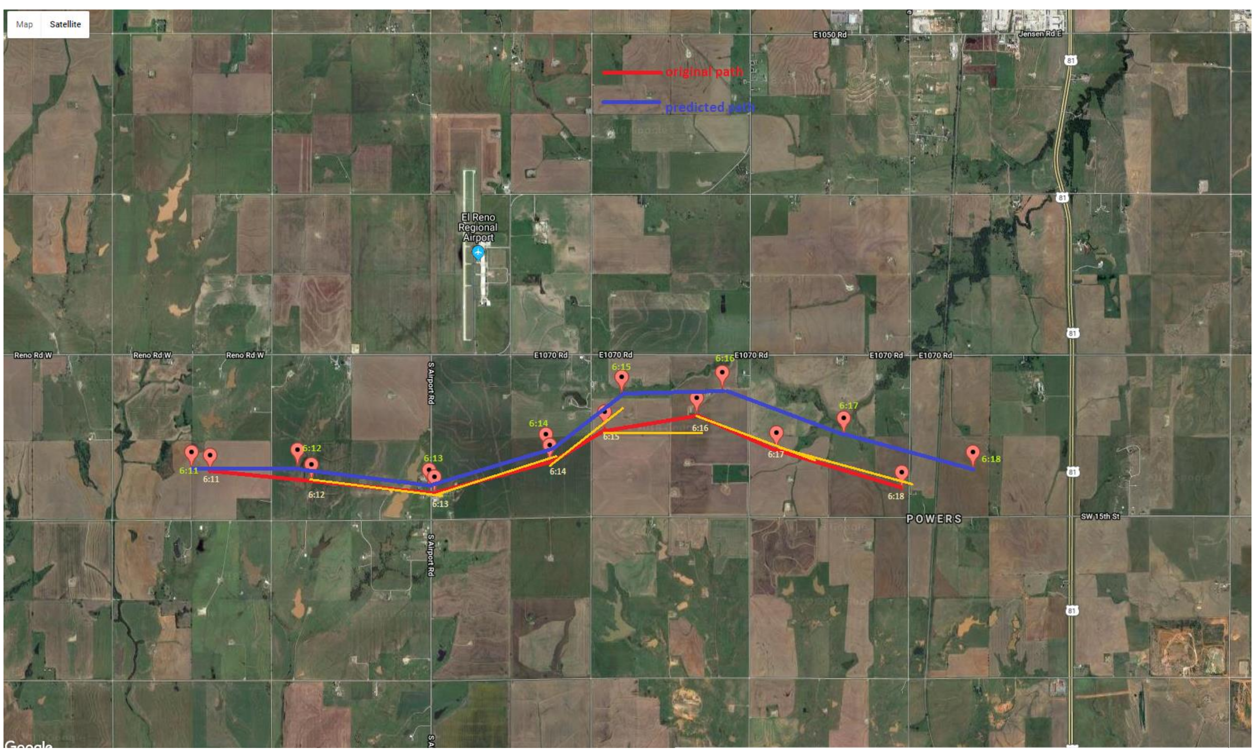

Figure 14: Tornado Path Prediction based upon previous location provided by Doppler radar. One-minute data from 6:11pm – 6:18pm

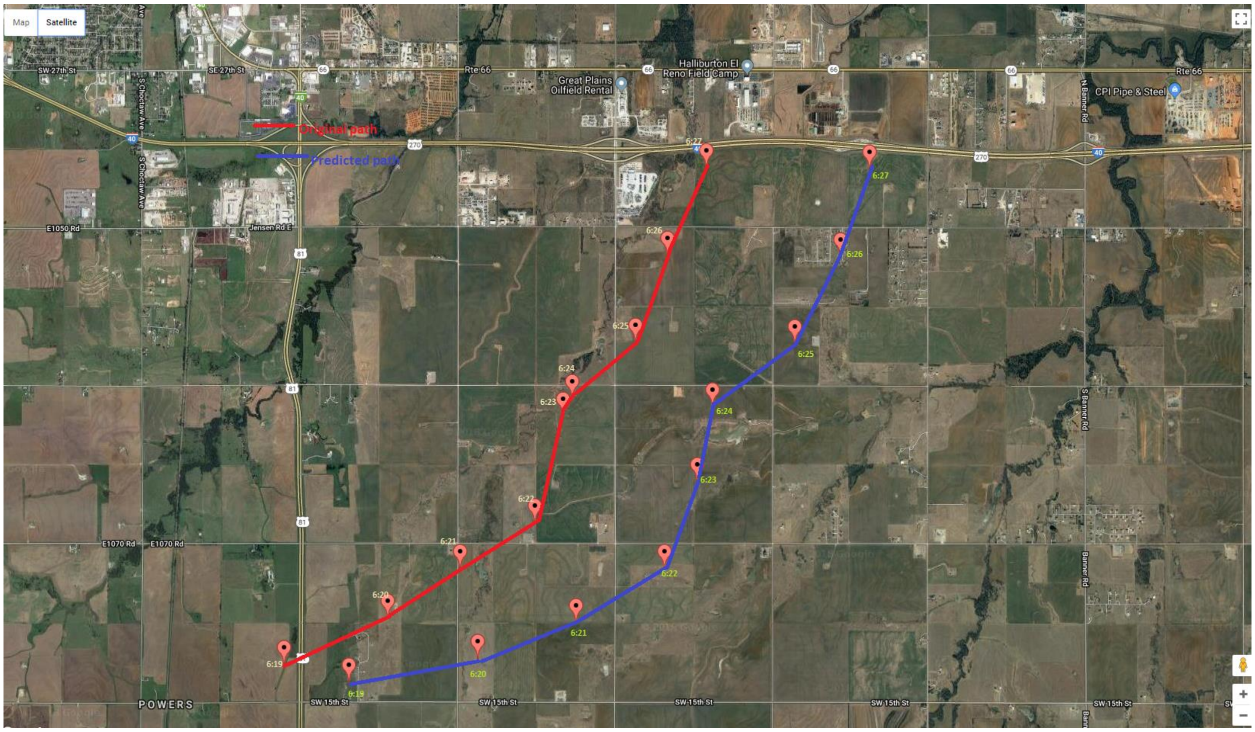

Figure 15: Original and Predicted Path for one-minute data from 6:19pm – 6:27pm

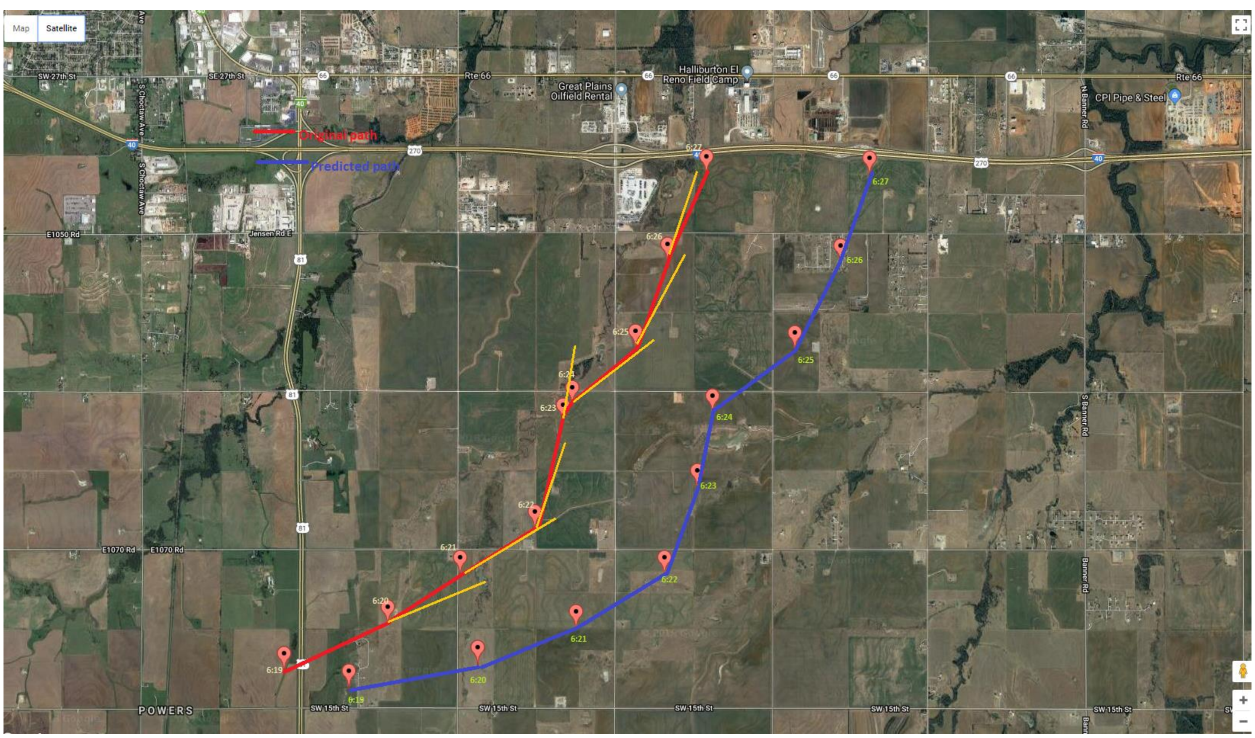

Figure 16: Tornado Path Prediction based upon previous location provided by Doppler radar. One-minute data from 6:19pm – 6:27pm

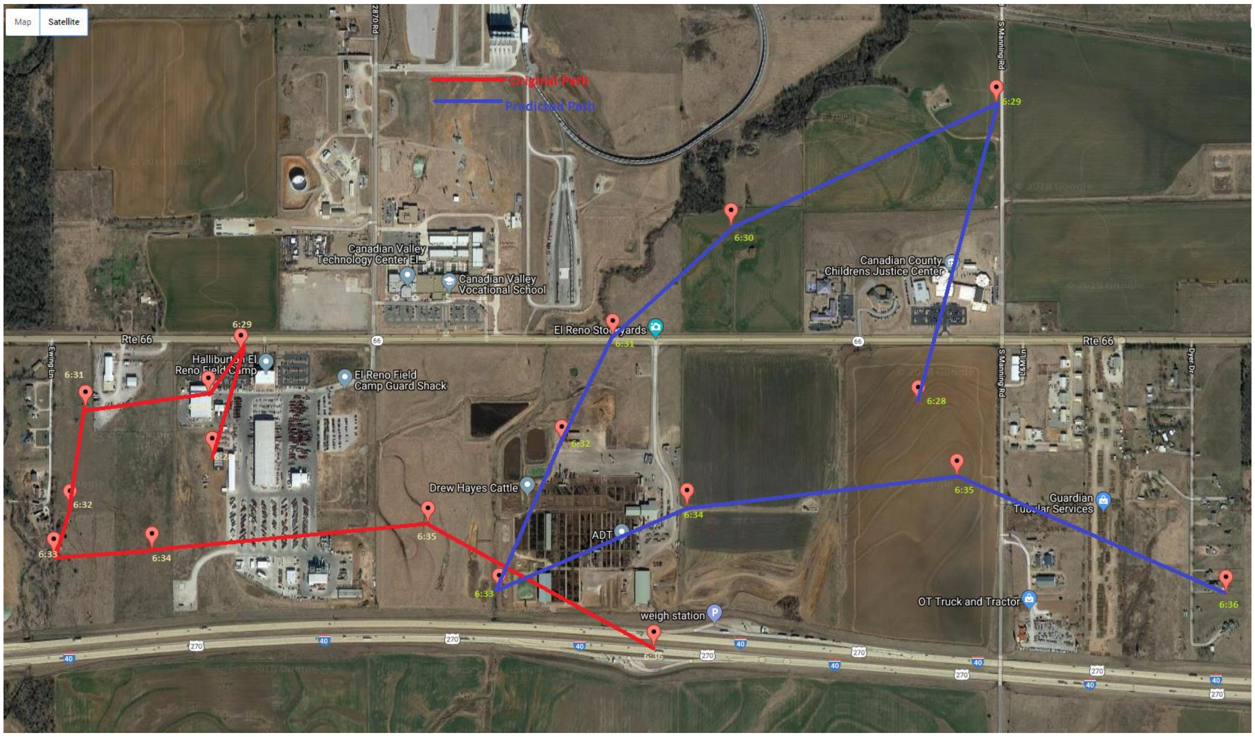

Figure 17: Original and Predicted Path for one-minute data from 6:28pm – 6:36pm

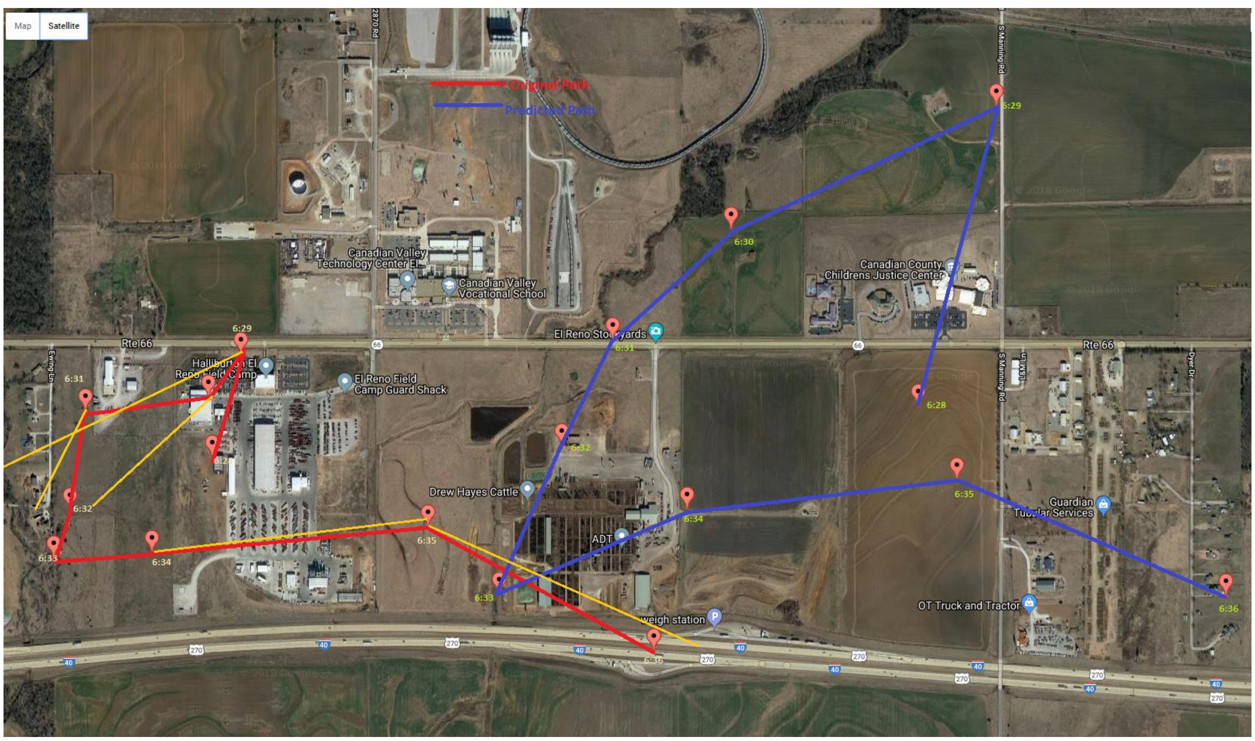

Figure 18: Tornado Path Prediction based upon previous location provided by Doppler radar. One-minute data from 6:28pm – 6:36pm

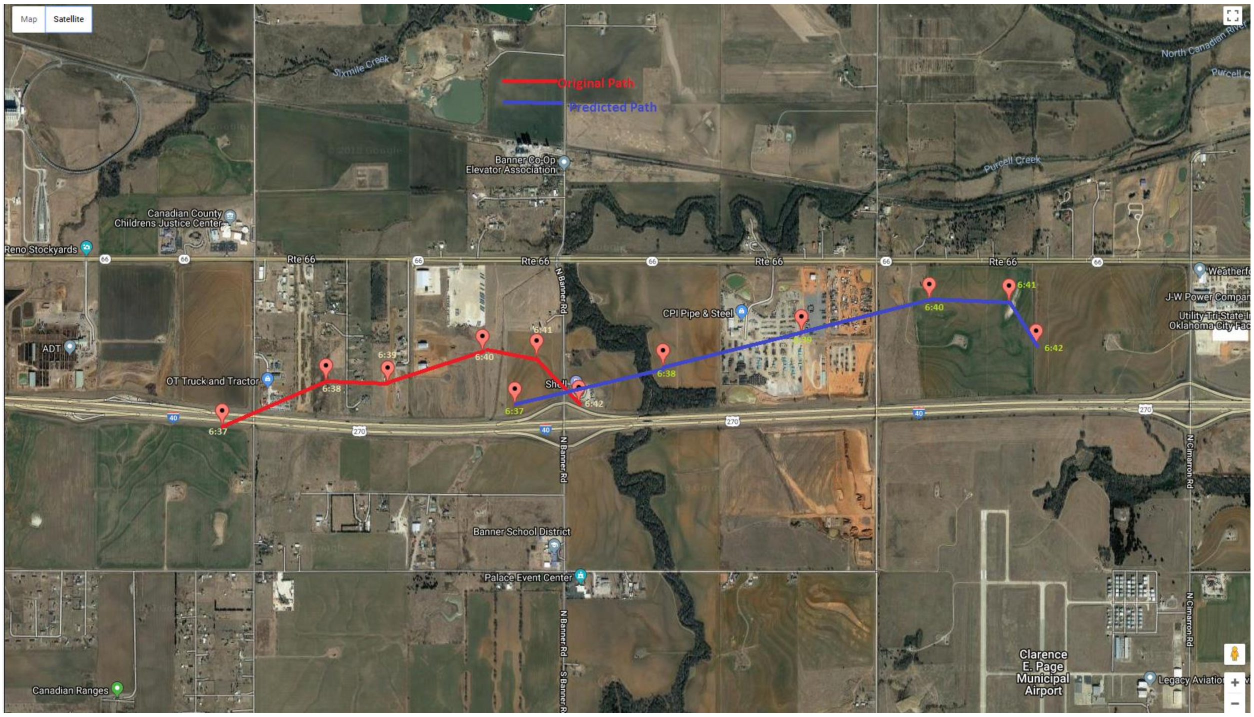

Figure 19: Original and Predicted Path for one-minute data from 6:37pm – 6:42pm

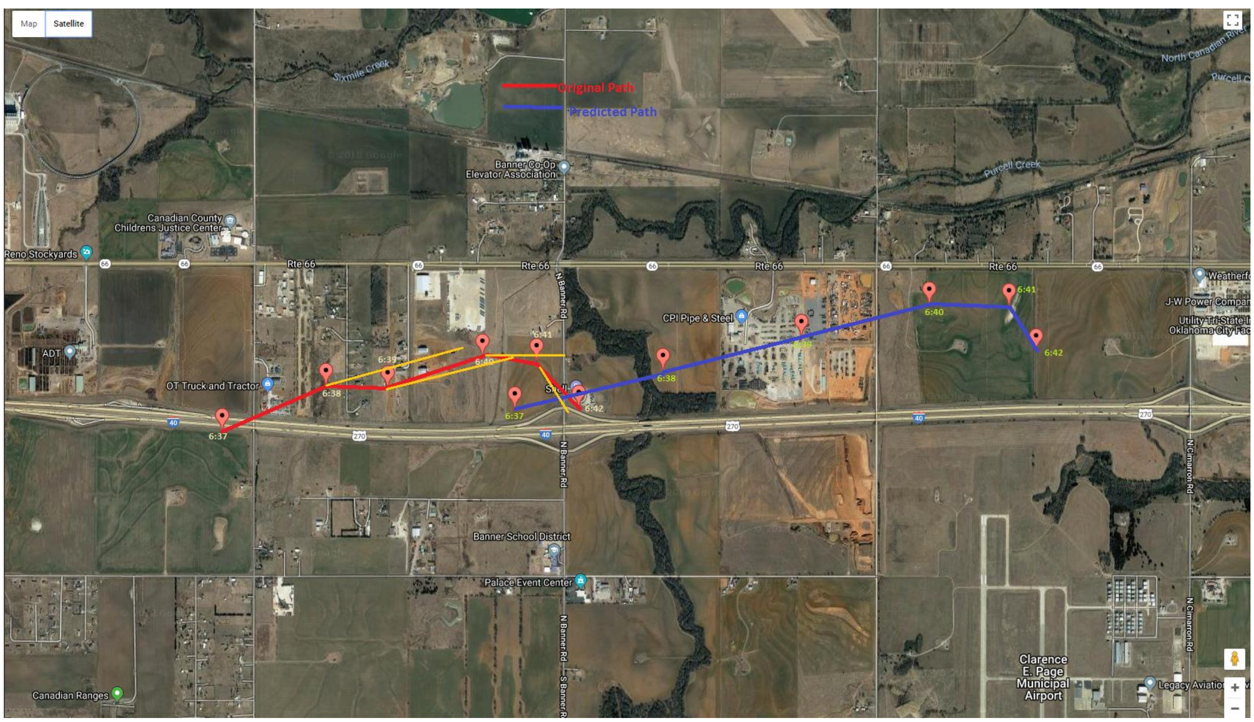

Figure 20: Tornado Path Prediction based upon previous location provided by Doppler radar. One-minute data from 6:37pm – 6:42pm

4.4 Original and Predicted Path Directions

To predict the locations of the tornado, it is essential to determine the direction that tornado travels in. The direction of a tornado is provided by the radars along with its linear speed. In the present model, the direction was calculated in degrees by determining the angles of the original tornado path. The average error between the original and the predicted angles was found to be 5.94 degrees for one-minute interval data and 1.86 degrees for two-minute interval data. The error for one-minute interval data is listed in Table XIII and two-minute interval data in Table XIV.

The calculated error for the one-minute path should have been lowered than the two-minute path, however, in the present calculation, this was not the case. This may be due to the fact that the data regarding the original angles was not provided and had to be approximated using tangent inverse formula. Furthermore, the eye of the tornado does not travel in the straight line and hence, the radars and satellite provide the movement of a tornado for the warnings and evacuation purposes.

Table XIII

ANGLE PREDICTION ERROR (ONE-MINUTE INTERVAL)

Time	**Original Angle**	**Predicted Angle**	**Error**
	Degrees	Degrees	%
6:04			
6:05	-25.70	-63.43	10.48
6:06	-39.34	-39.35	0.00
6:07	-68.86	-46.04	6.34
6:08	-45.70	-72.47	7.44
6:09	-5.97	-54.39	13.45
6:10	-9.95	-11.4	0.40
6:11	-4.10	-9.29	1.44
6:12	-4.63	1.32	1.65
6:13	12.37	-8.79	5.88
6:14	26.37	17.13	2.57
6:15	7.02	37.61	8.50
6:16	-19.43	2.47	6.08
6:17	-14.54	-20.79	1.74
6:18	3.56	-15.04	5.17
6:19	20.13	-10.2	8.42
6:20	29.08	10.47	5.17
6:21	26.71	20.31	1.78
6:22	71.77	32.09	11.02
6:23	58.72	69.52	3.00
6:24	35.81	78.44	11.84
6:25	65.92	38.27	7.68
6:26	61.39	62.73	0.37
6:27	64.21	72	2.16
6:28	70.89	65.8	1.41
6:29	46.30	75.58	8.13
6:30	185.50	205.27	5.49
6:31	258.89	223.45	9.84
6:32	247.86	244.65	0.89
6:33	182.59	247.62	18.06
6:34	4.29	24.78	5.69
6:35	-24.03	6.34	8.44
6:36	-6.52	-23.73	4.78
6:37	19.63	-9.35	8.05
6:38	-1.79	14.74	4.59
6:39	15.31	14.04	0.35
6:40	-4.28	14.47	5.21
6:41	-41.77	-1.33	11.23
6:42	-19.94	-59.3	10.93

Table XIV
ANGLE PREDICTION ERROR (TWO-MINUTE INTERVAL)

Time	Original Angle	Predicted Angle	Error
	degree	degree	%
6:03			
6:05	-41.05	-62.76	6.03
6:07	-32.31	-44.12	3.28
6:09	-55.62	-61.98	1.77
6:11	-7.95	-10.13	0.61
6:13	-4.39	-5.78	0.39
6:15	17.15	24.09	1.93
6:17	-5.61	-9.38	1.05
6:19	-4.74	-6.94	0.61
6:21	24.38	25.92	0.43
6:23	50.10	46.54	0.99
6:25	39.82	56.97	4.76
6:27	63.59	68.15	1.27
6:29	65.93	68.27	0.65
6:31	196.47	208.12	3.24
6:33	255.15	247.28	2.19
6:35	3.85	11.83	2.22
6:37	-14.67	-16.515	0.51
6:39	11.91	13.8	0.53
6:41	8.33	7.91	0.12
6:43	-41.77	-58.5	4.65

4.5 Tornado Width and Predicted Locations

The accuracy of the prediction model was also determined by considering the width of tornadoes. The original tornado path was divided into circles of diameters equal to 0.1 miles, 0.2 miles and 0.3 miles for the two-minute interval data. To look at each point closely, the data was divided into three different segments which comprised of location from 6:03 pm – 6:15 pm, 6:17 pm – 6:29 pm and 6:31 pm – 6:43 pm. The above mentioned diameter had been chosen because the actual width/diameter of the tornado ranges from 0.17 miles – 0.28 miles (6). The circles were drawn along the original path and if the predicted location was inside the circle then it would counted as a success, otherwise failure. The results are listed in Table XV and shown in figures 21-29 for different segments of two-minute intervals. Upon comparing the results, it was noted that 81% of the locations were predicted successfully with 0.1 miles diameter, 88% locations predicted successfully with 0.2 miles diameter, and finally, 92% of the locations were predicted successfully with the diameter of the circle was increased to 0.3 miles.

Table XV
PREDICTED LOCATIONS WITHIN TORNADO WIDTH (TWO-MINUTE INTERVAL)

	Number of Circles	Success	Failure	% Success	% Failure
6:03pm - 6:15pm					
0.1 miles	52	45	7	87	13
0.2 miles	31	29	2	94	6
0.3 miles	21	20	1	95	5
6:17pm - 6:29pm					
0.1 miles	23	19	4	83	17
0.2 miles	15	13	2	87	13
0.3 miles	10	9	1	90	10
6:31pm - 6:43pm					
0.1 miles	48	36	12	75	25
0.2 miles	31	26	5	84	16
0.3 miles	21	19	2	90	10

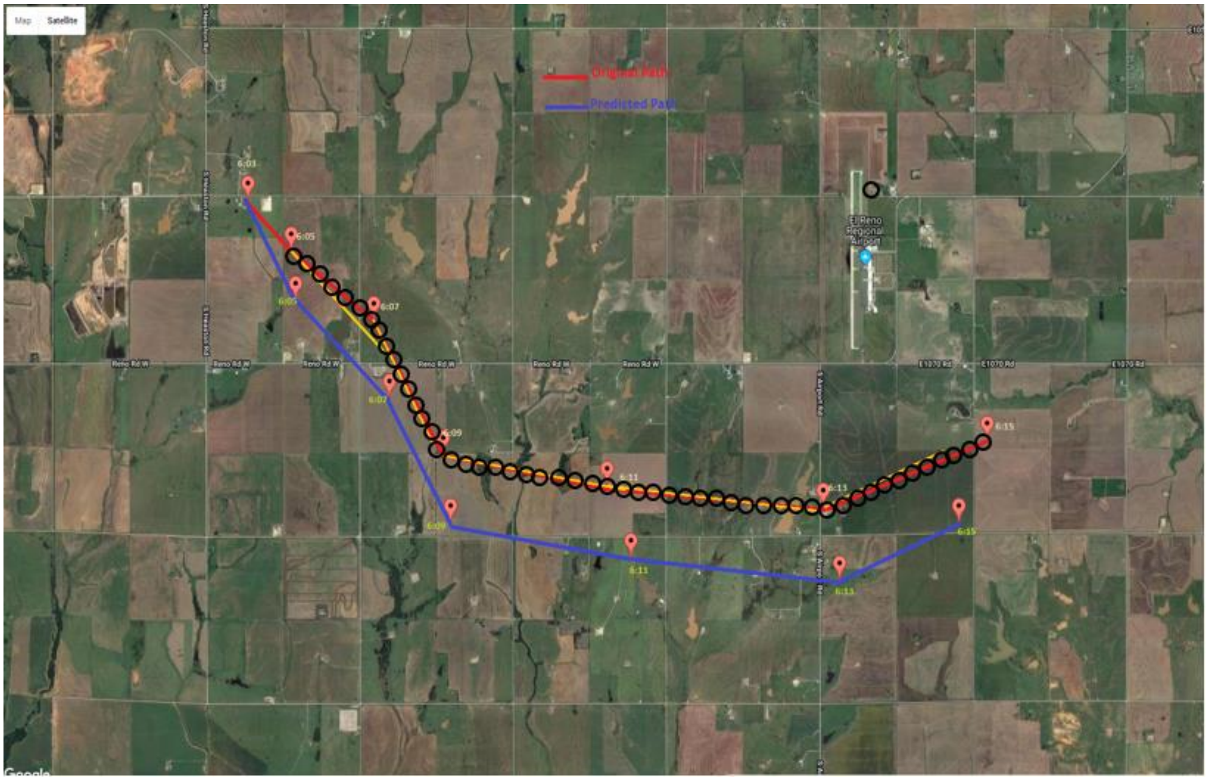

Figure 21: Tornado Path Prediction with a tornado width of 0.1 miles. Two-minute data from 6:03pm – 6:15pm

Figure 22: Tornado Path Prediction with a tornado width of 0.2 miles. Two-minute data from 6:03pm – 6:15pm

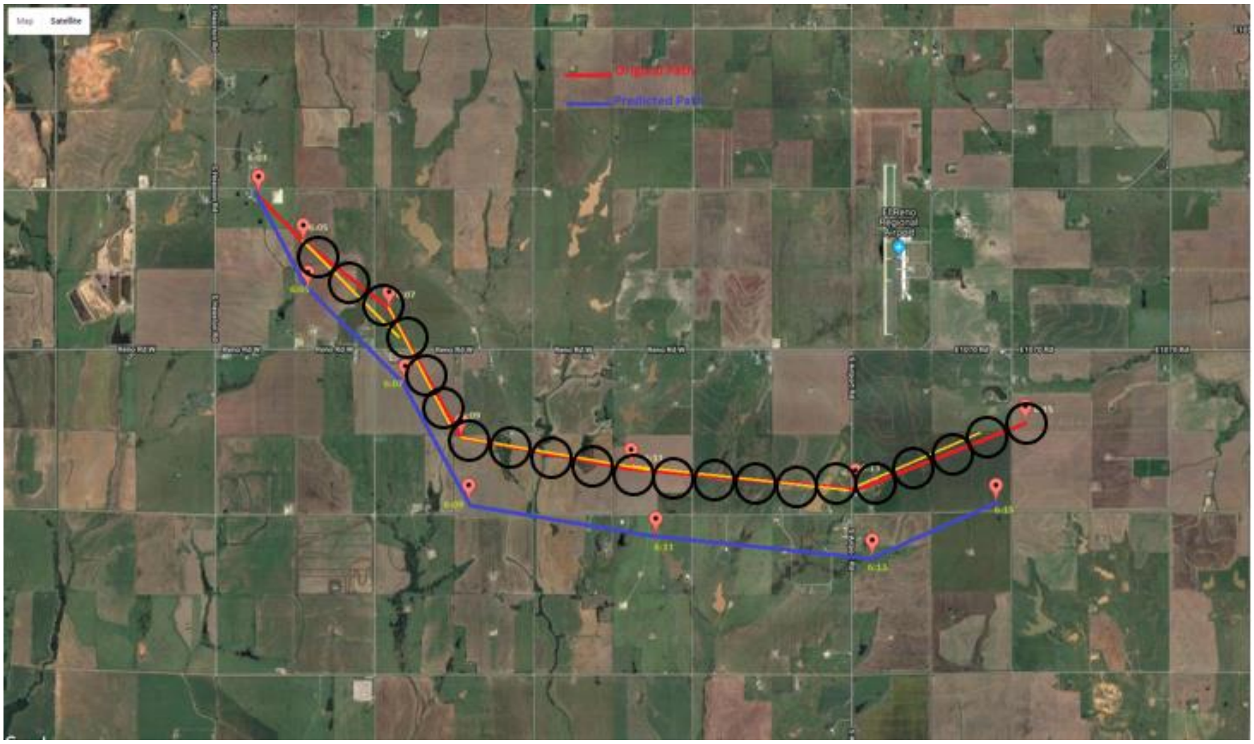

Figure 23: Tornado Path Prediction with a tornado width of 0.3 miles. Two-minute data from 6:03pm – 6:15pm

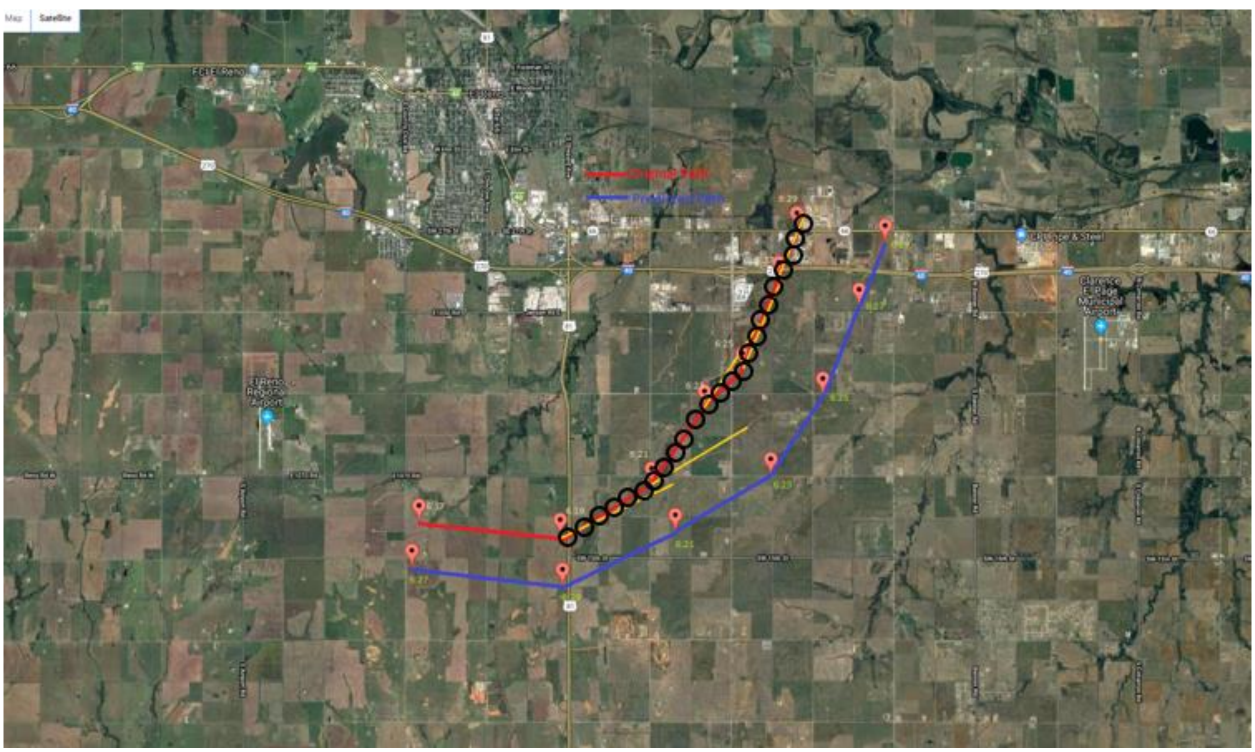

Figure 24: Tornado Path Prediction with a tornado width of 0.1 miles. Two-minute data from 6:17pm – 6:29pm

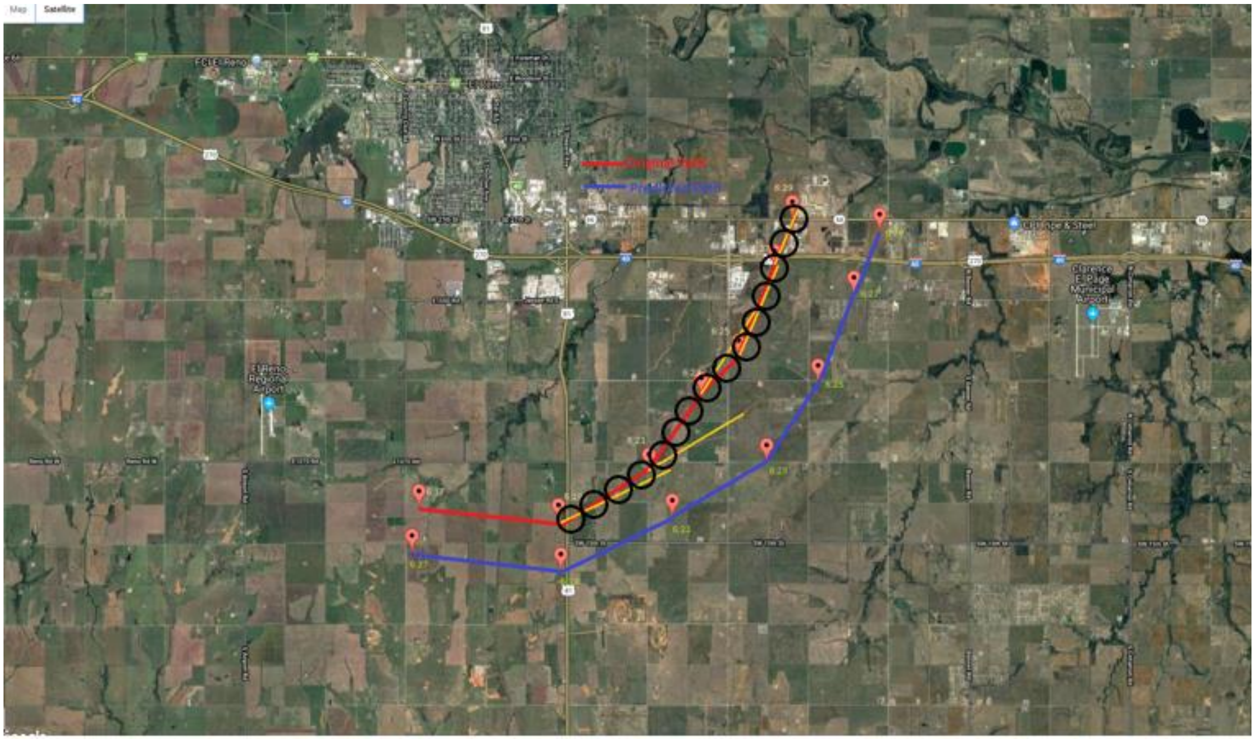

Figure 25: Tornado Path Prediction with a tornado width of 0.2 miles. Two-minute data from 6:17pm – 6:29pm

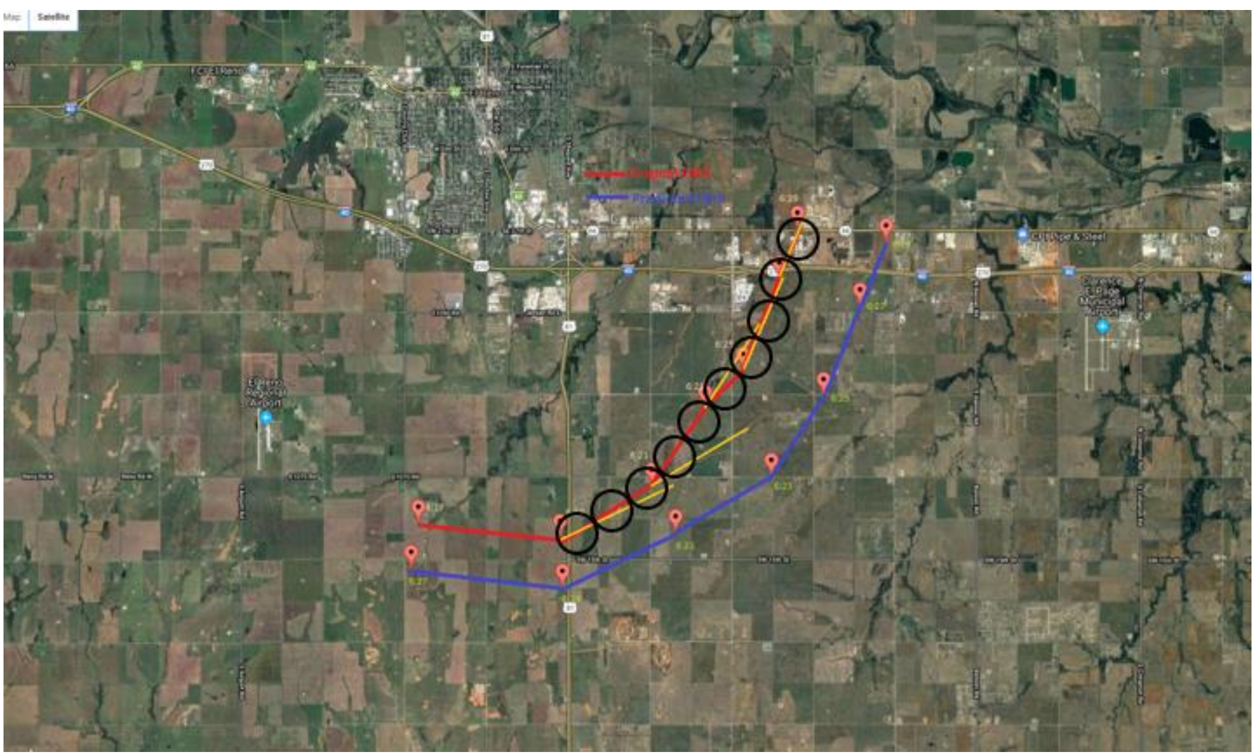

Figure 26: Tornado Path Prediction with a tornado width of 0.3 miles. Two-minute data from 6:17pm – 6:29pm

Figure 27: Tornado Path Prediction with a tornado width of 0.1 miles. Two-minute data from 6:31pm – 6:43pm

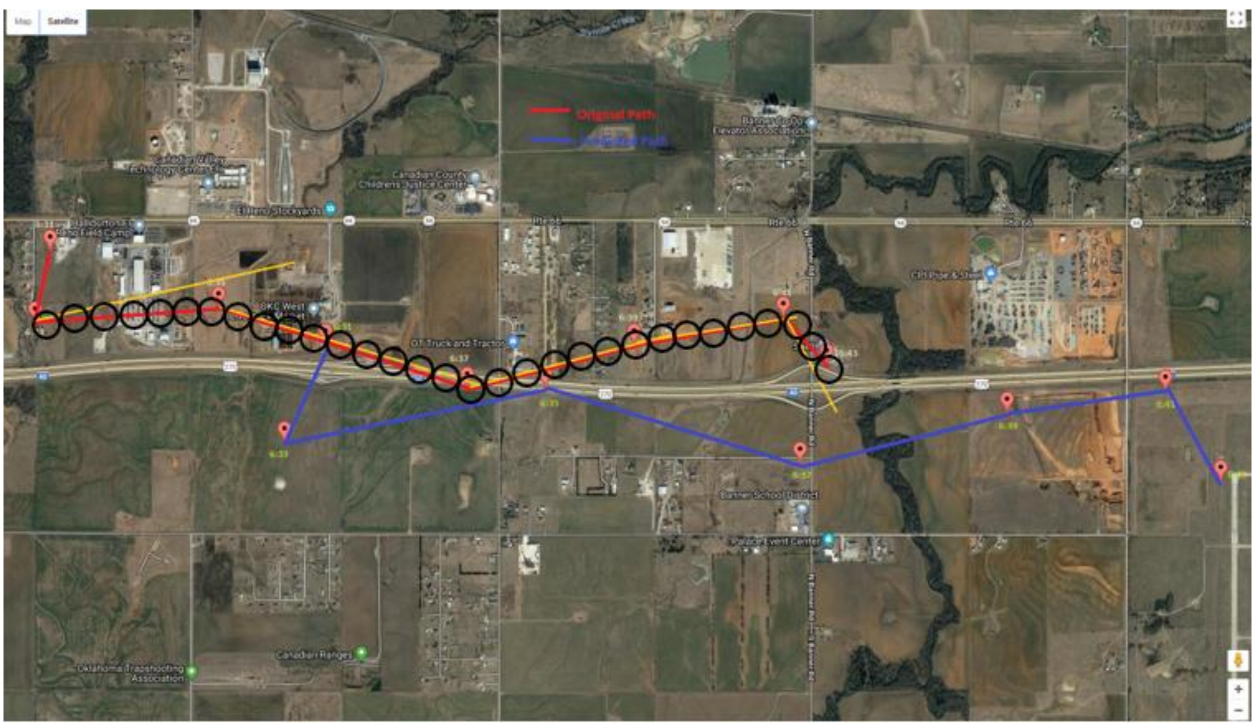

Figure 28: Tornado Path Prediction with a tornado width of 0.2 miles. Two-minute data from 6:31pm – 6:43pm

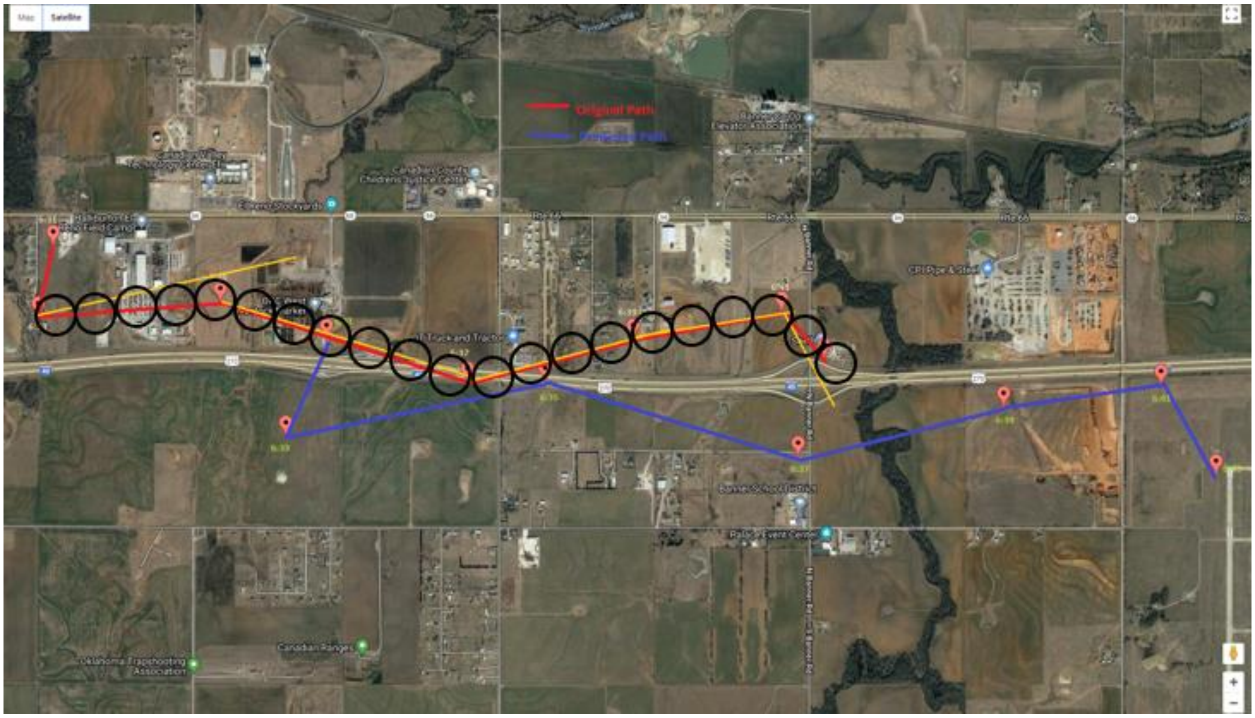

Figure 29: Tornado Path Prediction with a tornado width of 0.3 miles. Two-minute data from 6:31pm – 6:43pm

4.6 Confusion matrix for Tornado Warnings

A response to tornado warnings issued by UAVs was considered and listed as a confusion matrix in Table XVI. Despite being an effective communication mechanism, there is a possibility that people would ignore the warnings generated through UAVs by the officials and choose to seek shelter inside their houses. Since UAVs are not currently used as a warning mechanism, their efficiency cannot be determined in terms of an individual’s response.

Table XVI
CONFUSION MATRIX FOR TORNADO WARNINGS AND INDIVIDUAL'S RESPONSE

		People Seek Shelter		
		Yes	No	Total
Warnings issued by UAVs	Yes	Seek Shelter True (+ve)	Do not seek shelter False (-ve)	Warnings issued by UAVs (Yes)
	No	Did not provide warning, People seek shelter False (+ve)	Did not provide warning, People do not seek shelter True (-ve)	Warnings issued by UAVs (No)
	Total	People Seek Shelter (Yes)	People do not seek Shelter (No)	

4.7 Probabilistic Table for Distance Reduction

The probabilistic table was constructed for both one-minute and two-minute path intervals to compare the results for Model 1 and Model 2 in relation to the distance reduction between original and predicted locations. Table XVII and XVIII represents the one-minute interval data for Model 1 and Model 2. Upon comparing the results in these tables, it was noted that the 50% of the predicted and the original locations had a distance somewhere between 0.8 – 1.6 miles. On the other hand, in Model 2, about 47% of the predicted and the original locations had a distance less than 0.1 miles. Likewise, Table XIX and Table XX show the results for two-minute interval data for Model 1 and Model 2. A comparison of the findings indicated that about 55% of the predicted and the original locations had a distance between 0.8-1.6 miles for Model 1. A majority of the locations for Model 2 had a distance between 0.1-0.2 miles.

TABLE XVII

MODEL 1 - PROBABILISTIC TABLE (ONE-MINUTE INTERVAL)

Distance Range	**Total Number of Predicted Locations**	**Percentage of Predicted Locations**
Miles		%
0.0 - 0.1	2	5
0.1 - 0.2	7	18
0.2 - 0.4	4	11
0.4 - 0.8	6	16
0.8 - 1.6	19	50

TABLE XVIII

MODEL 2 – PROBABILISTIC TABLE (ONE-MINUTE INTERVAL)

Distance Range	**Total Number of Predicted Locations**	**Percentage of Predicted Locations**
Miles		%
0.0 - 0.1	18	47
0.1 - 0.2	14	37
0.2 - 0.4	5	13
0.4 - 0.8	1	3
0.8 - 1.6	0	0

Table XIX

MODEL 1 - PROBABILISTIC TABLE (TWO-MINUTE INTERVAL)

Distance Range	**Total Number of Predicted Locations**	**Percentage of Predicted Locations**
Miles		%
0.0 - 0.1	0	0
0.1 - 0.2	0	0
0.2 - 0.4	2	10
0.4 - 0.8	7	35
0.8 - 1.6	11	55

Table XX
MODEL 2- PROBABILISTIC TABLE (TWO-MINUTE INTERVAL)

Distance Range	**Total Number of Predicted Locations**	**Percentage of Predicted Locations**
Miles		%
0.0 - 0.1	6	30
0.1 - 0.2	7	35
0.2 - 0.4	5	25
0.4 - 0.8	2	10
0.8 - 1.6	0	0

5. Conclusions and Recommendations

Although the development in the area of warning mechanisms has greatly reduced the number of fatalities over the last 50 years, reducing these fatalities to zero is still quite challenging. A tremendous amount of research has been conducted to increase the warning lead time so that the residents and emergency personnel have plenty of time to implement an action plan for the disaster. Though the average national lead time for tornado warnings is 13 minutes, it has been seen in some scenarios that people are provided with warnings and tornado watches hours in advance before tornado's arrival. Furthermore, recent improvements in forecasting and warning guarantee that every individual receives a tornado warning and act to seek shelter. Despite these efforts, however, tornado warnings are not perceived by residents as expected by the officials, and hence, tornado-related fatalities and injuries continue to occur.

The lack of understanding on resident's side pertaining to tornado warnings have been the leading cause of these fatalities and injuries. Warnings are generated but not necessarily heeded by the individuals. The authorities believe that after issuing tornado warnings almost everyone in tornado path would react immediately to take shelter. However, due to the high false alarm ratio especially in tornado-prone areas, residents tend to disregard or ignore these warnings.

NWS continue to focus on providing longer lead times, however, these efforts can be counterproductive if the public response to the warnings is not considered properly. At the end of the day, it depends on people which warnings mechanism they trust to seek shelter. In addition, the common perception regarding the path of tornado suggests that the majority of tornadoes travel from the southwest quadrant toward the northeast quadrant. Although this assumption could be valid for some tornadoes, at the same time it could be misleading when residents use this information to take shelter inside their houses as they think they are not in tornado's path. Given the unpredictability of tornadoes, they can deviate from their usual path at any time. As seen in El Reno, Oklahoma tornado of May 31, 2013, where three storm chaser had died due to tornado taking a sharp left turn.

As far as the housing types are concerned, the mobile home residents are the most vulnerable population in tornadic events. Low-intensity tornadoes with heavy winds are sufficient to rip apart these type of housings. The death toll from tornadoes can potentially increase with the increase in the usage of mobile homes. Therefore, it is imperative that under tornado warnings, these residents must not take shelter inside their homes.

Given the severity of the issue regarding sheltering and evacuation, the path of the tornado is determined by predicting the exact locations along with their latitude and longitude points so the houses in the path are identified and the residents are notified to immediately seek shelter. In addition to the residents, lives of emergency first responders are also in danger as they try to reach areas under tornado watch to provide immediate relief. By using the predicted path, emergency managers should be able to allocate their services to prevent harm to their personnel as well. The result from Fig. 29, 30 & 31 illustrate that by using the prediction model, more than 90% of the locations with the diameter of 0.3 miles are predicted successfully. Moreover, the distance between the predicted and the actual locations was reduced significantly when the previous location provided by the radars was used to predict the next location. In addition to predicting the locations of the tornado, the usage of UAVs (Unmanned Armed Vehicles) is proposed to convey warnings to the residents. These UAVs will be controlled by the emergency managers and supervisors and by having the real-time access to these areas under the tornado watch through UAVs they can guide residents towards safe areas. UAVs will also be helpful in providing emergency response applications post-tornado. Tornado clean up involves various hazards that include gas leakage, frayed electrical wiring and fire hazardous from vehicle gas tanks. By using chemical sensing application, UAVs can demonstrate the areas under gas leakage. Hence, those areas can be either avoided or dealt by the fire department.

The same model can be used to predict more tornadoes that have occurred or will occur in the future. The absence of data regarding the movement of tornadoes was a hurdle in predicting more tornadoes. A complete record of locations must be kept by NWS to further study the path of tornadoes. Additionally, as the current database only contains the end and the begin point location of tornadoes, a detailed analysis of tornado path is recommended.

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