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Texas Transportation Planning for Future Renewable Energy Projects: Final Report

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16. Abstract

There will be a significant increase in the number of renewable energy production facilities in Texas. The construction of wind farms requires the transport of wind turbine components that create increased loads on rural roads and bridges. These rural roads and bridges are typically not designed for such loads. This will result in a greater burden on the transportation infrastructure in Texas.

Given the upward trend in wind energy production, the Texas Department of Transportation (TxDOT) is looking to plan for the impacts of future renewable energy projects on roads while facilitating the development of new renewable projects in and around Texas. CTR created an operational planning tool that TxDOT can use to propose route plans for wind turbine components passing along Texas routes and develop recommendations for planning construction of new wind farms as well as maintenance strategies for the roads.

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Chapter 1. Mapping Existing and Future Wind Farms

1.1 Introduction

Wind energy is available in abundance in most places and is one of the cheapest sources of renewable energy. The cost of electricity production using wind is similar to fuel-based electricity production. Since wind energy production typically results in zero emissions, the cost is lower when the externalities associated with greenhouse gas emissions are considered. In addition to the natural benefits of wind energy, in the last few years, significant improvements in the cost and performance of wind power technology have been achieved. Wind energy is the fastest growing source of energy globally (Brown and Escobar, 2007), and the U.S. has become the largest generator of wind power in the world (AWEA, 2008). There is currently more wind power capacity under construction than at any time in the history of the U.S. wind industry, with an expected target of 25% of all U.S. energy coming from renewable projects by 2025 (AWEA, 2014). In concrete terms, more than 13,000 megawatts (MW) of utility-scale wind development are under construction across more than 95 projects in 21 states. However, the majority of wind construction activity continues to be focused within Texas (>8,000 MW), as Figure 1.1 depicts.

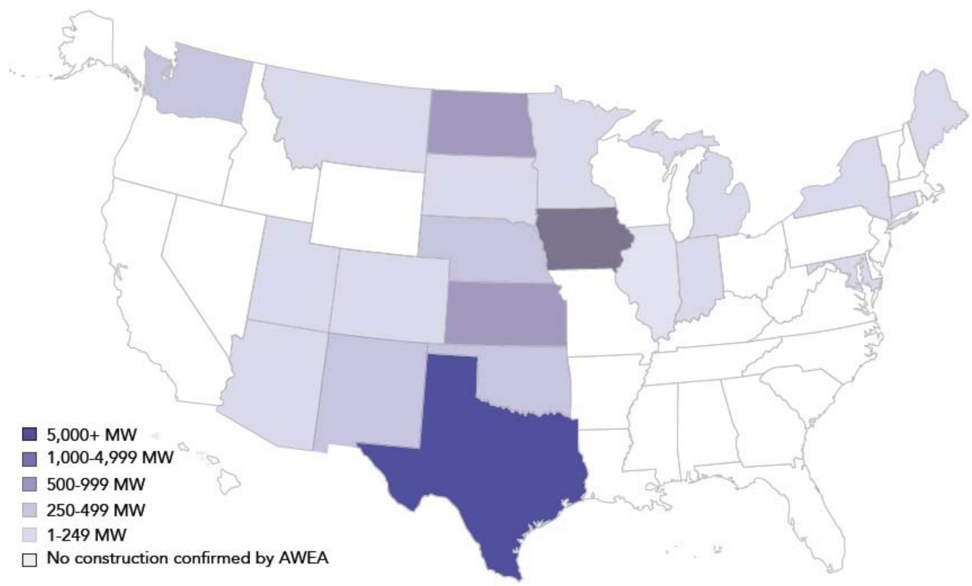


Figure 1.1 Map of wind power capacity under construction

Source: U.S. Wind Industry First Quarter 2014 Marker Report (AWEA)

The number of renewable energy production facilities in Texas is predicted to significantly increase over time. The construction of wind farms requires the transport of wind turbine components that create increased loads on rural roads and bridges. These rural roads and bridges are typically not designed for such loads. Thus, the continued and increasing construction of wind farms will result in a greater burden on the transportation infrastructure in Texas.

Given the upward trend in wind energy production, the Texas Department of Transportation (TxDOT) is looking to plan for the impacts of future renewable energy projects on roads while facilitating the development of new renewable projects in and around Texas. Our research team created an operational planning tool that can be used to propose route plans for wind turbine components passing along Texas routes and developing recommendations for planning construction of new wind farms as well as maintenance strategies for the roads. The first step in determining ideal routes for the wind turbine component transportation throughout the state is to identify future wind farm locations. The purpose of this first chapter is to document the process of assembling the data and estimating a predictive model that will then be used to forecast the number and location of new wind farms year-by-year through 2025.

1.2 Prediction Method

To predict the number and location of new wind farms year-by-year through 2025, the research team used a methodology that included the following steps:

1) Texas was divided into several census block groups.
2) For each zone (census block group), information on several attributes that may impact the number of wind farms installed per year was collected. These attributes include distance from the centroid of each zone to the nearest urban road, distance from the centroid of each zone to the nearest primary electric transmission line, and wind power potential of each zone.
3) Based on information available online (as detailed in Section 1.3), an estimate of the amount of wind power energy 'installed' each year (from 1996 to 2015) in each zone was made.
4) One record was created in our estimation sample for each year and each zone and the installed wind power energy was appended, as well as the other zone characteristics (see Step 2).
5) A regression model (see Section 1.4) was estimated using the records generated in the previous step.
6) The parameters estimated in Step 5 were used to predict the amount of wind power energy that will be installed each year (from 2016 to 2025) in each zone.

In subsequent steps of the project, the figure representing the amount of energy installed will be converted to the number of wind turbines installed, which will then be translated to estimate the associated quantity of wind turbine components that will be transported across Texas roads.

In the next section we explain in detail the assembly of data needed for the estimation of our regression model and the implementation of our prediction method.

1.3 Collection and Assembly of Data

The data collection process was conducted from January to April 2015, and consisted of two efforts: locating constructed and under-construction wind farms, and obtaining zone characteristics data. Both types of data were obtained from data sources available online. The research team compiled the information in two different files: a spatial GIS dataset for Texas, and a spreadsheet with the installed wind power energy in each zone each year and the related zone characteristics.

The following sections describe how the research team assembled each of the data files in a suitable form for estimation.

1.3.1 Spatial GIS Data

Spatial GIS data was collected in the form of six main shapefiles, or digital map features: census block groups, wind farms locations, wind power potential, roads, transmission lines, and competitive renewable energy zones.

Census block groups map

From the census website[1] we downloaded a shapefile with the 15,811 census block groups in Texas as a GIS polygon. Using the 'calculate geometry' tool of ArcMap (GIS software), we located the centroid of each census block group. The location of the centroid was used to compute the distance to the nearest road and the nearest transmission line.

Wind farms map

The U.S. Geological Survey, under the Data Series DS-817, provides a spreadsheet version of a dataset identifying windmill locations across the United States. The research team filtered the data for Texas and found 7,715 valid windmill locations available with their exact latitude and longitude.[2] Manufacturers, windmill dimension and specification, years of operation, site name, etc., are also available from the spreadsheet. The most recent data in the spreadsheet is from 2013. The locations of these windmills were entered in GIS for further estimation using the 'locate X/Y' tool in ArcMap.

Wind farms constructed in 2014 and those that are expected to be completed and operational in 2015 were dealt with in a separate way, as their exact locations were not in the public record. The research team had facility, county, and company name for the announced wind farms (the Public Utility Commission [PUC] of Texas maintains the dataset labeled "New Electric Generating Plants in Texas since 1995").[3] Using these keywords, the team looked for any news articles and memoranda of understanding pertaining to the proposed location of these wind farms, as well as their respective county websites. Once there was some local information (e.g., 40 miles northeast of Amarillo), the team used Google Maps to find out the latitude and longitude of that proposed facility. If the local information for the announced wind farm was not available, the mid-point of that county was taken as the facility's location. Once latitude/longitude data was available, it was plotted in GIS for future estimation.

Wind power potential map

The shapefile with the wind power potential in Texas was downloaded from the National Renewable Energy Laboratory (NREL) website.[4] The NREL file included designations of Wind Power Class (WPC), which is a way to classify the wind resources based on wind power density and wind speed. The indexing of WPC is based on the work of NREL, AWS Truepower, and the

[1] See https://www.census.gov/.
[2] This dataset is available for public download and can be sourced from http://energy.usgs.gov/OtherEnergy/WindEnergy.aspx#4312358-data.
[3] This data can be downloaded at https://www.puc.texas.gov/industry/electric/reports/Default.aspx.
[4] See http://www.nrel.gov/gis/data_wind.html.

U.S. Dept. of Energy's Wind Powering America program. Table 1.1 presents the wind power classification in detail (see Harrison, 2012).

Table 1.1: Wind power classes based on mean annual wind density and mean annual wind speed at 50 m (164 ft) height

Wind Power Class	Wind Power Density (Watts/sq meter)	Wind Speed (meter/second)
1	0–200	0.0 – 5.6
2	200–300	5.6 – 6.4
3	300–400	6.4 – 7.0
4	400–500	7.0 – 7.5
5	500–600	7.5 – 8.0
6	600–2000	8.0 – 11.9

The available Texas wind data on NREL's website was last updated on June 22, 2012, and it provides the WPC for each zone in the grid with a resolution from 200 to 1000 meters. According to NREL's website, areas with a WPC of 3 or higher are suitable for most utility-scale wind turbine installations; areas with class 2 may be suitable for rural applications; and class 1 areas are usually not suitable for wind turbine applications. We appended the WPC index score (based on a range of 1 to 6) to each census block group using the 'Intersection' tool in ArcMap. Figure 1.2 shows the distribution of the six WPCs across Texas.

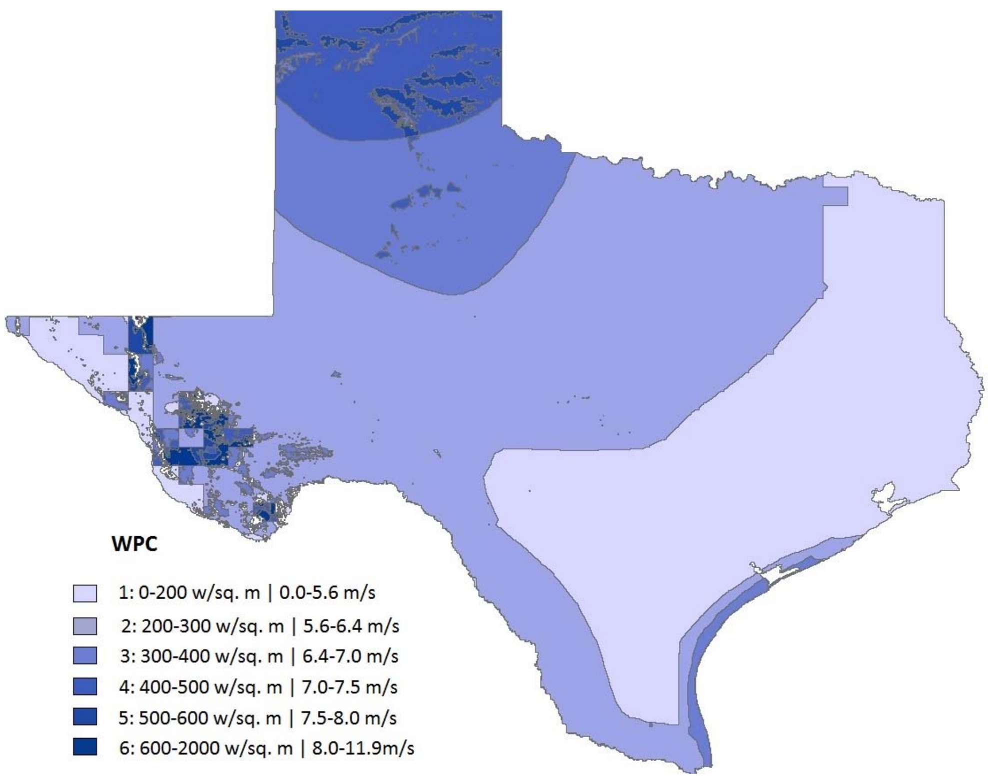


Figure 1.2 WPC classification

Roads map

A shapefile with all the primary and secondary roads of Texas was downloaded from the census website. Distances between every census block group centroid and the nearest road were calculated using the 'Near' tool in ArcMap.

Transmission lines map

Another important factor that has contributed to the rapid expansion of wind power energy in Texas is that Texas has a plan for the installation of transmission lines (Diffen, 2009) and several laws to make the transmission inexpensive for the developers of wind power energy. The PUC identified the top 25 wind regions based on wind capacity and then tested several scenarios of expansion of transmission lines. They decided to complete almost 3,600 circuit miles of new transmission lines by the end of 2013, connecting the Panhandle, Central West Texas, and Central Texas. Most new wind farms will likely locate according to this plan, since the developers are not required to make a significant investment in transmission. In addition, since 1998, the Electric Reliability Council of Texas (ERCOT) has imposed a standardized interconnection process that avoids discriminating against new plants trying to connect to ERCOT transmission lines. And finally, another aspect that makes Texas so attractive for wind power energy in terms of transmission is that ERCOT determines transmission rates using a "postage-stamp" system. Just as you pay the same rate to mail a letter whether it is going across the country or simply across town (the price of a stamp), moving power from a wind farm across the state costs the same as moving power from a wind farm just outside town. As a consequence, the location of the transmission lines should be an important factor in our model.

A shapefile with all the primary transmission lines in Texas was constructed using the 'Drawing' tools (or 'Sketch') of ArcMap. Distances between every census block group centroid and the nearest transmission line were calculated using the 'Near' tool in ArcMap. It is important to note that transmission line locations have changed over time (as mentioned earlier, transmission lines have expanded significantly since 2013), so we constructed two different transmission lines map: one for years earlier than 2013 and another one for 2013 and later.

Competitive Renewable Energy Zones map

The research team considered the Competitive Renewable Energy Zones (CREZ) already defined by PUC as potential future location sites for wind farms. PUC identified the top 25 wind regions based on wind capacity and grouped them into four groups: North Texas, West Texas, Central Texas, and Panhandle. We digitalized the CREZ map we found online (at the PUC website) using the 'Drawing' tools of ArcMap and we classified each of our zones (census block groups) in one of these four areas.

1.3.2 Wind Power Energy and Zone Characteristics Spreadsheet

Using the 'Joint' tool of ArcMap, we computed the total amount of wind power energy (in megawatts) installed each year in each zone. We created one record for each zone-year combination in an Excel file and we appended the zone characteristics, as well as two time variables: (1) the percentage of change of the U.S. gross domestic product (GDP) from the previous year to the current year (information was obtained from the World Bank website), and (2) a dummy variable that takes the value of 1 if the record corresponds to 2005 or a year after 2005, and otherwise takes 0. Texas's success in creating installed wind power capacity is partially attributable to the Renewable Portfolio Standard (RPS). The RPS was first introduced in Texas in 1999 under Senate Bill 7 to ensure continuous growth in the renewable energy generation in Texas despite the increasing competitiveness of the electricity market. The RPS mandated that electricity providers generate 2000 MW of additional renewable energy by 2009. This 10-year target was met in 6 years. Then Senate Bill 20 was introduced in 2005, mandating that the state's total renewable energy generation must reach 5880 MW and 10000 MW by 2015 and 2025 respectively. By instituting the RPS, wind power development in Texas has more than quadrupled. Because of its competitive pricing, available federal tax incentives, and the abundance of wind resources, wind power is expected to remain competitive with coal-fired plants (SECO, 2011). We consider that the year 2005 is a critical year in our analysis and we expect this dummy variable to account for the RPS effect.

1.4 Model Formulation and Estimation

In order to identify future wind farm locations, the research team studied current Texas wind farm locations to identify any siting trends. We believe that such trends can differ in each zone according to zone characteristics. Therefore, we partitioned the zones into categories based on the trends identified. Our categories are defined by WPC and the CREZs. We defined a dummy variable (*WPC3*) that takes the value of 1 if the WPC of zone *q* is 3 or higher; otherwise its value is 0. We also used the four groups of CREZs we defined in Section 1.3.1 (North Texas, West Texas, Central Texas, and the Panhandle). Three of these four groups—North Texas, Central Texas, and the Panhandle—are relatively homogenous regarding *WPC3,* i.e., almost 90% of the zones included in each of the groups have almost the same value for the *WPC3* variable. The only group that shows a significant difference in the *WPC3* variable among zones is West Texas (see Figure 1.3). So we defined five categories for our zones: (1) West Texas with low WPC (i.e., WPC3=0), (2) West Texas with high WPC (i.e., WPC3=1), (3) North Texas, (4) Panhandle, and (5) Central Texas. The trends for the amount of energy installed during a particular year in a particular zone and the energy installed in the previous year for that zone are graphically represented in Figure 1.3. We can see that West Texas is the zone category where the first wind farms were installed (1990s and early 2000s). Then, after the RPS introduction in 2005, the Panhandle and North Texas started to gain some relevance in the installation of wind farms. Finally, Central Texas came into the picture only after 2008. We also can see that the five categories reveal a significant increase in the amount of energy installed—or soon to be installed—in the past year (2015), highlighting the importance of wind power energy in Texas. However, the magnitude of this increment differs in each zone category, with the Panhandle being the zone category with the most remarkable increment and West Texas (at both WPC levels) the one with the smallest increment. Several other variables were tested for possible inclusion in our categorization, such as land use and distance to urban roads, but were not included as they did not show a significant effect on trends.

Two different models for the amount of energy installed each year in each zone were tested: (1) a market segmentation model (providing a different regression model for each of our five zone categories) and (2) a single regression on the entire data set that includes the segmentation variables as independent variables. Since we wanted to predict the trend based on earlier data points, we used a panel regression framework to estimate the difference between the amount of energy installed during a particular year in a particular zone and the energy installed in the previous year for that zone.

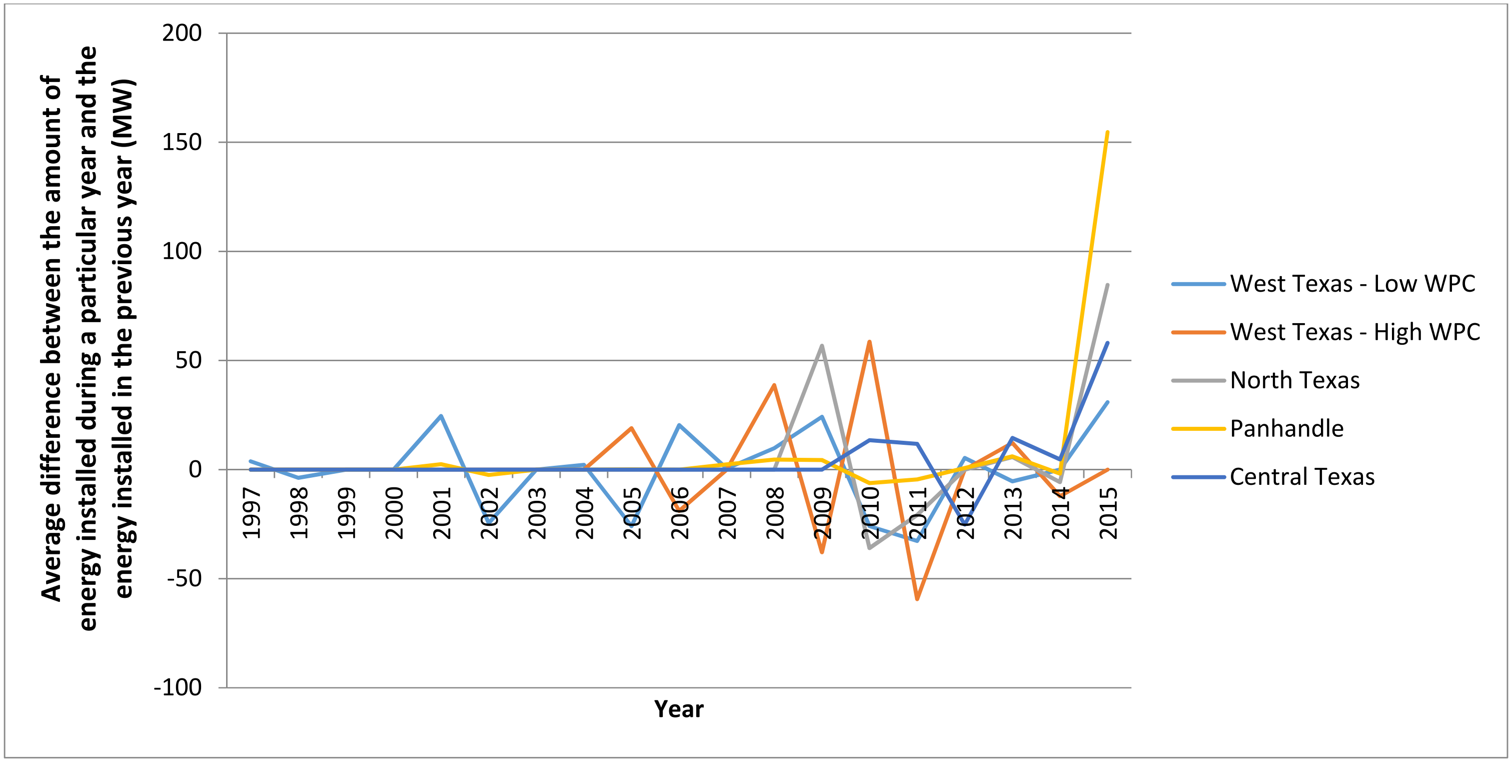


Figure 1.3 Trend of average difference of amount of energy installed per year by zone category

The panel regression model used to estimate the difference between y_{qt}, the amount of wind energy installed (in megawatts) during year *t* in zone *q* (with *q* belonging to the i^{th} category), and y_{qt-1}, the amount of wind energy installed (in megawatts) during year *t-1* in zone *q*, has the following form (Equation 1.1):

$$y_{q,t,t-1} = y_{q,t} - y_{q,t-1} = Constant \quad + \beta_{GDP} * GDP_{t,t-1} + \beta_{RPS} * RPS_t + \beta_{DLines} * \left(DLines_{q,t} - DLines_{q,t-1}\right) \tag{1.1}$$

where $GDP_{t,t-1}$ is the percentage of change of the U.S. GDP from year *t-1* to year *t*, $DLines_{q,t}$ is the distance (in miles) between the centroid of zone *q* and the nearest primary electric transmission line existent in year *t*, and RPS_t is a dummy variable that takes the value of 1 if year *t* is 2005 or later, and the value of 0 otherwise. The values of the coefficients accompanying each independent variable, β_j , were estimated first using a market segmentation framework in which a separate regression was estimated for each of the five zone categories (see Appendix A).

The market segmentation model was then compared to a simpler model. This second model is a single linear regression using the zone category variables as explanatory variables and has the following form (Equation 1.2):

$$y_{q,t,t-1} = y_{q,t} - y_{qt-1} = Constant + \beta_{GDP} * GDP_{t,t-1} + \beta_{RPS} * RPS_t + \beta_{DLines} * \left(DLines_{q,t} - DLines_{q,t-1}\right) + \sum_{i=1}^{4} \beta_{Zcat}^{i} * Zcat_q^i \tag{1.2}$$

where $Zcat_q^i$ is a dummy variable that takes the value of 1 if zone *q* belongs to category *i* and the value of 0 otherwise. We used category 5 (Central Texas) as base. The values of the coefficients accompanying each independent variable were estimated using a panel linear regression framework (results are presented in Appendix B).

In order to test both models, the following *F*-statistic is computed (Equation 1.3):

$$F = \frac{(SSE_R - SSE_{UR}) / (number\ of\ restrictions)}{SSE_{UR} / (N-M)} \tag{1.3}$$

where SSE_R corresponds to 81,303,210 (the sum of square residuals of the restricted model, i.e., the second model [defined by Equation 1.2]) SSE_{UR} is equal to 81,261,122 (the sum of square residuals of the unrestricted model, i.e., the market segmentation model [defined by Equation 1.1]), there are twelve restrictions (degree of freedom=12), *N*=14,140 (number of observations), and *M*=20 (number of parameters). The computed value of *F* is 0.61. This value is compared with 1.75, the critical value of an *F*-statistic with 12 degrees of freedom and a 95% confidence level. Since our computed *F*-statistic is less than 1.75, the null hypothesis cannot be rejected and the second model is preferred.

Finally, one additional variable is added to the preferred specification in order to capture in a better way the time trend of our dependent variable. We defined $w_{q,t-1,t-2} = y_{q,t,t-1} - y_{q,t-1,t-2}$ and we included this variable as an extra explanatory variable, as well as interaction effects with the segmentation variables. This new specification attempts to improve upon the second model specification by using the change in wind energy installed in the previous year as an explanatory variable. This third model specification has the following form (Equation 1.4):

$$\begin{aligned} y_{q,t,t-1} = y_{q,t} - y_{qt-1} = Constant + \beta_{GDP} * GDP_{t,t-1} + \beta_{RPS} * RPS_t \\ +\beta_{DLines} * \left(DLines_{q,t} - DLines_{q,t-1}\right) + \sum_{i=1}^{4} \beta_{Zcat}^{i} * Zcat_q^i \\ +\beta_w * w_{q,t-1,t-2} + \sum_{i=1}^{4} \beta_w^i * Zcat_q^i * w_{q,t-1,t-2} \end{aligned} \qquad (1.4)$$

The results of the estimation of our final specification are presented in Appendix C. Our specification provides several insights. GDP is an indicator of the economic status of the country; high GDP is related to high consumption of services and goods, including energy. Thus, an increase in GDP has a positive impact on the wind power energy installed, as expected (see Apergis and Payne, 2010 and Ohler and Fetters, 2014 for similar results). Due to the persistent efforts to provide transmission facilities to wind energy producers in Texas and the direct relation between energy production and transmission, wind farms tend to be located close to the electric transmission lines. The introduction of the RPS in 2005 has a positive impact in the amount of energy installed, as expected. Of all the CREZs defined by PUC, the zones located in West Texas will have fewer wind farms, in comparison with the other three (Central Texas, North Texas, and the Panhandle). On the other hand, the Panhandle will evidence the highest amount of energy installed in the coming years. Surprisingly, a higher WCP is related to a lower wind power energy installed in West Texas. This can reflect the fact that the West Texas area, although it was the pioneer of the installation of wind farms, is getting less popular for wind energy installations, in comparison with the other three CREZ groups, and the places with high WPC in West Texas are already taken. Finally, the negative effect of $w_{q,t-1,t-2}$ on the difference of wind energy installed makes the trend more smooth over the period examined.

1.5 Wind Power Installation Prediction

Table 1.2 presents the results of our prediction method. We applied our model to each zone year by year through 2025, keeping constant the zone characteristics, but varying the percent change of GDP following the predictions available on the World Bank website (second row of Table 1.2). We can see that the total amount of wind energy installed will slightly increase with time, as well as the average wind power energy installed in each zone. Figure 1.4 shows the trend of the average difference between the amount of energy installed during a particular year and the energy installed in the previous year. From 2005 to 2015 the actual data is shown and from 2016 to 2025 we used our model to predict the trend. We can see clearly that, starting 2017, the amount of wind energy installed will increase year by year, with an asymptotic tendency to 1,500 MW. Our model also can be used to test different scenarios. For example, we can measure what is going to happen with the wind energy installed in the coming years after a new transmission line is built.

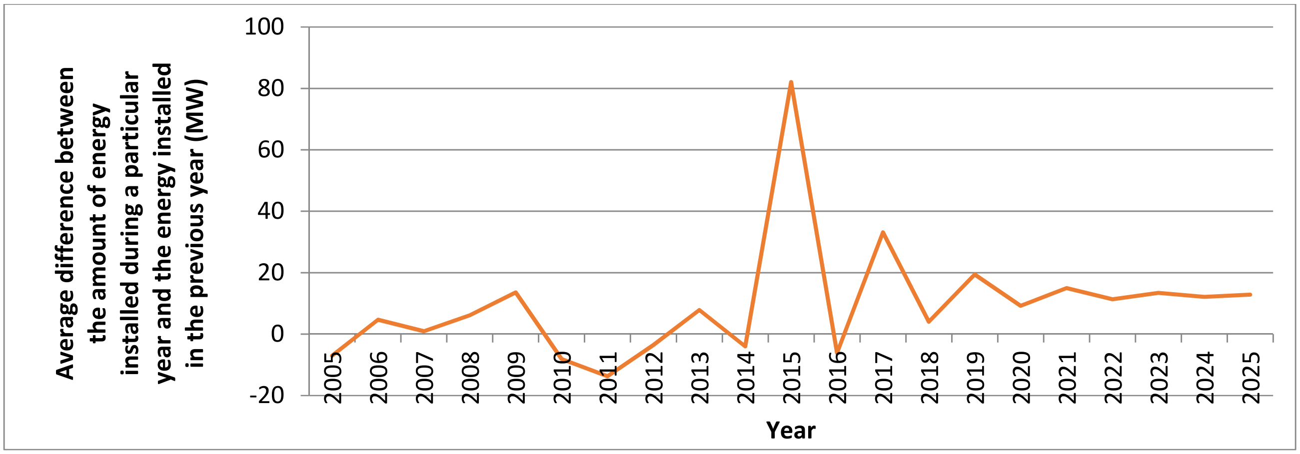


Figure 1.4 Trend of average difference of amount of energy installed per year through 2025

Table 1.2: Prediction method results

Year	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
Percentage of change of the U.S. GDP from previous year	3.28	2.97	2.76	2.64	2.56	2.50	2.47	2.45	2.42	2.40
Total wind power energy installed (MW)	5,660	6,954	8,330	9,610	10,882	12,355	13,424	14,893	16,462	18,030
Average wind power energy installed (MW)	55.0	72.8	73.5	105.1	107.7	132.3	132.9	145.4	166.9	180.5
Maximum wind power energy installed (MW)	650.8	759.0	801.5	891.6	932.0	1,023.5	1,119.1	1,175.8	1,227.3	1,287.7

1.6 Visualization of the Results

The research team compiled the information gathered from the model estimation and created an interactive visual tool in the form of an ArcGIS map. Three critical estimations are shown on GIS maps; the amount of wind energy installed each year, cumulatively, the number of wind turbines installed, and the percentage of land used for wind farms. We predicted **the amount of wind energy "installed"** each year in Texas through 2025, using census block groups as space unit. This map shows the amount of energy installed (in MW) through each year. Please note this map (and all the rest of the maps described in this section) describes cumulative data: the tab corresponding to 2012, for example, shows the amount of energy installed from the beginning of Texas history to the last day of 2012.

The darker colored polygons are regions where there is a greater amount of wind energy installed. Referring to Figure 1.5, which shows the prediction for the year 2025, these regions are seen in greater numbers in the north and western portions of the state. This is due to the model formula that is discussed in the third chapter of this section. The prediction model also estimates that there will not be any wind turbine energy present in the eastern section of the state. The link to the map with the information regarding the amount of wind energy installed from can be accessed here: http://arcg.is/1OYv8c0.

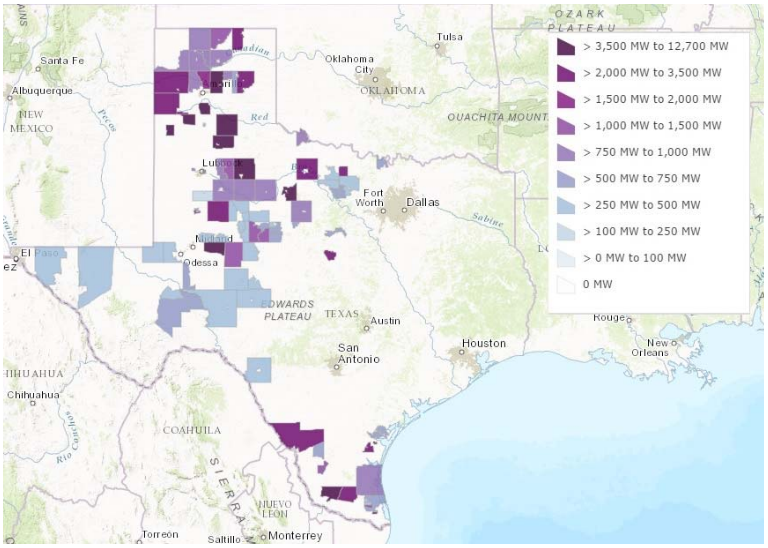


Figure 1.5: The figure shows the amount of wind energy installed in Texas for the year 2025

Then we translated the amount of energy to **number of turbines installed.** As we will see in detail later, the most common wind turbine installed so far in Texas is the one with capacity 1.5MW. So we divided the total amount of energy installed by 1.5 and we obtained an approximation of the number of wind turbines installed. Since the main goal of this visualization is to check if our predictions are physically feasible (make sure we are not predicting too many turbines in a small area), we conclude that this approximation is rational because wind turbines commonly have a 1.5MW capacity, if not more.

The regions with the highest number of turbines are the darker blue colors, while the less dense regions are indicated with a lighter blue shading. Figure 1.6 shows the number of turbines installed for the year 2025. The map with the number of turbines installed from 2003 to 2025 can be accessed here: http://arcg.is/1jUvRzW.

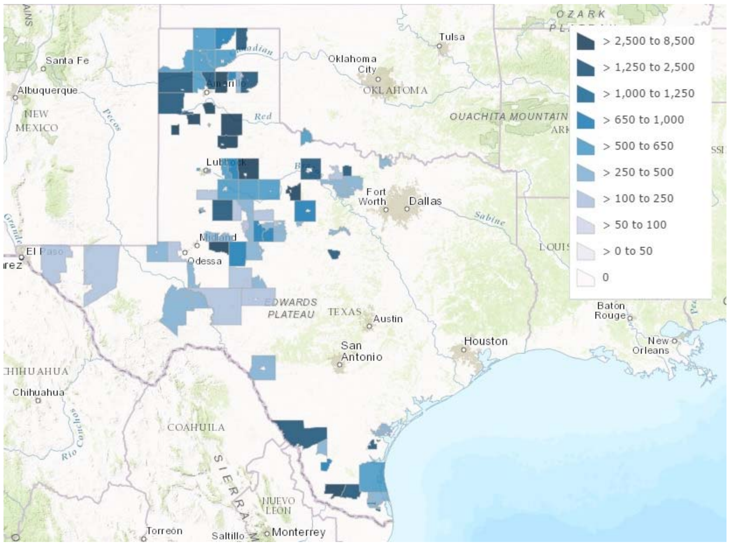


Figure 1.6: Number of turbines installed in Texas for the year 2025

Finally, we tried to make sure the turbines can be actually installed in each zone. According to previous literature and the data collected during Task 2, a 1.5MW turbine uses a space between 3 and 5 hectares. So we considered that each of the turbines translates in a space of 5 hectares and we computed the percentage of space used for wind turbines in each zone (considering as available space all the land space reported in the census data).

Figure 1.7 shows relatively transparent polygons of regions in north and west Texas. According to the legend the majority of those regions are projected to have approximately 5% or less of the land used for wind farms in the year 2025. However, as discussed earlier there are plans to construct more wind farms in the state. The map of **percentage of land used for wind farms** can be seen here: http://arcg.is/1OnpehS for the years 2014–2025. We did not show years previous to 2014 because the percentage of land used for wind farms is less than 1% for all zones in those years. Let's consider the year 2025 (since our map is cumulative, 2025 corresponds to the critical year in terms of space) and let's go deep in the data: we can see that in 100 of the 114 census block groups that ended up with wind farms installed the percentage of land required for wind turbines is less than 30%. For the other 14 zones, the percentage of land needed is less than 50%. Of course we should discount also the urban areas and the protected areas, but unfortunately we did not find the data necessary to do that for the entire Texas. However, the approximations we have made during this process have been always considering the critical case, so we think that margin plays in our favor. The research team only identified three critical zones that overlap with city areas (Lubbock, Tulia, Pampa), but they are surrounded by other zones that also have wind farms installed and there appears to be plenty of space left.

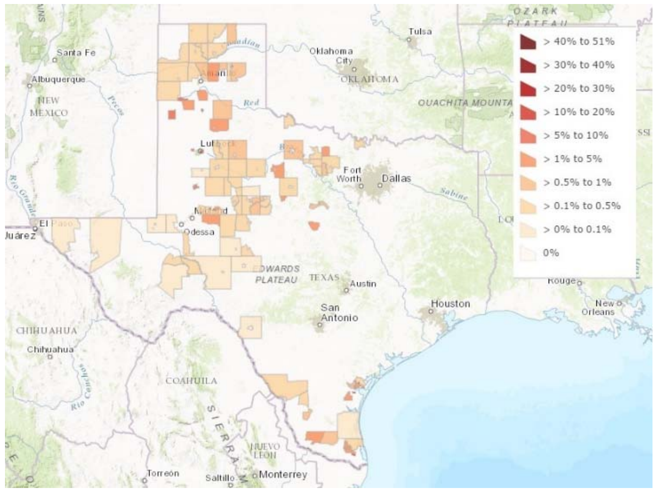


Figure 1.7: Percentage of land used for wind farms installed in Texas for the year 2025

Chapter 2. Survey Design, Results, and Analysis

Using the information that was collected, the research team converted the information about potential locations and amounts of wind energy produced from each zone each year to a count of wind farms within each zone. After determining the number and location of wind farms, the research team then estimated the quantity of wind turbine components that will be transported to those locations.

The first chapter of the report presented the process of assembling the data and estimating a predictive model that was used to forecast the number and location of new wind farms year-by-year through 2025. In the current chapter, we document our study of the wind turbine components industry: to help support Texas's wind energy generation, this project aimed to understand the challenges faced by transportation companies in moving wind turbine freight in the state. To this end, the research team prepared a survey to understand the type of wind turbine freight transported by trucking companies, the types of vehicles they use, and the challenges they faced in moving wind turbine freight on Texas roads. We have also included our predictions of how the dimensions of the wind turbine components will develop in the future.

2.1 Survey Design

Since wind turbine components fall into the oversized and overweight (OS/OW) load category, the transportation of these components needs special permission from Texas Department of Motor Vehicles (TxDMV). This state agency issues permits and schedules to companies specializing in wind turbine component transportation on Texas roadways. Hence, we decided to survey companies that transport wind turbine components.

In designing the survey, our goal was to document the difficulties and realities transport companies face. Our target respondents were schedule managers and company officials who were responsible for transporting these loads from the point of supply to the destination point. The research team prepared a short email to determine the level of interest in participating, followed by a longer email to transport company managers with the link to the survey questionnaire, and a question sheet to be used for the phone interview if respondents indicated that they'd rather be contacted by phone than fill out the survey. The researchers ensured that the response dimensions for questions about events and behavior included field experience, frequency, regularity, duration, and regulations. Most of the questions were open ended, designed to collect the maximum possible information. The complete survey can be found in Appendix D. We divided our survey into three categories: (1) characterization of the company, (2) infrastructure and service, and (3) permit and regulation issues.

2.1.1 Survey Section 1: Characterization of the Company

In this section of the survey, we asked for a description of the wind turbine components and typical dimensions transported by the company. Our goal for this section was to determine whether the company specializes in transporting a particular type of turbine component or provides a more comprehensive service, as some transport challenges are specific to the load dimension. To understand each company's transportation demand, we asked about the typical turbine components transported, load dimensions, and the type and number of fleet vehicles, as well as number of loads transported annually. One goal of this task was to identify companies' major shipping origin/destination points and routes, so we included a question to obtain that information. The responses helped the research team to re-affirm the current growth trend as well as the projected regions for new installations through 2025.

2.1.2 Survey Section 2: Infrastructure and Service

Section 2 elicited information on the challenges faced by transport companies: conflicting interstate regulations, infrastructure challenges, the labor market, and changing turbine sizes. Texas and neighboring states have different regulations regarding load dimensions. Thus, loads for interstate transfer have to be managed to comply with these varying regulations. Further, re-routing is often required due to road elements such as bridges, tunnels, and tight bends. We asked about regulation difficulties and the possibility of encountering obstacles on a road segment after the permit for that segment was obtained. The research team also asked about the available pool of skilled drivers, thus measuring the companies' readiness to serve the market given a surge in the Texas wind farm industry. Experts in the field agree that the wind industry is moving towards more efficient turbine design, resulting in changing dimensions. As a result, transport companies do have to adapt their fleet dimensions. Hence, this survey section inquired about the effects of changes in turbine size on the fleet required.

2.1.3 Survey Section 3: Permits and Regulations

In this section, we wanted to obtain information on any difficulties faced during the process of getting permits from TxDMV as well as any differences between a project's desired and actual schedules. Moreover, we inquired about the use of escort vehicles accompanying the OS/OW loads. This section also asked for details about the difficulties of navigating the conflicting interstate regulations employed by neighboring states. Finally, we requested any suggestions the respondents had for infrastructure improvement to facilitate the transportation of wind turbine components.

2.2 Identification of Manufacturers and Transporters

As part of this project, we contacted several companies that transport wind turbine components in the U.S., especially Texas, in order to discuss the challenges faced by their respective organizations in transporting wind turbine freight in Texas. We conducted an internet-based search for companies that transport wind turbine freight in the U.S., and contacted them via website contact forms, email, and phone. The organizations we contacted included Lone Star Transportation, Daseke, BNSF Logistics, Landstar, Siemens, General Electric, Anderson Trucking Service, American Wind Transport Group, Daily Express, Energy Transportation Inc., Oehlerking Hauling Inc., DHL, Integrated Wind Energy Services LLC, Dad's Transportation LLC, Nooteboom, Badger Transport Inc., and Mammoet.

We contacted several wind turbine manufacturers with shipping points in Texas as well. In addition to conducting internet-based research, we contacted Trinity Structural Towers to identify the major wind turbine manufacturers operating in Texas, as roughly 15% to 20% of OS/OW wind turbine traffic originated from Trinity manufacturing plants between 2007 and 2009. Kerry Cole of Trinity Structural Towers provided several manufacturers that operate in Texas; we contacted Alstom, GE Energy, Vestas, Siemens, Nordex, Gamesa, and Acciona. Appendix E provides information about the companies contacted by the research team, including the name of the company, the person contacted, email address, phone number, website, date contacted, and whether or not we received a response from the company.

2.3 Survey Results

We were able to interview at length two transportation companies that transport wind turbine freight in Texas: Lone Star Transportation and BNSF Logistics. Representatives from these companies graciously took the time to talk with us about wind turbine freight, and responded to our survey questionnaire. Mr. David Ferebee from Lone Star Transportation noted that his company transports blades, nacelles, rotors, and tower sections of wind turbines. These components have varying sizes and dimensions depending on the manufacturer and the size of nacelle being installed. He added that Lone Star Transportation has about 700 trucks and various types of trailers (information about the types and dimensions of Lone Star Transportation's trailers is included in Appendix F).

Mr. Robert Sutton from BNSF Logistics stated that his company is a non-asset-based third-party logistics firm that coordinates the movement of nacelles, hubs, tower sections, and blades for various manufacturers, but does not own tractors or trailers. BNSF Logistics mainly focuses on coordinating the transportation of wind turbine components on railroads and manages the transloading of these components at its transload sites. Currently, most of their transload operations are focused in West Texas. Mr. Sutton further noted that the number of components handled by his company varies each year, as the wind industry fluctuates in accordance with the national policy related to the production tax credit; they expect to handle several thousand components in 2015 and 2016, and many of these components would either terminate in Texas or move through Texas to reach other locations.

In addition, we were able to interview Ms. Maria Iredale of Vestas, a global energy company that deals exclusively in wind energy. Vestas manufactures, sells, installs, and services wind turbines and is the world's largest supplier of these products. Ms. Iredale is the Regional Director for Project Transportation in the Americas. She is responsible for organizing delivery of major turbine components (e.g., the nacelle, tower base, blades) in the region.

The detailed interviews can be found in Appendix F. In the next sections we will discuss the main findings of our survey.

2.3.1 Physical Challenges

The excessive size of wind turbine components such as blades and tower sections makes their transportation challenging (Figure 2.1). According to Cotrell et al. (2014), transportation of long, wide wind turbine blades is difficult around turns, through narrow passages, and under overhead obstructions on roads and railways in the U.S. The report further notes that due to these physical limitations, only blades up to a maximum of about 62 meters (203 ft) can currently be transported by road. Moreover, the report states that transportation of wind turbine tower sections with large diameters is also challenging owing to similar physical limitations, and diameters of tower sections are generally limited to 4.3 meters (or 4.6 meters in some cases) to ensure their safe movement under overhead obstructions.

Figure 2.1: A truck hauls a massive 55-meter blade manufactured by Siemens

Source: Del Franco (2014)

When asked about physical challenges (including height-width clearance, weight limit restrictions, and any other physical obstacles) faced by the company in transporting wind turbine components on Texas roads, Mr. Ferebee from Lone Star Transportation responded that his company typically does not face any such issues as they survey routes beforehand. Further, they work closely with the state agency to plan and secure routing clearances. However, sometimes construction can change routing of a project, causing route interruptions. Likewise, Mr. Sutton from BNSF Logistics responded that his company generally does not face any unforeseen physical challenges, as their route survey process (completed beforehand) determines any pinch points, tight turns, bridges with weight limits, low clearances, etc., in routes that would impede the movement of freight. Mr. Sutton added that even after a permit has been issued for a specific route, the most common unforeseen challenge is related to some municipalities that are unwilling to allow transportation of large wind turbine freight through their communities. In addition, Ms. Iredale from Vestas stated that their transporters will occasionally face some unexpected physical issues along a route. However, she noted that she has never had an issue rerouting the delivery, and almost always delivers products to their sites on time.

2.3.2 Regulatory Challenges

Different states have varying permit rules for transportation of OS/OW loads on roads, which reduces the efficiency of freight transportation, according to the American Wind Energy Association (2015). The American Wind Energy Association (2015) also notes that streamlining the permit rules across different states can help reduce transportation time and cost.

When asked about this issue, Mr. Ferebee stated that while assigning equipment for the transportation of a particular component, Lone Star Transportation plans for the varying requirements of the different states. In regard to employing escort vehicles for transportation of wind turbine freight, Mr. Ferebee noted that escort vehicles can be difficult to secure depending on the market conditions. He further added that different states have varying requirements for use of escort vehicles for wind turbine components. When asked if his company faces any difficulties in obtaining a permit from the TxDMV to transport wind turbine components, Mr. Ferebee stated that Lone Star Transportation does not face any such issues. Ms. Iredale made a similar comment on the varying requirements for escort vehicles, stating that some states require more escorts than others for a given wind turbine component. However, she stated there is no shortage of escort vehicles to move her deliveries in Texas.

2.3.3 Shortage of Drivers

Another challenge in transportation of wind turbine components is a shortage of skilled drivers. Mr. Sutton from BNSF Logistics noted that the size and weight of wind turbine components create unique challenges for truck drivers, and hiring and retaining skilled drivers is paramount for the safety of wind turbine freight. He added that there is a shortage of these type of skilled drivers, and with an aging driver population, this issue will become more challenging in the future. Ms. Iredale shared his concern, commenting that there is a shortage of qualified drivers with the expertise and certifications required to move wind turbine components. She added that she has often had equipment that needed delivery, but no driver to transport it.

Del Franco (2014) states that "as the current crop of drivers grows older, there are fewer people choosing the profession." The article also states that according to the Professional Logistics Group, the average age of drivers who hauled heavy cargo was 50 years in 2004. The article further notes that as several of these drivers are now close to retirement, it has been challenging for transportation companies to attract new drivers as replacements, given the long hours of this occupation and the extensive amount of time drivers are away from home.

2.3.4 Increasing Size of Wind Turbine Components

As wind turbine components increase in size and weight, representatives from transportation companies such as Lone Star Transportation and BNSF Logistics stated that their companies need to purchase new equipment or retrofit the old equipment to handle the larger and heavier components. Mr. Ferebee noted that while the first wind turbine blades in the U.S. were about 13 meters (42.6 ft) long, the blades Lone Star Transportation moves today are up to 60 meters (196.8 ft) long.

Likewise, Mr. Sutton stated that the length and curvature of the wind turbine blades is increasing over time, and the nacelles are continuing to get heavier as the output of the machines increases. Elaborating further, he noted that in the recent past, most wind turbine blades were about 42 to 45 meters (137.8 to 147.6 ft) in length, but currently blades are in the 55 to 58 meter (180.4 to 190.2 ft) length range—and manufacturers are likely to produce blades in the 62 to 65 meter (203.4 to 213.3) length range in the future. Similarly, Ms. Iredale commented that wind turbine components are bigger, heavier, and longer each year. Currently, Vestas produces blades that are up to 57.5 meters (188.6 ft) in length. However, models with blades up to 62 meters (203.4 ft) will be available soon, she added. In addition, current nacelles sold by Vestas are as heavy as 75 tons, and require a 13-axle configuration to transport via truck. However, Ms. Iredale noted there is a push to increase nacelle size in her company; those heavier nacelles will require a 19-axle configuration.

2.3.5 Shipping Origin and Destination Points

Regarding origin and destination cities or towns for shipment of wind turbine freight in Texas, Mr. Sutton stated that most of the in-state components currently are being transported to West Texas for installation. He added that domestically manufactured components generally originate outside of Texas and their origin locations are dependent on the manufacturers' locations. Wind turbine components that are imported, such as blades and towers, are generally shipped into the gulf ports, including Galveston, Houston, and Corpus Christi. For Vestas, Ms. Iredale stated that their wind turbine components are shipped in from out of state. Either they are transported from their Colorado manufacturing facilities, or they are shipped into the ports from their overseas manufacturing facilities.

2.3.6 Emphasis on Railing

As the size of wind turbine components increases, it seems that some companies are transitioning from trucking these parts over long distances to transporting by rail. Mr. Ferebee noted that some components are now getting too large to transport by road. Mr. Sutton stated that that BNSF primarily uses rail as their means of transport, and Ms. Iredale emphasized that Vestas is "at the forefront of railing" wind turbine components, and uses rail as much as possible to transport their wind turbines. However, Vestas may be an exception rather than evidence of a trend. In *Windpower Monthly*, Holger Erdhart, a project manager at Siemens, stated that he "does not think that there is a trend towards using more rail than road" (Daubney, 2013), as it is only cost-effective when there is a large amount of equipment moving between two points. However, the article notes that Vestas claims rail can allow for significant cost and emissions reductions when compared to trucking.

2.4 Most Common Dimensions of Wind Turbine Components

The dimensions of wind turbine components vary depending on their manufacturers and model number. To understand the differences and commonalities among installed wind components, we decided to analyze data using the installed turbine data publicly available on the U.S. Geological Survey (USGS) website[5]. The USGS created this dataset using publicly available data, as well as searching for and identifying individual wind turbines using satellite imagery. The locations of all wind turbines, including the publicly available datasets, were visually verified with high-resolution remote imagery to within plus or minus 10 meters. Additional information on the dataset can be found in Diffendorfer et al. (2014).

After obtaining the USGS data, the research team cleaned it up and created a Texas subset using the 'subset' function of the software package R. After that, the team decided to use MS Excel and its functionalities such as filters, pivot tables, and VLOOKUP to obtain the desired result. The data contains information through July 2013. The analysis was performed based on installations generating around 11,000 MW in Texas with a total of 7,123 wind turbines installed. Appendix G contains information about the number of wind turbines manufactured by each company and turbine model.

2.4.1 Major Manufacturers

Figure 2.2 demonstrates that General Electric is a major manufacturer in Texas, trailed by Mitsubishi and thereafter Vestas. It is interesting to see that four companies dominate the Texas market in this regard, but many small companies do exist in the market (albeit with very small market share).

[5] Specifically, see http://energy.usgs.gov/OtherEnergy/WindEnergy.aspx#4312358-data

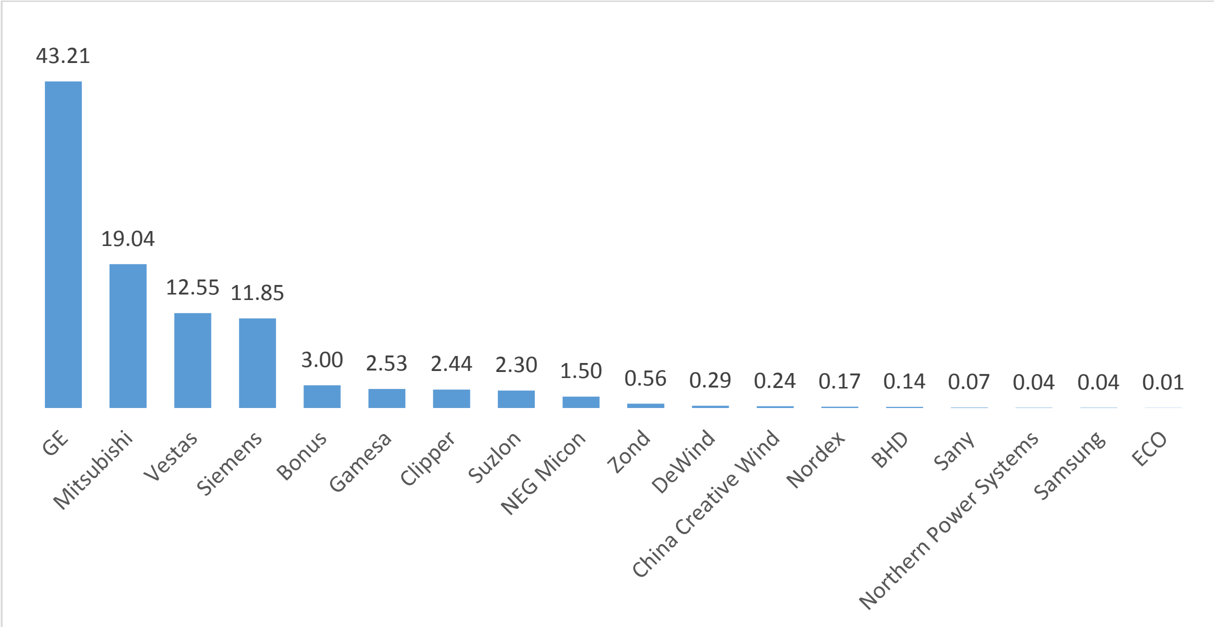


Figure 2.2: Total turbine installation percentage in Texas

2.4.2 Windmill Capacity

Figure 2.3 makes clear that most of the windmills installed have a power generation capacity of 1.5 MW. However, a considerable number of windmills have installation capacities of 1 MW and greater than 2 MW. According to our study of dimensional trends, we could very likely see a surge in the installation of windmills of higher capacity.

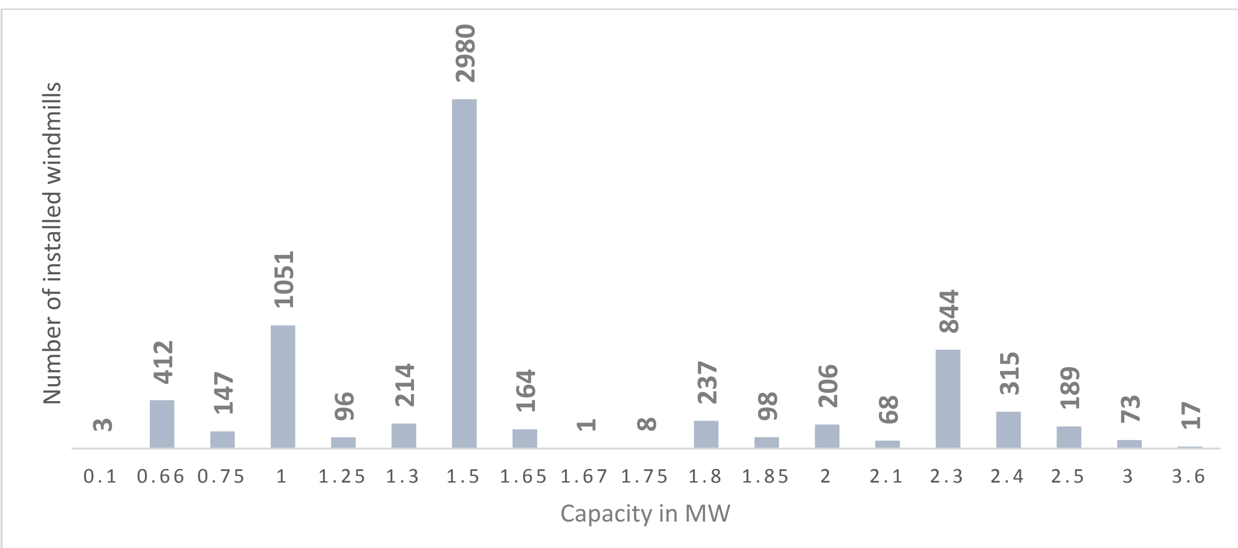


Figure 2.3: Windmill installations in terms of power-generating capacity

2.4.3 Tower Height and Blade Length

As Figures 2.4 and 2.5 indicate, the most common total windmill height is about 118 meters (387.1 ft), with a blade length of 38.5 meters (126.3 ft) and a tower height of 80 meters (262.5 ft). Most windmills have blade lengths of 38.5, 29.5, 45, 23, or 41 meters (126.3, 96.8, 147.6, 75.5, or 134.5 ft). Only a few windmills have blade lengths greater than 50 meters (164 ft).

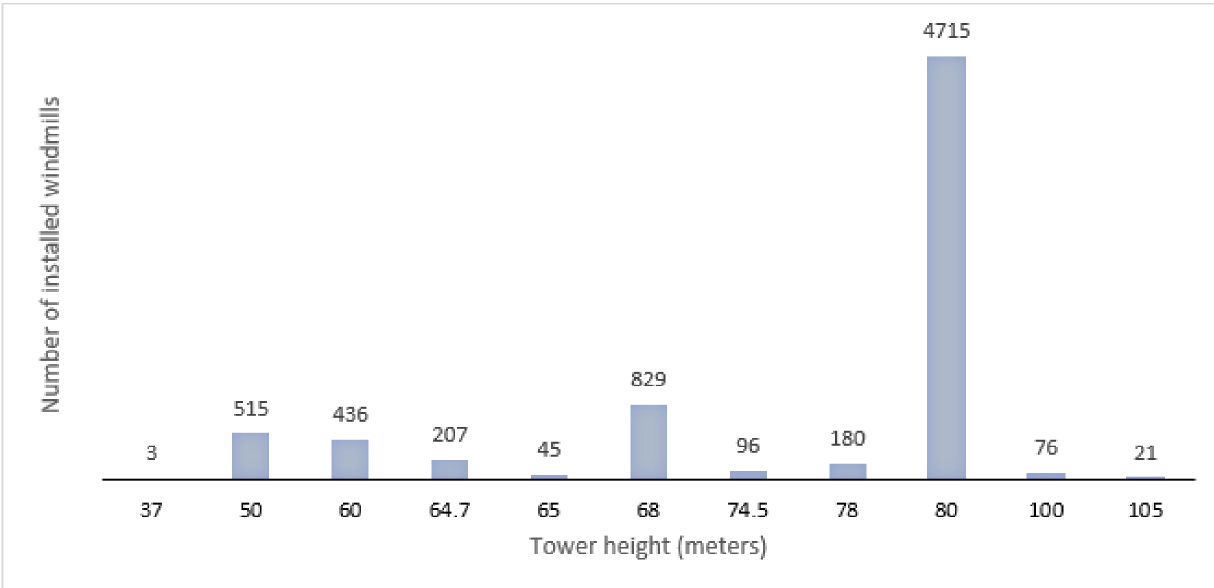


Figure 2.4: Number of installed windmills by tower height

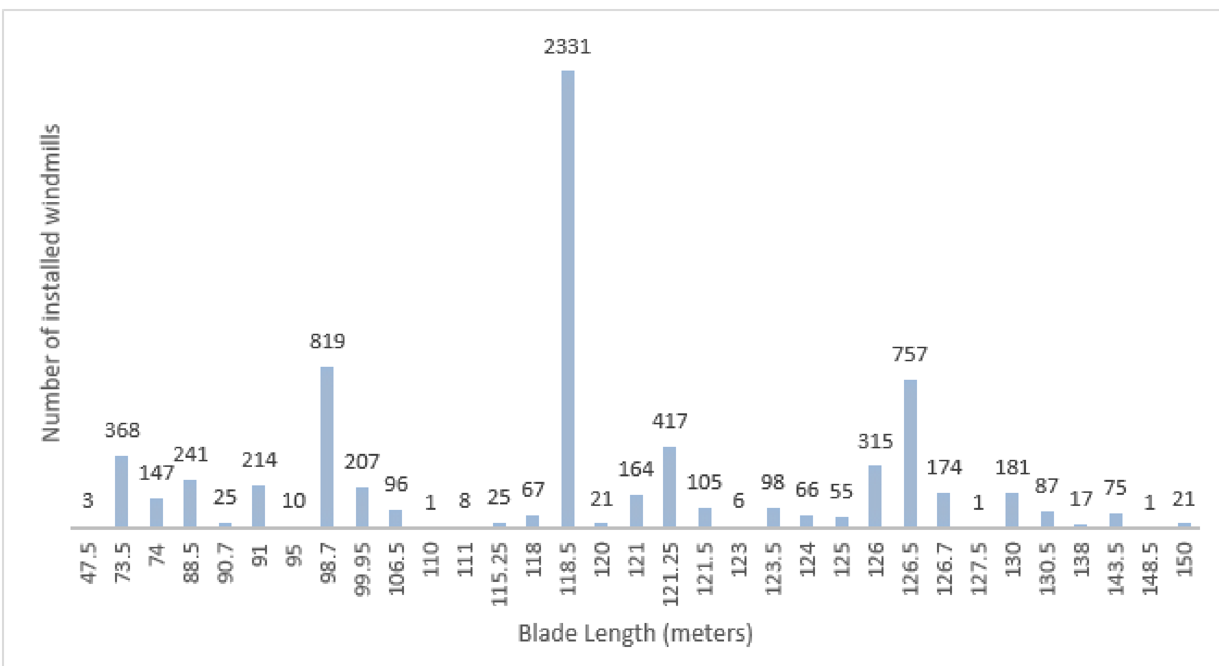


Figure 2.5: Number of windmills installed by blade length

2.4.4 Typical Dimension of Trucks Transporting Wind Component Load

Wind components—OS/OW in nature—must be carried by special vehicles. In all, seven rigs are needed to deliver a typical turbine parts. This equipment includes three tower parts (main, top, and midsection); a nacelle containing turbine generators, the gear box, and electrical apparatus; and three long blades. According to a previous study for TxDOT titled *Impacts of Energy Development on the Texas Transportation System infrastructure* (Grebenschikov et al., 2011), transporting companies typically use a Schnabel and steering dolly combination to move the tower components. A 13-axle trailer is used to transport the nacelle. These weights are typical for the 1.5MW windmill that predominates in Texas. Table 2.1 shows the aforementioned windmill transporting truck vehicle types, dimensions, and weights.

Table 2.1: Special vehicles used for windmill component transportation

Vehicle	Component	Width	Length	Height	Weight (lbs)
13-Axle Schnabel with 6-Axle Steerable Dolly	Tower, Main Section	15'1"	177'	15'8"-16'4"	232,000
11-Axle Schnabel with 6-Axle Steerable Dolly	Tower, Midsection	15'1"	159'11"	15'8"-16'4"	199,000
Schnabel Dolly	Tower, Midsection	14'2"	122'	14'6"	128,800
5-Axle Stretch Lowboy	Tower, Midsection	14'2"	104'	17'4"	112,000
Dolly Trailer	Tower, Top Section	11'6"	124'	14'2"	91,000
13-Axle Trailer	Nacelle	12'6"	120'6"	14'6"	218,000
Specialized Blade Trailer	Blade	8'6"	175'	14'6"	78,000
Double Drop Trailer	Hub/Rotor	11'2"	50'	14'	85,000

Source: Grebenschikov et al. (2011)

In addition to these details, Appendix F contains the details of the fleet used for OS/OW loads by Lone Star Transportation. Figure F.1 illustrates the typology of vehicles involved in wind component transportation.

2.5 Analysis of the Future of Wind Turbine Design

The past decades have seen important advances in the technologies involved in wind-based energy generation. Since 1980, there has been a consistent annual increase of 5% in the energy yield of the turbines due to technology evolution (Herbert et al., 2007). Improvements in materials, aerodynamics, and the overall structural design of rotors and towers, together with enhancements of the electrical generators and advancements in meteorological studies, allowed this overall increase in the efficiency of wind power generation.

2.5.1 Technology Overview

Three-bladed rotors on a horizontal axis are currently the predominant wind turbine technology used for electricity generation. This design was established in the 1980s and has proven to be the most efficient option for large-scale energy production. Other options that were considered included single-bladed and double-bladed machines. Many authors point out that the decisive factor in eliminating one- and two-bladed wind turbines from the commercial market has been the visual impact (Kaldellis and Zafirkas, 2011; Islam et al., 2013). However, there is a tradeoff between aerodynamic efficiency and energy return given by the number of blades: increasing the number of blades enhances the aerodynamic efficiency of the rotor but diminishes the return. From one to two blades the efficiency increases by 6%, though from two to three there is an addition of only 3%. The single-bladed design is the most structurally efficient and gives the highest return because it allows for the largest blade section dimension, since all the installed blade surface area is in a single beam. However, this type of blade requires a counterweight to balance the rotor statically, which reduces the efficiency and creates complex dynamics for the blade hinge to relieve loads. The two-bladed rotors also have two disadvantages. First, when the blades are vertical, the forces required to yaw the rotor are low, but when the blades are horizontal, the forces are much higher. The cyclic forces impose significant stresses on several parts of the structure, causing fatigue faster. These forces are much lower when a three-blade machine is yawed, as the asymmetric forces encountered as the rotor rotates are much smaller. The second reason why two-blade designs fell out of favor is that they need to rotate faster than a three-bladed rotor to realize peak efficiency, which creates much more noise.

Another technology available is the vertical axis wind turbine. This type of wind turbine is not used in large-scale energy generations and little research has been done in the past decades to improve its efficiency. Nevertheless, Howell et al. (2010) point out that vertical axis wind turbines do have some substantial advantages over the horizontal axis ones. They do not need to constantly yaw into the local wind direction; they capture wind in any direction, which makes them adaptable to more complex terrains. Due to lower rotational speed, they are also quieter than the vertical axis turbines and therefore can be located within urban areas. Finally, they are also mechanically better able to withstand higher winds through changing stalling behavior, offering a potential operational safety advantage during gust conditions. All these characteristics make this technology appropriate for small-scale in-locus power generation, which may become a trend in self-sustaining residences (Müller et al., 2009; Ishugah et al., 2014).

The basic components of the horizontal axis wind turbine are the rotor, which has wing-shaped blades attached to a hub; a nacelle that houses the drivetrain, the gearbox, the generator, and the control system; and a tower (in addition to the electrical equipment). Regarding transportation, the blades are of special relevance because they are a single, long piece and therefore constitute an oversized load. The same can be said about the tower, but the transport of towers can be a little more flexible depending on the technology used. The nacelles, on the other hand, are not necessarily oversized, but overweight, which also generates challenges for transportation.

The operation of the horizontal axis turbines has implications regarding technology and sizes. These types of turbines can capture only a portion of the wind energy when the wind speeds increase beyond the power level for which the electrical system was designed (the rated power). The turbine power output is controlled by rotating the blades around their long axis to change the angle of attack with respect to the relative wind as the blades spin around the rotor hub (control of the blade pitch). The turbine is pointed into the wind by rotating the nacelle around the tower (control of the yaw). Wind sensors on the nacelle tell the yaw controller where to point the turbine. These wind sensors, along with sensors on the generator and drivetrain, also tell the blade pitch controller how to regulate the power output and rotor speed to prevent overloading the structural components. Therefore, the smaller the variation in wind speeds and direction, the greater the efficiency of the system. Generally, a turbine will start producing power in winds of about 5.36 m/s (17.5 ft/s) and reach maximum power output at about 12.52 m/s–13.41 m/s (41.7 ft/s–43.9

ft/s). The turbine will feather the blades to stop power production and rotation at about 22.35 m/s (73.3 ft/s). Most utility-scale turbines are upwind machines, meaning that they operate with the blades upwind of the tower to avoid the blockage created by the tower (U.S. Department of Energy, 2008).

2.5.2 Evolution of Sizes

The sizes of the wind turbines have increased significantly over the past decades, for both technical and economic reasons. According to aerodynamic properties, the power output of a wind turbine is proportional to the square of the rotor diameter and the cube (third power) of the wind speed. Besides, wind is less turbulent and reaches higher speeds far from the ground (the increase in wind speed with elevation is referred to as *wind shear*), which means that both an increase in the rotor diameter and in the tower height can increase the energy yield of the turbine. From the cost perspective, bigger components generate more energy and also have a lower ratio of installation and maintenance cost per unit of energy produced, allowing for economies of scale and faster return on investment. Indeed, a review conducted by Kaldellis and Zafirakis (2011) shows that reducing the turnkey cost of wind energy installation was fundamental in making this technology competitive against other energy sources.

The turbine capacity has increased from 50 kW in 1980 to 7.5 MW in 2010, while the rotor diameters went from 15 meters to 126 (Yaramasu et al., 2015) (49.2 to 413.4 ft), as illustrated in Figure 2.6. Today, the largest land-based wind turbine available in the market is the Enercon E126, which has a rated capacity of 7.5 MW. This turbine has a 135m (442 ft) concrete tower and a rotor with a diameter of 127 meters (416.6 ft). There is an even larger wind turbine available for offshore locations, the Vestas V164, which has a rated capacity of 8.0 MW and a rotor diameter of 164 meters (538.1 ft). There are also at least five companies working on projects to design 10MW offshore wind turbines.

Indeed, the development and expansion of offshore turbines is another important driving force behind this growth in the size of wind turbines. Yaramasu et al. (2015) report that a market survey indicates that nowadays the average rotor diameter and power ratings of offshore wind turbines are higher compared to the onshore wind turbines. In 2013, the average capacities of onshore and offshore wind turbines were reported as 1.93 and 3.61 MW, respectively. These numbers may increase, since the most frequent capacities of the turbines being installed nowadays are around 2 to 3 MW onshore and 4 to 6 MW offshore (EWEA, 2015).

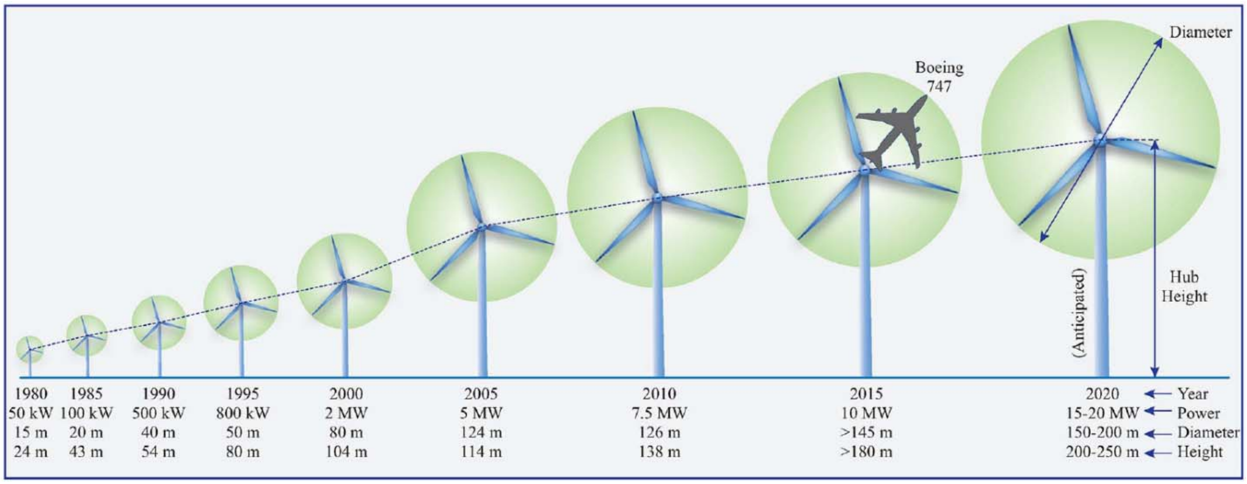


Figure 2.6: Growth in size and capacity of wind turbines since 1980

Source: Yaramasu et al., 2015

Texas trends

Texas is by far the leading U.S. state in wind energy generation. That standing was achieved through consistent investments; new wind farms or expansions of old wind farms have been initiated almost every year since 1999. Following the technological evolution, wind turbines installed in Texas have also increased in size and capacity through the years, as shown in Figures 2.7 to 2.10 and Table 2.2. Currently, the largest and most powerful wind turbines installed in this state are 3.6 MW, with a tower height of 138 meters (452.8 ft) and rotors 116 meters (380.5 ft) in diameter. They were installed in 2012 in Lynn County. Although the figures show a clear increase in component sizes in the past decades, the sizes seem to be stabilizing over the past five years. In the past two years, the sizes of wind turbines installed have decreased noticeably. Further investigation is necessary to determine the specific reasons for such reduction.

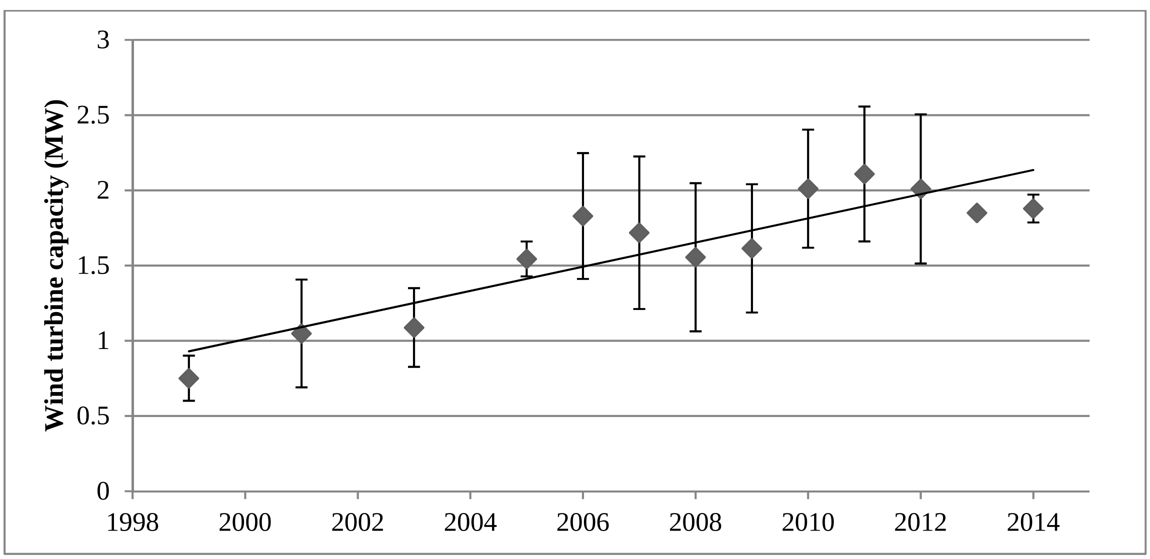


Figure 2.7: Evolution of turbine capacities installed in Texas

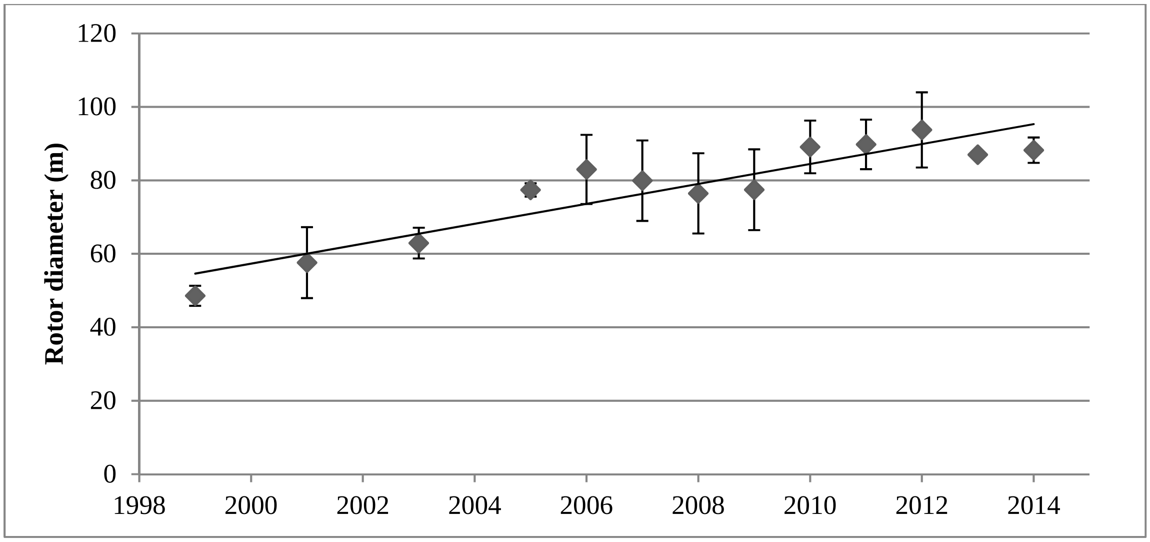


Figure 2.8: Evolution of rotor diameters of turbines installed in Texas

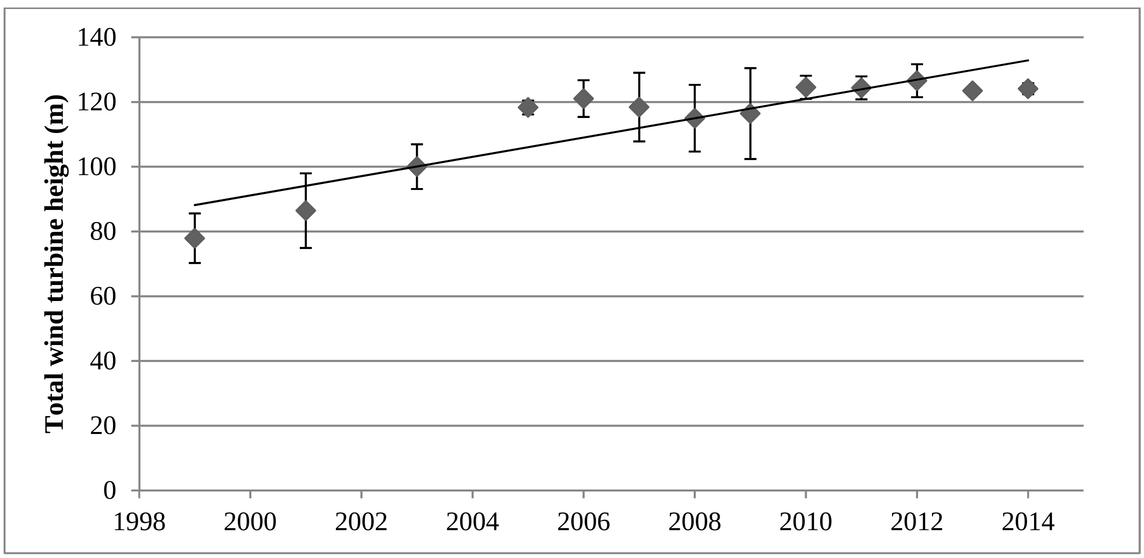


Figure 2.9: Evolution of wind turbine total heights

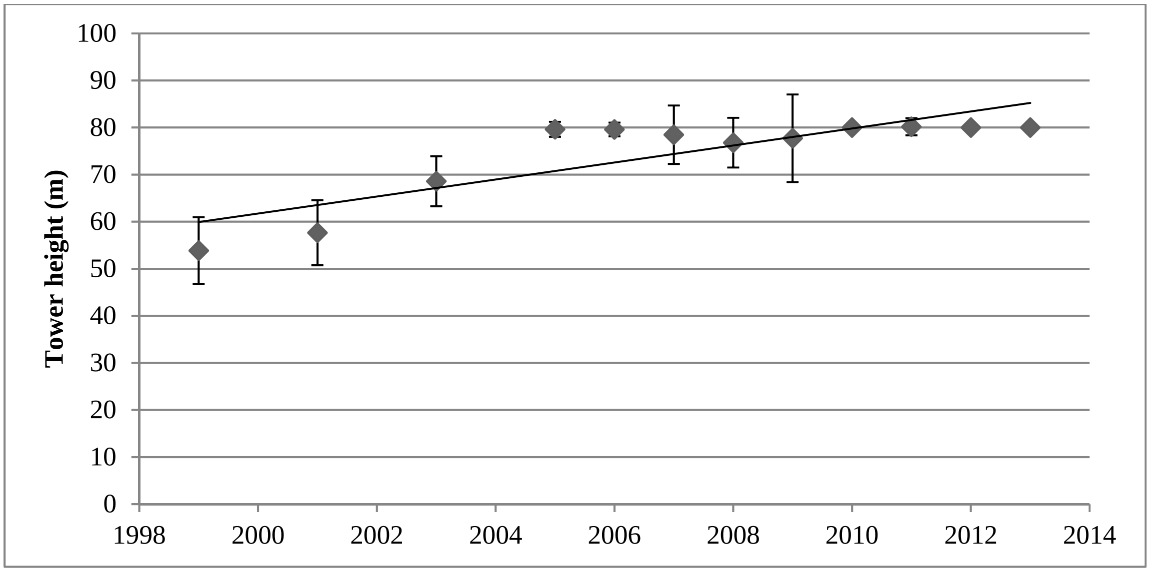


Figure 2.10: Evolution of tower heights

Table 2.2: Evolution of sizes of wind turbines installed in Texas

Year	No. of turbines	Capacity (MW)		Rotor diameter (m)		Tower height (m)		Total height (m)	
		Average	Std. Dev	Average	Std. Dev	Average	Std. Dev	Average	Std. Dev
1999	193	0.75	0.150	48.57	2.727	53.84	7.102	77.92	7.664
2001	870	1.05	0.358	57.61	9.661	57.65	6.917	86.45	11.533
2003	187	1.09	0.262	62.92	4.183	68.58	5.318	100.04	6.910
2005	438	1.54	0.116	77.39	1.811	79.63	1.589	118.32	2.152
2006	420	1.83	0.418	82.98	9.415	79.58	1.459	121.07	5.678
2007	808	1.72	0.507	79.91	10.948	78.48	6.206	118.44	10.594
2008	1813	1.56	0.492	76.45	10.923	76.78	5.287	114.99	10.306
2009	1199	1.61	0.426	77.45	11.007	77.72	9.303	116.44	14.035
2010	476	2.01	0.392	89.09	7.176	80.00	0.000	124.55	3.588
2011	118	2.11	0.448	89.79	6.747	80.17	1.833	124.38	3.543
2012	423	2.01	0.496	93.73	10.230	80.00	0.000	126.59	5.083
2013	98	1.85	0.000	87.00	0.000	80.00	0.000	123.50	0.000
2014	134	1.88	0.092	88.22	3.456	80.00	0.000	124.11	1.728

2.5.3 Future Trends

Scaling up turbines to lower costs has been effective so far, but it is not clear if the trend can continue indefinitely, especially for onshore applications (IEA, 2013). Although E126 is a 7.5MW onshore wind turbine already available on the market, many in the field do not expect turbines with diameters exceeding 100 meters (328.1 ft) to become popular for inland applications due to logistics, transportation, and assembly limitations (see Thresher et al., 2007; U. S. Department of Energy, 2008; Gardner et al., 2009). For example, Thresher et al. (2007) argues that cranes with large lifting capacities are difficult to transport, require large crews, and therefore have high operation, mobilization, and demobilization costs. The authors also mention that concepts such as on-site manufacturing and segmented blades are also being explored to help reduce transportation costs. It may be possible to segment molds and move them into temporary buildings close to the site of a major wind installation so that the blades can be made near or at the site.

Another important limitation of onshore wind farms is space, since horizontal wind turbines must be spaced a significant distance from each other. This aerodynamic constraint limits the amount of power that can be extracted from a given wind farm footprint. Generally, to maintain 90% of the performance of isolated horizontal axis wind turbines, the turbines must be spaced 3–5 turbine diameters apart in the cross-wind direction and 6–10 turbine diameters apart in the downwind direction (Islam et al., 2013). On the other hand, space is not usually an issue in offshore wind farms, and for this type of application, the market trend indicates that 10–20 MW turbines will be operational in near future with rotor diameters exceeding 150 meters (492.1 ft) (Yaramasu et al., 2015).

In a review of the evolution of wind turbines as electric power generators, Kaldellis and Zafirkas (2011) present future tendencies and needs of the field. For onshore turbines, they point to the need for reduction in overall costs, the need for better spatial planning in terms of social and environmental conditions, and more sophisticated assessment of wind resources. They also mention the need for improvements in design and reliability.

At present, onshore wind farms are more economical than developments offshore. Offshore wind farms take longer to develop, as the sea is inherently a more hostile environment. However, in the coming years, as offshore turbines are manufactured on a larger scale, prices will come down, making offshore wind energy increasingly competitive (EWEA, 2015). If offshore installations increase, two-bladed wind turbines may resurge, since their lighter weight makes installation easier and the offshore location eliminates noise concerns. Besides, the ocean’s flat surface provides the turbines with less turbulent wind, which is an important aspect when considering increases in efficiency.

As technology evolves, the current wind turbine configurations are expected to become more efficient and produce more energy, leading to a permanent stabilization of sizes, especially for onshore applications. For future trends in electric efficiency, see Yaramasu et al. (2015) for a comprehensive review of wind energy technologies from the electrical engineering perspective. As mentioned in the previous section, in the past two years there was a small decrease in the size of the installed wind turbines in Texas. Further investigation is necessary in order to identify the reasons behind the choice of smaller units and to determine whether this trend will continue. Interestingly, the survey results point to the opposite direction, indicating that the transportation companies assume a future increase in size and capacity of the wind turbines to be installed in Texas.

Regarding possible changes in technology, Islam et al. (2013) mention that one possible trend for inland wind farms could be the use of vertical axis wind turbines. According to those authors, vertical axis wind turbines could potentially produce more than 10 times the energy on the same land area than conventional turbines, as vertical axis turbines can be placed closer together. As mentioned earlier, small vertical axis wind turbines may also become a feature in urban environments for self-sufficient buildings. Another recently proposed technology is the vortex bladeless wind turbine. This technology relies on an aerodynamic phenomenon called *vorticity*, in which the wind flowing around a structure creates a pattern of small vortices or whirlwinds that cause the structure to oscillate. The idea is to capture the kinetic energy from this oscillation and convert it into electricity. Although those bladeless turbines may revolutionize inland wind power generation, this technology is still far from becoming a reality and will not reach the market in the next decade.

2.5.4 Guidelines for Future Scenarios

In the next step of the project, the research team developed scenarios of future wind turbine transportation demand in Texas. The present literature review indicates that the important aspects to consider in establishing these scenarios include the following: common sizes and capacities installed in the past five years; current wind turbine sizes available in the market; wind turbines under development by manufacturing companies (especially the most frequent Texas suppliers); location of the future wind farms; available area and topography of the future wind farms; and access to the wind farms.

Chapter 3. Parameters of Importance for the Classification of OS/OW loads

In this next chapter we present a review of all the parameters that TxDOT is currently considering to evaluate and regulate the transportation of OS/OW loads across Texas roads. While the Texas Department of Motor Vehicles (DMV) issues OS/OW permits and administers the website detailing the OS/OW regulations, TxDOT continues to be the agency that specifies the regulations.

Of course, the transportation of heavy and large loads can cause damage to roadside signs, signals, markings, bridges, and tunnels. Heavy loads also damage bridges and reduce pavement life. Overall, the transportation of wind turbine components (or huge and large loads in general) not only raises safety concerns, but also leads to the need for expensive repair work. We also searched the literature for models and empirical relationships between pavement damage and the characteristics and dimensions of loads and trucks. These relationships are used in our tool to predict the pavement damage based on the characteristics of the road and the dimensions of the trucks and loads.

3.1 Parameters Review for OS/OW Load Permits

Vehicles that carry loads exceeding legal size and weight limits must obtain OS/OW permits. Tables 3.1 and 3.2 present the maximum size and weight limits for operating *without* a permit.

Table 3.1: Maximum size limits for movement without Texas OS/OW permit

Width Limit	
Maximum width permitted on holidays	14 feet, except for manufactured housing
Maximum width permitted on controlled access highways (Interstate Highway System)	16 feet, except for manufactured housing
Maximum width permitted without a route inspection certification by applicant on file	20 feet
Height Limits	
Maximum height permitted on holidays	16 feet
Maximum height permitted without a route inspection certification by applicant on file	18 feet, 11 inches
Length Limits	
Truck or single vehicle	75 feet
Front overhang	25 feet
Rear overhang	30 feet
Maximum length permitted without a route inspection certification by applicant on file	125 feet

Table 3.2: Maximum weight limits for movement without Texas OS/OW permit

Axle Group	Maximum
Single	25,000 pounds
Tandem (two axle)	46,000 pounds
Tridem (three axle)	60,000 pounds
Quadrem (four axle)	70,000 pounds
Quint (five axle)	81,400 pounds
Six or more axles	Determined by the Texas Motor Carrier Division based on an engineering study of the equipment and measurements.

The maximum non-OS/OW permit weight for an axle or axle group is based on 650 pounds per inch of tire width or the following axle or axle group weight, whichever is the lower limit.

- An axle group must have a minimum spacing of four feet between axles within the group.
- Weight may not exceed the manufacturer's rated tire carrying capacity.
- The weight of two or more consecutive axle groups with an axle spacing of less than 12 feet between groups will be reduced by 2.5% for each foot less than 12 feet.
- The weight for an axle group should be distributed equally between axles in the group to not allow more than a 10% weight difference between any two axles in the group.

OS/OW permits are assigned in the form of a fixed route using the Texas Permit Routing Optimization System (TxPROS) tool, which is available on the TxDMV website. This tool makes available a variety of permit types, so that the correct permit type can be obtained for the many types of routes, loads, and truck configurations. Some examples include General Single-Trip, House Move, Multi-State, Self-Propelled Off Road Equipment, etc.[6] Generally, wind components being transported within Texas take the General Single-Trip permit; if the load is meant to travel through more than one state, a multi-state permit is needed.

TxDMV issues a single-trip permit for the movement of non-divisible vehicles and/or loads exceeding legal Texas size and **gross weight** limits up to 254,300 pounds. Single-trip permits may be used for only one movement, during the times specified on the permit, from a specific point of origin to a specific destination. A vehicle **width** greater than 20 feet, **height** of more than 18 feet 11 inches, and **length** beyond 125 feet requires a route inspection certificate prior to permit issuance. Additionally, TxDMV issues a super-heavy single-trip permit if loads exceed 254,300 pounds in total gross weight or exceed the maximum permit weights on any axle or axle group or exceed 200,000 pounds with less than 95 feet of **axle spacing**.

For multi-state routes, TxDMV issues multi-state, single-trip permits under the Western Regional Permitting Agreement, as enacted by the Western Association of Highways and Transportation Officials (WASHTO). Other member states are Arizona, Idaho, Montana, Oregon, Utah, Washington, New Mexico, Colorado, Oklahoma, Louisiana, and Nevada. Under this agreement, each participating state may issue regional permits allowing operations in other member states. However, these permits involve additional restrictions, as other states have their

[6] For details, please refer to http://www.txdmv.gov/motor-carriers/oversize-overweight-permits

own restrictions on weight, size, and other parameters that can differ from those in Texas. For example, some additional parameters for routing decisions involve **curfew hours**, escort requirements, and other permit conditions that must accompany permit. (Appendix A lists the Texas requirements that other WASHTO states must accommodate.) For example, in Oklahoma, no OS loads can pass through Oklahoma and Tulsa Counties between 7:00 and 9:00 a.m. and 4:00 to 6:30 p.m., except on Saturday and Sunday. Texas has curfew hours between 7:00 and 9:00 a.m. and 4:00 to 6:00 p.m. in Beaumont, Lubbock, San Antonio, Vidor, and Tarrant County, while Houston's curfew is between 6:00 and 9:00 a.m. and 4:00 to 7:00 p.m. Therefore, routing a load originating from the Port of Houston to Oklahoma will have to accommodate these curfew hours. These kinds of permits can be used for only one movement, during the times mentioned on the permit (not to exceed five working days), from a specific point of origin to a specific destination. Permits are also issued for non-divisible loads.[7]

Vehicles whose dimensions and weights exceed the specifications listed in Figure 3.1 are characterized as OS/OW under the Western Regional Permitting Agreement. Appendix H provides the Western Regional Vehicle Weight Table.

Size

- Width – 14'
- Height – 14'
- Length:
  - 110' overall. Semitrailers longer than 53' may not carrier more than one item and may not be operated in a truck-tractor and semitrailer combination.
  - In Oregon, an unladen combination of vehicles may consist of the towing or power unit and not more than one jeep, one semitrailer and one booster, provided semitrailer length is not more than 62'. Movement is authorized unladen with fewer vehicles, or with the jeep and/or booster loaded on the semitrailer. However, the absence of both the jeep and the booster (carried as load or in use) invalidates this provision.

Weight

- 600 pounds per inch of tire width
- 21,500 pounds per axle
- 43,000 pounds per tandem axle
- 53,000 pounds per tridem (wheelbase more than 8' and less than 13')
- 160,000 pounds gross weight
- In no case may the gross weight exceed the sum of the permitted axle, group axle weights or the weight specified by the permit, whichever is less.
- A minimum of five axles
- The weight on any group of axles shall be determined by the Western Regional Vehicle Weight Table.

Figure 3.1: Size and weight requirements for multi-state permits

Source: TxDMV, 2015

[7] The restrictions for multi-state permits are available at http://www.txdmv.gov/component/k2/item/2189-multi-state-washto-permit-conditions.

Apart from these restrictions, many other types of user-provided information are used for route decisions. The permit applicant has to enter **permit type** and **start date of the permit** at the start of this process. After that, vehicle information has to be provided, such as year, make, and registration. Details such as load description and industry category are also provided. These load parameters are considered in issuing permits: **load width**, **height**, **loaded length**, **trailer length, loaded front hang, loaded rear hang, divisibility of loads, ground clearance of trailer, availability of hydraulic lift, and loaded gross weights.** Once this information is entered, the software directs the applicant to enter **spacing** and **weight information** for each axle, as well as the number of axles, number of tires, tire widths, and details about the first axle (such whether it is steering, articulated, or fixed). After this, for route determination, applicants enter their **origin** and **destination**. This locational information can be entered in four different forms: a) an address, b) the intersection of two streets, c) a latitude/longitude pair, and d) border crossing. The applicant can specify desired route alignment by providing **via points, cities,** or routes over **specified roadways**. The permit applicants can also split the route, add a leg to the route for obtaining the trailer to be loaded, or add a trip to return the unloaded trailer. Based on all these variables, TxPROS generates detailed driving directions with instructions and restrictions.

3.2 The Current Strategy for Routing the OS/OW Loads across Texas

The routing decisions of OS/OW loads are influenced by a number of factors, such as (a) vertical clearance, (b) horizontal clearance, (c) bridge structure strength, (d) pavement structure strength, (e) seasonal restriction, and (f) roadway geometry (e.g., radius of curvature). One critical factor in assigning the route is bridge structure strength, which in turn is influenced by the bridge's condition, including extent of any damage, its own dead load, and live (traffic) load. To assess a bridge's safety, the intended OS/OW permit vehicles are used as the live load variable in the route assignment calculations. The calculations also draw on data from bridge weigh-in-motion (WIM) systems. Using strain transducers or gauges attached to bridges or embedded in bridge decks, the WIM system provides information on axle and gross weight, axle spacing, and speed and position for commercial motor vehicles.

The movement of OS/OW loads may require additional traffic control or assistance from transportation/law enforcement personnel. This may in turn lead to lane closures, route diversions, etc., to accommodate permitted vehicles. To coordinate network interruptions, agencies can use technologies such as GPS (to track speed and location) and vehicle-mounted transponders (for unique identification). As described earlier, TxDMV uses a web-based, integrated, GIS-based mapping system with real-time restriction management (TxPROS) to issue permits. TxPROS reduces the time required to issue OS/OW permits, improves public safety, improves TxDOT's knowledge of structures and restrictions affecting OS/OW load passage, and optimizes the routes. TxPROS was designed with these features:

1. Real-time restriction management
2. Automated multiple optimal path routing of OS/OW loads
3. Ability to interface with supporting TxDOT and non-TxDOT information systems
4. Reporting, tracking, and statistical analytic capabilities

As the previous section describes, the TxPROS routing operation provides a variety of user input options and error-correcting features. The TxPROS routing algorithm uses a modified dual

Dijkstra routing algorithm on directed and reverse graphs. Generally, the transportation network is represented in the form of links and nodes that represent roads and intersections. TxPROS directed and reverse graphs have about 4.3 million edges and 3.4 million vertices.

3.3 Pavement Damage

As we mentioned earlier, pavement damage is one of the main effects of the transportation of wind turbine components. We need to find a way to estimate pavement damage using the elements that will serve as input in our tool (such as characteristics of the roads, dimensions of the trucks or dimensions of the loads). It is not too difficult to determine a wheel or an axle load for an individual vehicle, but it is complicated to determine the number and types of wheel/axle loads that a particular pavement will be subject to over its design life. The most common approach we found in the literature is to convert damage from wheel loads of various magnitudes and repetitions to damage from an equivalent number of "standard" or "equivalent" loads. The most commonly used equivalent load in the U.S. is the 18,000 lb (80 kN) equivalent single axle load (normally designated ESAL). There are two standard U.S. ESAL equations (one each for flexible and rigid pavements) that are derived from American Association of State Highway and Transportation Officials (AASHTO) Road Test results. Both these equations involve the same basic form, but the exponents are slightly different. In the next paragraphs we will explain in detail these two formulas.

Pavement damage caused by varying truck axle group types and load weights can be measured in terms of a load equivalency factor (LEF). Smith and Diefenderfer (2009) state that the LEF of a specific axle and weight configuration is defined as the ratio of the damage caused by one pass of a given axle compared to the pavement damage caused by one pass of a standard 18,000-pound single-axle load that has dual tires on each side. The impact of a given axle load on pavement depends on the pavement's structural properties. The value of LEF computed for a given axle group depends on pavement characteristics, including the type of pavement (flexible or rigid), pavement terminal serviceability index, and axle group type and load.

Summing the LEF values for each axle indicates the total pavement damage caused by one pass of that truck. This summation of LEF from each axle is also referred to as the number of equivalent single-axle loads (ESAL) of the vehicle. Team (1995) notes that an 18,000-pound single-axle load is considered to be one ESAL. A vehicle's ESAL value indicates the amount of pavement damage it causes relative to an 18,000-pound single-axle load. For example, Team (1995) notes that a three-ESAL value for a given vehicle on a specific type of pavement indicates that the impact of one pass by the vehicle is the same as that of three passes by an 18,000-pound single-axle load. Figure 3.2 provides Team's (1995) ESAL values for various truck configurations.

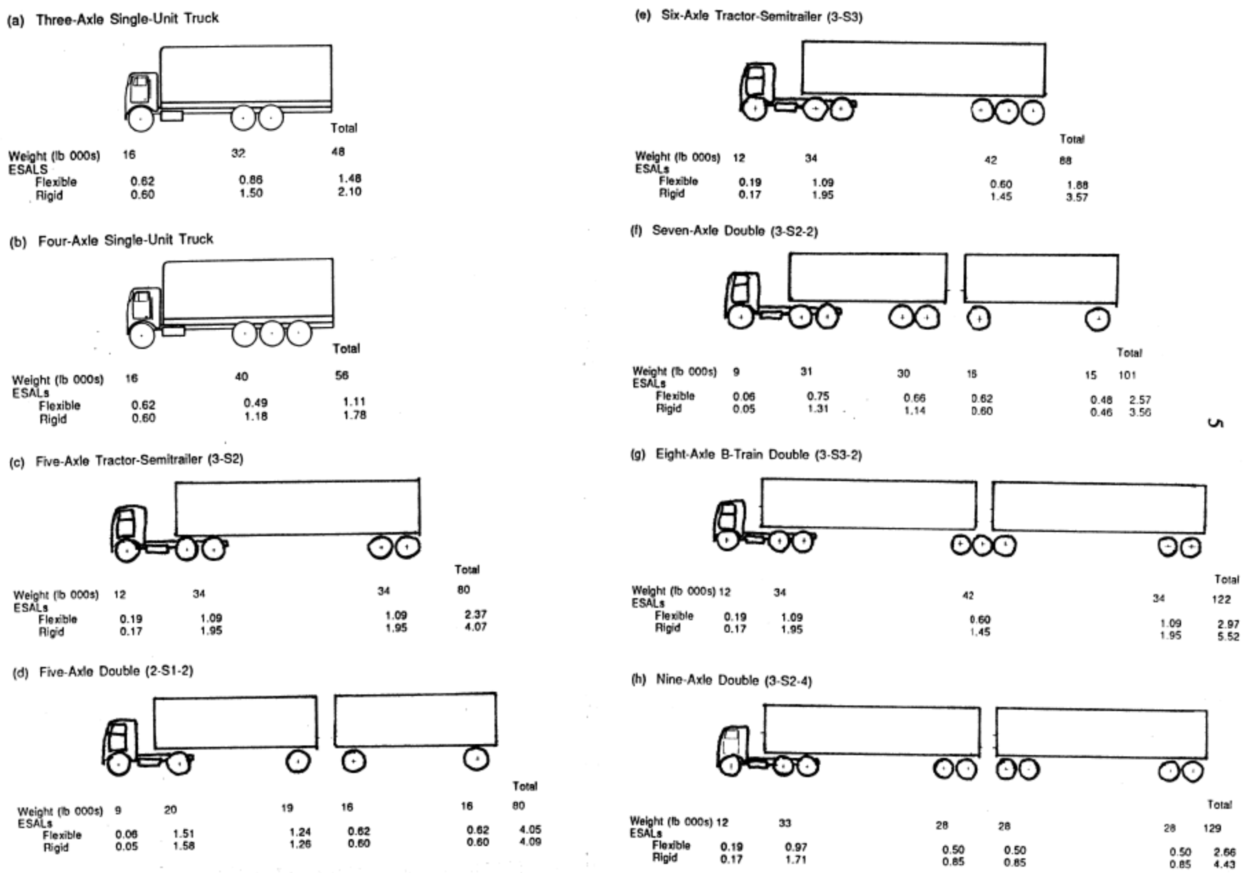


Figure 3.2: ESAL values for various trucks

Source: Team (1995)

In the next sections we describe the relationship we will use to compute the pavement damage (translated in LEF values) for the two types of pavements: flexible pavement and rigid pavement. All hard road pavements usually fall into these two broad categories.

3.3.1 Flexible Pavement

Flexible pavements are those which reflect the deformation of subgrade and the subsequent layers to the surface. Flexible, usually asphalt, is laid with no reinforcement or with a specialized fabric reinforcement that permits limited flow or repositioning of the roadbed underground changes. For flexible pavement, according to Smith and Diefenderfer (2009), the following equations (Equation 3.1–3.3) can be used to compute the LEF value for each truck axle, which is calculated using the weight and axle spacing, the pavement structural number (SN), and terminal serviceability level.

$$\text{LEF} = \log\left(\frac{W_{tx}}{W_{t18}}\right) = 4.79\log(18+1) - 4.79\log(L_x + L_2) + 4.33\log(L_2) + \frac{G_t}{\beta_x} - \frac{G_t}{\beta_{18}} \quad (3.1)$$

$$G_t = log\frac{(4.2 - p_t)}{(4.2-1.5)} \quad (3.2)$$

$$\beta 081\ (L_x + L_2)3.23(SN+1)^{5.19}\ L_2^{3.23} \quad (3.3)$$

where

W_{tx} = number of applications of given axle
W_{t18} = number of standard axle passes (single 18-kip axle)
L_x = load in kips of axle group
L_2 = axle code (1 for single axle, 2 for tandem axles, 3 for tridem axles, and 4 for quad axles)
β_{18}= value of β_x when $L_x = 18$ and $L_2 = 1$
p_t =terminal serviceability index
SN = structural number

Smith and Diefenderfer (2009) note that the equations are from Huang (2004), and are based on formulas provided in the 1993 AASHTO *Guide for Design of Pavement Structures*. The values of G_t and β_x computed in Equations 3.2 and 3.3 depend on the pavement terminal serviceability index (p_t) and the SN, which are then inputted into Equation 3.1 to compute *Wt18*/*Wtx*, which is the LEF for an axle group. The Massachusetts Highway Department's *Project Development and Design Guide* (2006) defines terminal serviceability index (p_t) as a pavement design factor that indicates the acceptable pavement serviceability index (measure of a pavement's ability to handle traffic on a scale of 0 to 5) at the end of the design period. The Design Guide defines SN as a measure of the structural strength of the pavement based on the type and thickness of each layer within its structure. Both terminal serviceability index and SN could be determined for Texas roads using the Pavement Management Information System (PMIS) (see TxDOT, 2014).

The summation of each axle group's LEF on a specific truck would be the ESAL value for that truck. Smith and Diefenderfer (2009) note that compared to the type and weight of axle groups, the pavement terminal serviceability and the SN have a small effect on the LEF value. They further note that a "single axle" is defined as an axle located at a distance less than 3.33 feet or greater than 8 feet from an adjacent axle. A "tandem axle" indicates two adjacent axles with a spacing of 3.33 to 8 feet. A "tridem axle" indicates three axles with a spacing of less than 12 feet between the first and the third axle. A "quad axle" is defined as four axles with a spacing of less than 16 feet between the first and the fourth axle.

3.3.2 Rigid Pavement

The rigid characteristics of pavement are associated with rigidity or flexural strength or slab action so the load is distributed over a wide area of subgrade soil. The rigid pavements are made of cement concrete—either plain, reinforced, or pre-stressed. For rigid pavement, Smith and Diefenderfer (2009) use the following equations (Equations 3.4–3.6) from Huang (2004), which are based on formulas provided in the 1993 *AASHTO Guide for Design of Pavement Structures*.

$$\text{LEF} = \log\left(\frac{W_{tx}}{W_{t18}}\right) = 4.62\log(18+1) - 4.62\log(L_x + L_2) + 3.28\log(L_2) + \frac{G_t}{\beta_x} - \frac{G_t}{\beta_{18}} \quad (3.4)$$

$$G_t = log\frac{(4.5 - p_t)}{(4.5 - 1.5)} \quad (3.5)$$

$$\beta_x = 1.00 + \frac{3.63\,(L_x + L_2)^{5.20}}{(D+1)^{8.46}\,L_2^{3.52}} \quad (3.6)$$

where

W_{tx} = number of applications of given axle
W_{t18} = number of standard axle passes (single 18-kip axle)
L_x = load in kips of axle group
L_2 = axle code (1 for single axle, 2 for tandem axles, 3 for tridem axles, and 4 for quad axles)
β_{18}= value of β_x when $L_x = 18$ and $L_2 = 1$
p_t =terminal serviceability index
D = slab thickness in inches

The LEF value for each axle group of a truck for rigid pavement depends on the weight and type of axle group, the pavement terminal serviceability, and slab thickness. The summation of LEF for each axle group of a specific truck would be the ESAL value for that truck.

3.3.3 Other Considerations

Based on AASHTO's research on pavements, Team (1995) and Cambridge Systematics (2006) note that ESAL values can be represented approximately as the fourth power of axle weight. For example, compared to an 18,000-pound single-axle, a 20,000-pound single-axle would create $(20/18)^4$ times (which is equal to 1.52 times) more pavement impact, or a 52% greater impact.

Cambridge Systematics (2006) notes that pavement damage caused by traffic loadings varies by the time of the year—the report notes that a specific traffic loading would cause less pavement damage during winter, when the ground is frozen, compared to other times during the year. The report further notes that five to eight times more pavement damage would be caused by a specific loading during spring (when pavement layers are in a saturated and weakened state due to partial thaw conditions and trapped water) compared to the damage caused by the same loading at other times during the year.

Chapter 4. Development of the Planning Tool

The research team used the information described in this report—along with the results of the first two chapters—to create the planning tool that will help to propose route plans for wind turbine components passing through Texas. In the previous chapter, the research team reviewed all the parameters that TxDOT uses to regulate OS/OW vehicles. These restrictions were established to try to manage the damages that these vehicles can cause on roadways, including pavement fatigue, damages to bridges and signs, and more. Pavement damage was specifically analyzed by our team in order to determine an expression that estimates this damage when given certain inputs.

Once the parameters of significance were collected, our team used the list of parameters to consider different routes for turbine components. We developed a tool (a TransCAD routine) that can map out a route given certain characteristics, such as the size and load weight of a truck. The tool will create a route by optimizing the travel distance, number of turns, and potential pavement damage, while checking restrictions due to bridge clearances, postings, pavement conditions, and any other conditions previously identified.

The remainder of this section is structured as follows: the next section describes the different data sources we used to create our TransCAD network. Section 4.2 describes the tool's development. Section 4.3 outlines briefly how to use the tool.

4.1 Data Sources

We used four different datasets to create our TransCAD network: a map of the Texas road system, critical vertical clearance data, bridge characteristics, and pavement characteristics. In the following subsections, we describe each of these four datasets, detailing how we modified them for inclusion in our TransCAD map.

4.1.1 Roads Data

The road network was extracted from the Texas Statewide Analysis Model (SAM) Version 3 developed by Alliance Transportation Group, Inc. for TxDOT. SAM is the primary tool for evaluating large intercity transportation projects throughout Texas. Although SAM has several functionalities, we are using only its network. Table 4.1 shows the SAM variables selected for use in our tool. After we disabled rail and air routes (thus removing them from the map), we used the SAM network as a base for our TransCAD network.

Table 4.1: Variables selected from the SAM data

Attribute Name	Description
Length	Length of link
Dir	Direction of link
NAME	Name of roadway
FAF_LNAME	Local road name
ExclusionSet	Denotes certain vehicle classes as excluded. For example, if link excludes SOV/trucks, use "HOV2;" if link excludes trucks, use "PassengerOnly."
AB_IntControl03	Filled using intersection control code lookup. Flag denoting signalized/stop sign intersection, grade separation, or centroid: 1 = signalized, 2 = stop sign, or 99=TAZ centroid.
BA_IntControl03	Filled using intersection control code lookup. Flag denoting signalized/stop sign intersection, grade separation, or centroid: 1 = signalized, 2 = stop sign, or 99=TAZ centroid.
LANES_AB_03	Directional # of lanes (for example, a roadway's northbound lanes)
LANES_BA_03	Directional # of lanes (for example, a roadway's southbound lanes)
AB_LaneConfig_03	Contains a code used to determine the lane group configuration. Code is # dedicated left, # shared left, # through, # shared right, and # dedicated right.
BA_LaneConfig_03	Contains a code used to determine the lane group configuration. Code is # dedicated left, # shared left, # through, # shared right, and # dedicated right.
POSTED_SPEED_03	Posted speed
SIGNAL	Type of signal system
RailCAPTrains	Estimated capacity of railroad (trains per day)
SAMV2_Passrail	Passenger rail links used in SAM V2
RouteID	ID for urban rail, intercity rail, high-speed rail, and air routes

4.1.2 Bridge Data

The bridge data includes detailed information about highway bridges in Texas, presented in a Microsoft Access file. This file was provided by TxDOT on December 15, 2015. It presents vast amounts of operational, structural, and usage data for each bridge. It includes information about bridge conditions, expected future traffic loads, and physical characteristics of the bridges. The data is organized by a detailed coding system, described thoroughly in the coding guide.

Some relevant parameters used specifically in this project include the vertical clearance heights, various characteristics contributing to an overall bridge condition rating, and the maximum allowable legal loads on the bridge. This dataset allows for easy access to relevant and updated information about state bridges, for use in various analyses. Broadly speaking, we used only five variables in our tool: latitude, longitude, structure function, maximum load allowed, and vertical clearance. Latitude and longitude were used to locate geographically the bridges in the

TransCAD map (TransCAD can work easily with Microsoft Access files). The variable 'Structure Function' tells us if the record corresponds to a route running "on" the structure or "under" the structure. This variable also helps to indicate which records correspond to pedestrian or railroad bridges, and removes them from the dataset used in the tool. The maximum load allowed is obtained from the variable 'Design Load' and can take one of the following values (in tons): 10, 15, 20, 25, or 100 (we assigned a high value to bridges that do not impose weight limitations, such as those records corresponding to routes that run "under" the structure). The vertical clearance is obtained from the variable 'Minimum Vertical Clearance'. When no restriction exists, we input a high value (100 feet) for vertical clearance.

4.1.3 Vertical Clearance Data for Signboards

Vertical clearance is an important factor in determining routes of oversized loads along freight networks, as the clearance height limits the size of loads that can pass underneath. In order to develop a corridor-based planning tool for route optimization of wind turbine components, it is necessary to consider the vertical clearance height on sections of the roadway network. The vertical clearance dataset is a GIS map representing the Texas freight network, overlaid with vertical clearances of relevant roadway elements (such as bridges and signs) as points along the network.[8] A screenshot of the ARC GIS map is shown in Figure 4.1.

Figure 4.1: Vertical clearance ArcGIS map

[8] The dataset is open-access and can be obtained here: http://services.arcgis.com/KTcxiTD9dsQw4r7Z/arcgis/rest/services/Freight_Network/FeatureServer/0

The dataset separates signboard clearances by both height and condition. The clearance height is further divided into three levels: 16 to 18 feet, represented by blue dots; 14 to 16 feet, represented by yellow dots; and under 14 feet, represented by red dots. Together, these data points (2,000 in total) paint a clear picture of the Texas roadway network by signboard vertical clearance height and conditions. The ArcGIS online map is exported as a shapefile and then included in our TransCAD network.

4.1.4 Pavement Data

TxDOT provided pavement data pulled from the Texas PMIS into a Microsoft Access file. PMIS data itemizes pavement characteristic data for the state-maintained highway system. The data is divided into sections of pavement one-tenth of a mile long and updated every fiscal year.

The PMIS data includes condition summaries that provide specifics on ride quality, skids, structural strength, district control, management, automated rutting measurements, texture, and distresses in Portland cement concrete and asphalt concrete pavement, among many other parameters. PMIS provides easy access to various data about pavement conditions and quality throughout the Texas road network, which is useful in determining access routes for heavy loads (such as windmill parts). Our tool uses three PMIS variables: latitude, longitude (used to locate the pavement sectors in the TransCAD map), and condition score. Condition score combines the scores for ride quality and pavement distress, using a scale from 1 (worst condition) to 100 (best condition). Since around 50% of the pavement sectors in our data have a missing value for the condition score, before we attached the pavement data to our TransCAD map, we computed the average condition score for each of the 10 highway categories of the pavement sectors (rural interstate, rural principal arterial, rural minor arterial, rural collector, rural local, urban principal arterial (interstate), urban principal arterial (other), urban minor arterial, urban collector, and urban local), and assigned the average condition score of the corresponding category to all the pavement sectors with a missing condition score.

4.2 Tool Development

The tool development was divided in two parts: data file creation and optimal path calculation.

4.2.1 Data File Creation

The first step was creating the dataset. The overview of the operations is as follows:

1) Read the Texas road network from the SAM Dataset.
2) Select only road links from the network (exclude rail and air).
3) Overlay the vertical clearance shapefile on the data with a band size of 0.5 miles.
4) Export this overlay map and save it.
5) On this overlaid map, overlay the bridge data with a band size of 0.05 miles (this data is fairly accurate, geographically).
6) Export and save this overlay map.
7) Open this saved map and overlay the pavement data with a band size of 0.05 miles.
8) Export and save this final map.

9) Open the dataview of the map, and delete the columns we are not using.

10) Use the vertical clearance data fields along with the bridge over/under data fields to add an attribute of maximum vertical clearance to all the links. (This is a four-digit code, with first two showing feet and next two showing inches, e.g., a clearance of 12 feet and 5 inches will have 1205 as the attribute).

11) Use the bridge data to fill in the maximum load capacity of certain links (in tons).

12) From the pavement data, assign a condition score to each road.

13) Export this dataset. This is our final dataset.

4.2.2 Optimal Path Calculation

Step 2 was to create a composite score metric from a potential route's section length and pavement damage and then add turn penalties. This process results in a batch file that can be run directly in TransCAD. Also, the dataset obtained from step 1 was reduced to the links meeting the weight and clearance criteria; the shortest path function can be run only on a valid link network. The overview of the operations is as follows:

1) Read a text file with the weight and height of the truck and also the optimization criteria.
2) Select links from the network matching these criteria.
3) Compute a composite score and save it in a new variable for each link.
4) Create a network file from this network (this is a TransCAD internal step—it needs to create a .net file before it can run shortest path) using the new scores as the attributes.
5) Open the shortest path dialogue box, where the user inputs the origin and destination and runs the composite shortest path algorithm.

Summing the optimization criteria yields the composite score. The shortest path is the route with the lowest composite score. This composite score is computed in units of distance and is obtained as the weighted sum of the travel distance and a pavement condition measure, plus a penalty for each turn the truck makes. The weight of the travel distance and pavement condition have default values of 0.9 and 0.1 respectively, but those values can be modified by the user. The turn penalty has a default value of 5 miles per turn (for both right and left turns), but this value can also be modified by the user later (the default value is based on Clossey et al., 2001, and Arkin et al., 2005). The default expression for the composite score corresponds to:

Composite Score = 0.9**Travel Distance in Miles* + 0.1**Pavement Condition* + 5**Number of turns*

The pavement condition figure is computed as *Travel Distance* * (100 – *condition score*)/100, using the condition score defined in Section 4.1.4. The pavement condition metric measures the existing pavement damage as reported by PMIS; roads with pavements in better condition contribute to lower, more favorable composite scores.

4.3 Tool Instructions

The tool delivered to TxDOT (as the project's first product, 0-6850-P1) contains the batch file, the four datasets, the compiled TransCAD network, and the complete user's guide. The four separate datasets were provided in addition to the already created network in case TxDOT would like to modify the network in the future. Detailed instructions on how to replicate the data creation process are provided in the appendix of the user's guide. However, the final dataset is the only map the user should open (see Figure 4.2 for a view of this map).

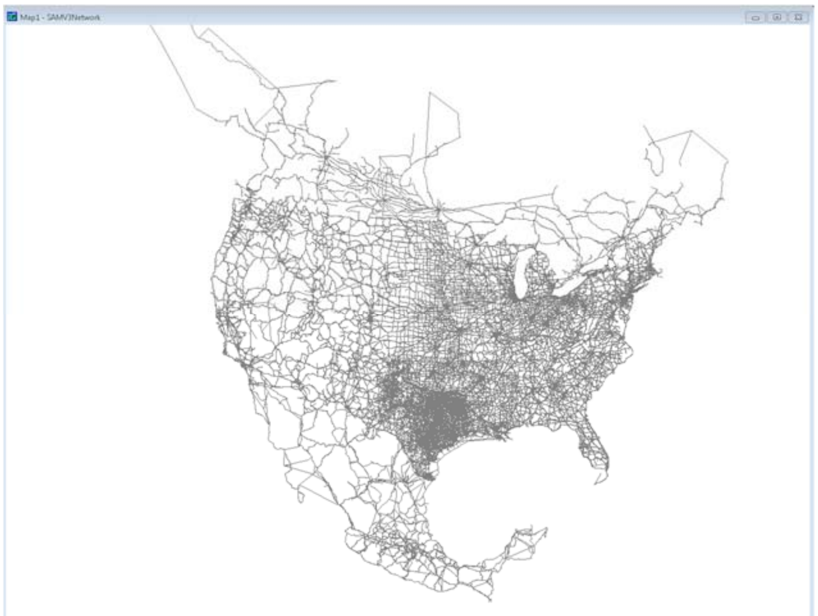


Figure 4.2: Final network (TransCAD screenshot)

Using the tool requires only two steps: open the map in TransCAD and enter some basic inputs regarding the truck, load, and start/end points. The tool will generate the shortest route based on those inputs.

To begin with, after the user opens the map, the user can modify the batch file and input the characteristics of the truck and the load (such as their dimensions), and also the desired optimization criteria specification. After running the batch file, TransCAD will start running the shortest path routine using our modified algorithm (see Figure 4.3).

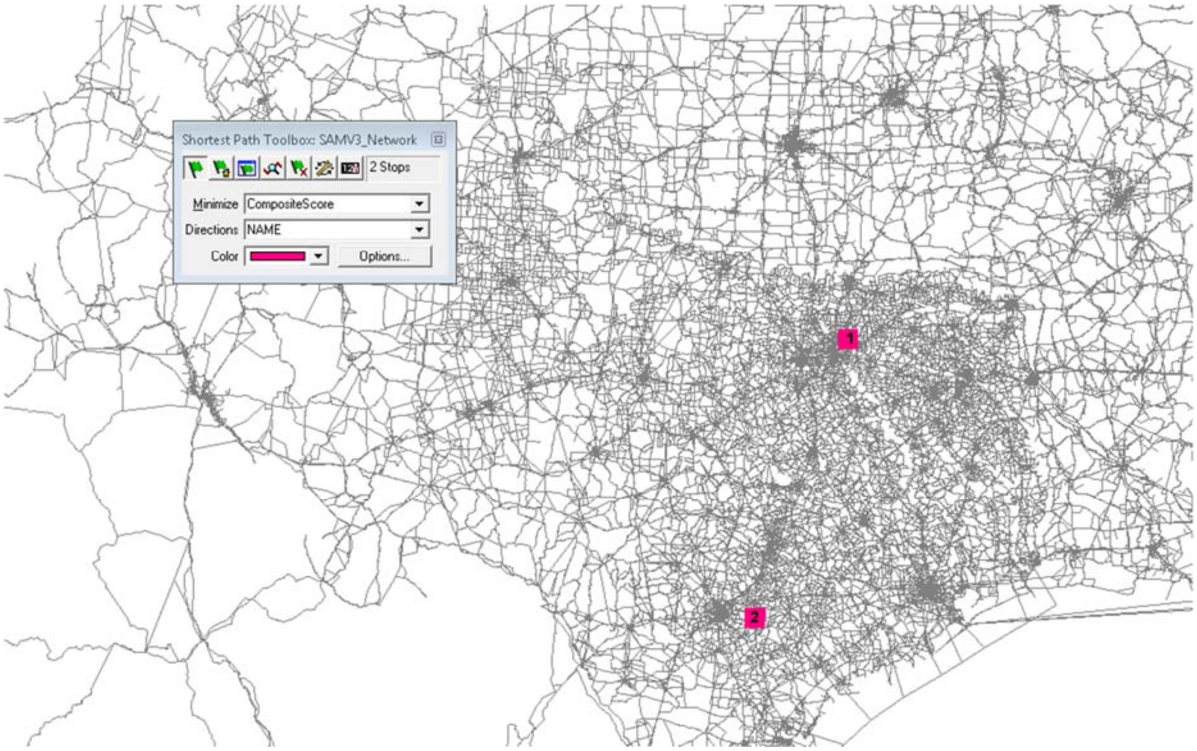
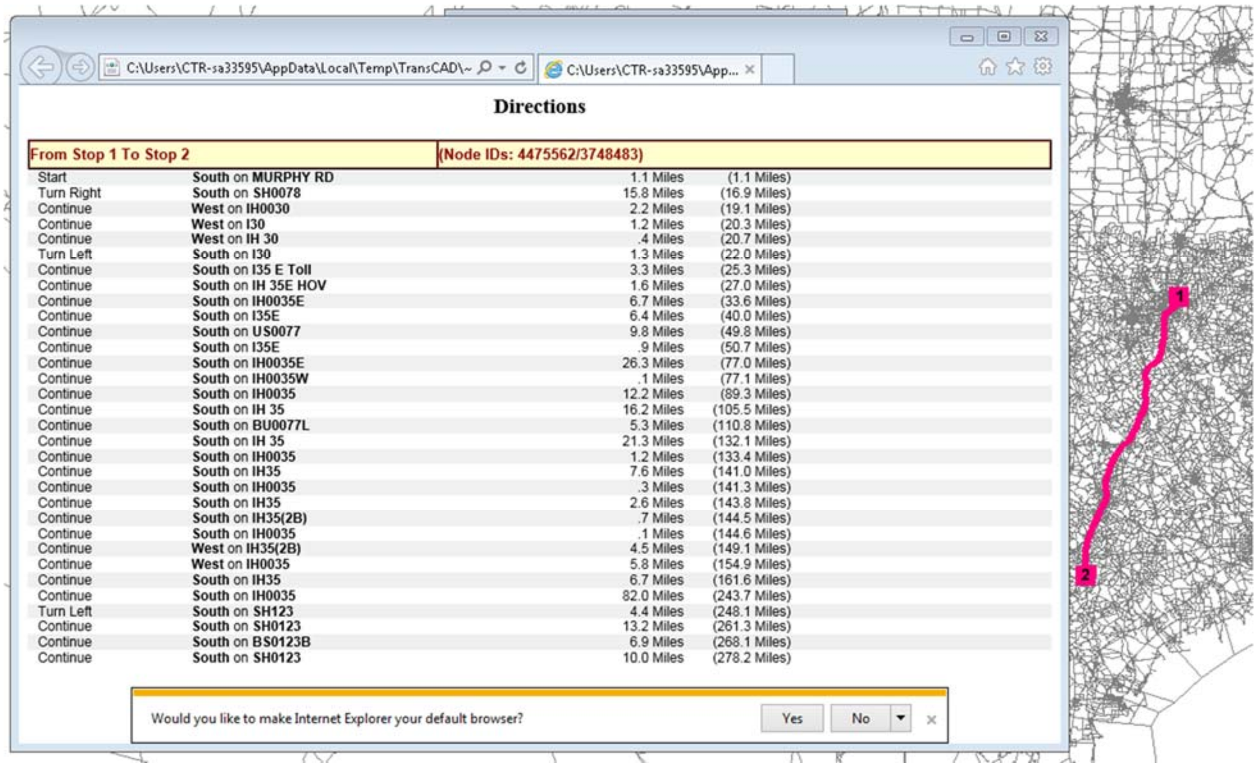


Figure 4.3: Shortest path routine (TransCAD screenshot)

At this point, the user inputs origin and destination (or multiple points, as multiple stops are allowed) and the routine will find the shortest path, creating a list of instructions in a .txt file and an accompanying map (see Figure 4.4 for an output example).



From Stop 1 To Stop 2	(Node IDs: 4475562/3748483)		
Start	**South** on **MURPHY RD**	1.1 Miles	(1.1 Miles)
Turn Right	**South** on **SH0078**	15.8 Miles	(16.9 Miles)
Continue	**West** on **IH0030**	2.2 Miles	(19.1 Miles)
Continue	**West** on **I30**	1.2 Miles	(20.3 Miles)
Continue	**West** on **IH 30**	.4 Miles	(20.7 Miles)
Turn Left	**South** on **I30**	1.3 Miles	(22.0 Miles)
Continue	**South** on **I35 E Toll**	3.3 Miles	(25.3 Miles)
Continue	**South** on **IH 35E HOV**	1.6 Miles	(27.0 Miles)
Continue	**South** on **IH0035E**	6.7 Miles	(33.6 Miles)
Continue	**South** on **I35E**	6.4 Miles	(40.0 Miles)
Continue	**South** on **US0077**	9.8 Miles	(49.8 Miles)
Continue	**South** on **I35E**	.9 Miles	(50.7 Miles)
Continue	**South** on **IH0035E**	26.3 Miles	(77.0 Miles)
Continue	**South** on **IH0035W**	.1 Miles	(77.1 Miles)
Continue	**South** on **IH0035**	12.2 Miles	(89.3 Miles)
Continue	**South** on **IH 35**	16.2 Miles	(105.5 Miles)
Continue	**South** on **BU0077L**	5.3 Miles	(110.8 Miles)
Continue	**South** on **IH 35**	21.3 Miles	(132.1 Miles)
Continue	**South** on **IH0035**	1.2 Miles	(133.4 Miles)
Continue	**South** on **IH35**	7.6 Miles	(141.0 Miles)
Continue	**South** on **IH0035**	.3 Miles	(141.3 Miles)
Continue	**South** on **IH35**	2.6 Miles	(143.8 Miles)
Continue	**South** on **IH35(2B)**	.7 Miles	(144.5 Miles)
Continue	**South** on **IH0035**	.1 Miles	(144.6 Miles)
Continue	**West** on **IH35(2B)**	4.5 Miles	(149.1 Miles)
Continue	**West** on **IH0035**	5.8 Miles	(154.9 Miles)
Continue	**South** on **IH35**	6.7 Miles	(161.6 Miles)
Continue	**South** on **IH0035**	82.0 Miles	(243.7 Miles)
Turn Left	**South** on **SH123**	4.4 Miles	(248.1 Miles)
Continue	**South** on **SH0123**	13.2 Miles	(261.3 Miles)
Continue	**South** on **BS0123B**	6.9 Miles	(268.1 Miles)
Continue	**South** on **SH0123**	10.0 Miles	(278.2 Miles)

Figure 4.4: Output example

Chapter 5. Route Plan Development

5.1 Introduction

The methodology and associated tool presented in this project come at a critical time in the wind industry, as they provide a number of highly valuable services that further optimize wind turbine transport. Previous tools focus on tour planning given an origin/destination pair; they are operational tools that provide, given truck and load dimensions, the best route solely in terms of distance. The tool we are presenting in the current report contributes in two ways:

(1) It improves upon route planning not only in terms of distance, but also considering the number of turns and pavement damage. Making a turn is a challenge when transporting turbine blades and tower sections, which are sometimes more than 100 feet long. Usually, routes must be scouted by an advance driver looking for sharp turns and obstructions such as stop signs that might need to be temporarily taken down. The trucks themselves are complex: a trailer with an independent back end is controlled remotely from a chase vehicle to allow the truck driver to make 90-degree turns, and each turn means several minutes of delay. In addition, the heavy loads of wind turbine components cause significant road deterioration, shortening the original life expectancy of pavement (Banerjee et al., 2015) and forcing authorities to invest in road repair instead of in transportation infrastructure improvement.

(2) Our methodology and related tool also go beyond route planning, and collectively represent a multi-faceted planning system that can predict what transportation infrastructure will be needed based on our systematically researched predictions of wind energy growth. In the process of adding these predictive components, we also include the capability for performing "what-if" analysis. For example, the methodology and associated tool can be used to (a) determine the exact locations and types of road infrastructure improvements that would most improve the routing of wind turbine components, (b) identify how the continually changing technology of wind turbines will impact transportation planning, (c) determine the best locations to install a wind turbine manufacturing plant, (d) analyze how the country's economic growth could influence wind energy production trends and the related transportation of components, (e) identify the best location for new electric transmission lines specific to wind power energy, and (f) evaluate what kind of improvements can be made to port-adjacent freight corridors and general infrastructure to optimize the path between the locations where wind turbine components are imported into and their inland destinations. In summary, the methodology and associated tool can be used not only by shippers that want to create the best routes for their needs and preferences, or by transportation agencies looking to strategize infrastructure repair and construction, but also by any public or private entity that wants to optimize planning of wind energy projects at the statewide level.

5.2 Route Plan

To propose a plan to transport the number of wind turbines necessary to produce the amount of energy we just predicted with our model, we need to make some assumptions about the wind energy industry and the related supply chain. Based on interviews with manufacturers and shippers, previous TxDOT reports, and the dataset listing the permits issued by TxPROS from 2007 to 2009, we base our route plan on the following assumptions:

- The most common wind turbine installed so far in Texas has a capacity of 1.5 MW, so we assume that future turbines will have that capacity.
- Transporting the 1.5MW turbine requires eight trucks with the following dimensions (in terms of height and load, including the corresponding wind turbine components): 1) height 16’4’’ and weight 116 tons, 2) height 16’4’’ and weight 100 tons, 3) height 14’6’’ and weight 64.4 tons, 4) height 17’4’’ and weight 56 tons, 5) height 14’2’’ and weight 45.5 tons, 6) height 14’6’’ and weight 109 tons, 7) height 14’6’’ and weight 39 tons, and 8) height 14’ and weight 42.5 tons.
- An estimated 17% of the wind turbines are transported by rail.
- We will consider that 15% of the total wind energy installed in Texas is also installed in neighboring states (New Mexico, Oklahoma, Arkansas, and Louisiana) and the related components are transported across Texas roads.
- The shipping points (route origins) and their respective share (percentage of the total turbines that come from that origin point) are:
    - Out of state: Arkansas (1.9%), Louisiana (5.6%), New Mexico (13.0%), and Oklahoma (10.1%).
    - Ports: Houston (16.6%), Galveston (4.8%), Corpus Christi (14.4%), Freeport (12.1%), and Beaumont (2.7%).
    - In-state production: Coleman (14.4%) and Fort Worth (4.4%).

The total area of Texas was sub-divided into 19 smaller zones based on possible trip origins (ports of entry, equipment manufacturers, etc.) and possible trip destinations (based on current installations and our predictions). All zones are visible in Figure 5.1. The Panhandle region, a current wind energy hub, was divided into three parts: Upper, Middle, and Lower. The remainder of West Texas was divided into four regions: El Paso, Big Bend, Odessa/San Angelo, and the South/Central region. Other regions with sizeable cities are the Wichita Falls area (to the northwest of Dallas-Ft. Worth), the Abilene-Fort Worth area, the Austin-San Antonio region, the Laredo region, and the Brownsville/McAllen region. East of these regions, we can find the Gulf Coast region, the Corpus Christi region, and the Houston region. North of Houston was categorized into the East, Northeast, and Upper Northeast regions. Finally, the area north of Austin but south of Dallas/Fort Worth was deemed the Central Texas region. Using our tool, we found the shortest path (in terms of our composite score) between each pair of zones and then we loaded on those paths the necessary trucks to satisfy the demand (eight trucks per wind turbine). Finally, we studied in detail each zone to identify the end and beginning of each path, paying particular attention to shipping points and the nearby area of the potential wind farms. We repeat this process for every year from 2016 to 2025.

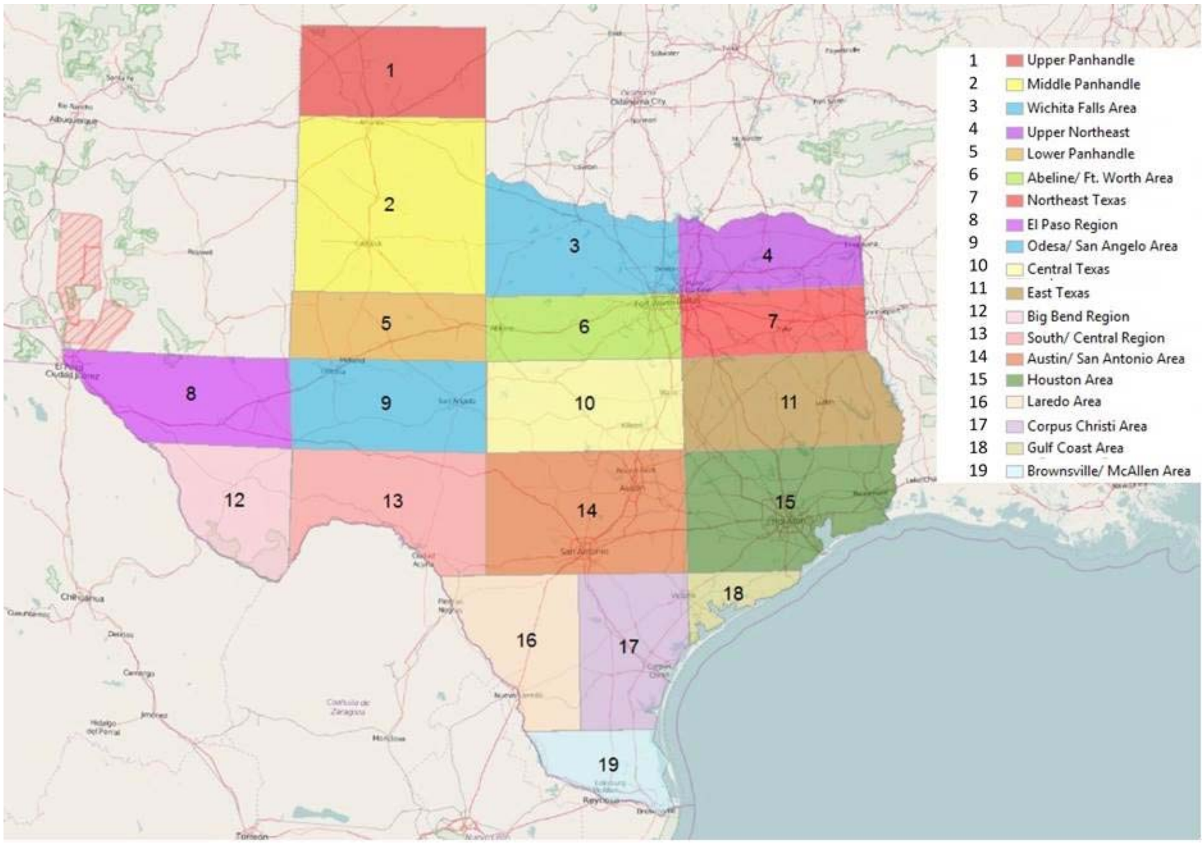


Figure 5.1: Geographic classification of Texas based on possible trip origins and destinations

The main routes of our plan are shown in Figure 5.2. The blue lines represent the trips of the turbine components that are shipped from Corpus Christi's port and go to the Panhandle or West Texas. The purple lines also feed the Panhandle, but the components are coming from the Houston area ports. The purple lines also go to Dallas area and Tyler. The green line connects Freeport with Fort Worth, and the red line Wichita Falls/Oklahoma with Midland (passing through San Angelo area). Finally, orange lines represent trips of the turbine components that come from New Mexico and travel into the Panhandle or the south of West Texas (Acuña area). In Appendix J we have included the directions that define each of these main paths. Additionally, we have included in Table 5.1 the most important section of highways for our route plan. We show in Table 5.1 the roads that receive the highest number of trucks during the 10-year period studied (2016 to 2025). Along with the name of the highway (and the specific section that is considered), we have included the number of trucks that will pass through the highway section.

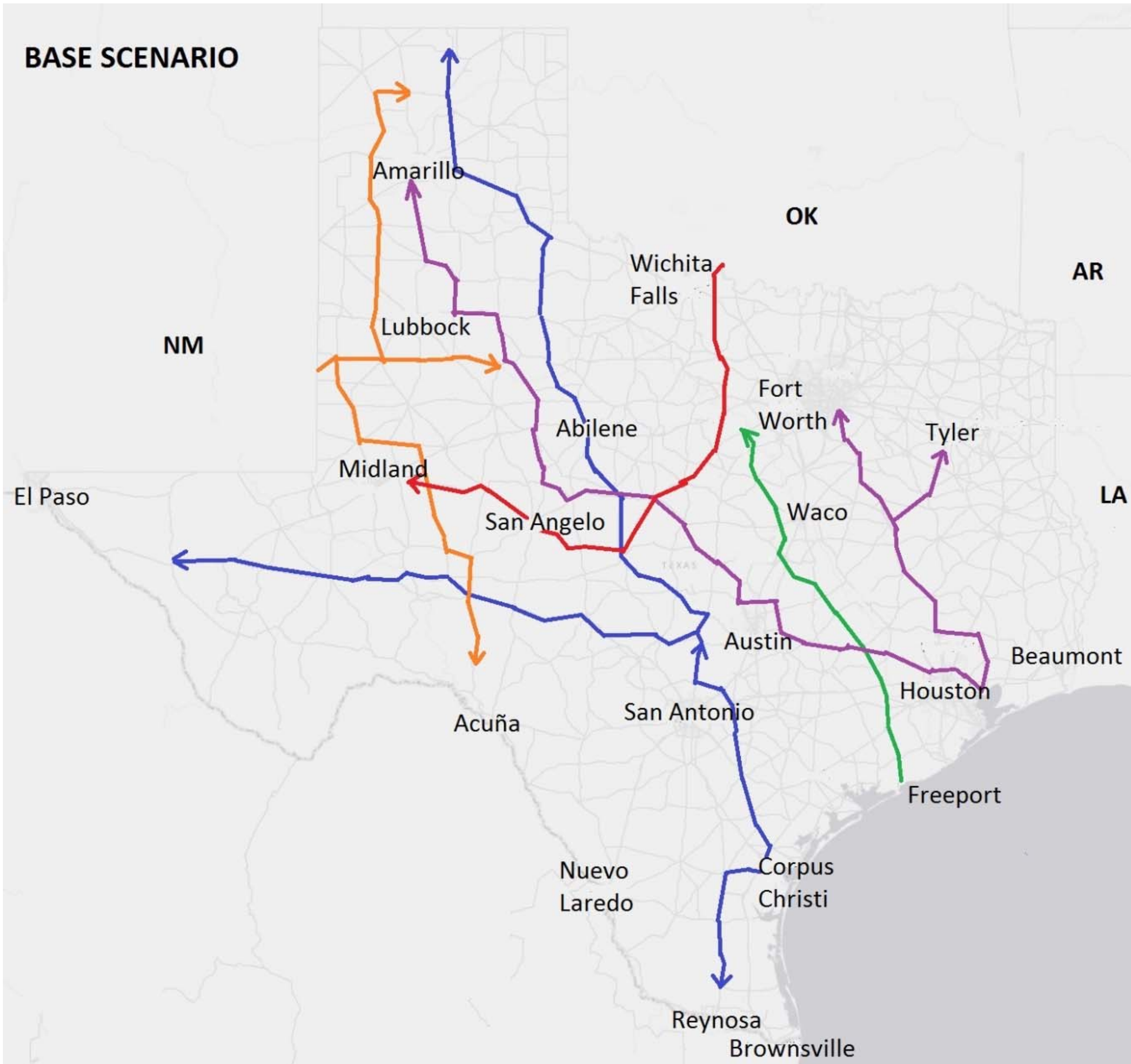


Figure 5.2: Route plan for the base scenario

5.3 What-if? Analysis

As we mentioned earlier, our methodology and associated tool can be used to propose changes in the Texas roads infrastructure and to study in detail potential new trends in the wind energy industry. For example, we replicated the prediction process to create a scenario (Scenario A) in which three critical points are "relaxed" (we changed the vertical clearance of three specific bridges from 16 feet to 17 feet). The new route plan is presented in Figure 5.3 (along with the location of the three bridges, which are identified by stars in the figure).[9] The main routes are very similar in the base and new scenario cases, except for those that end in the Texas Panhandle. The relaxation of the vertical clearance of the first bridge modifies the blue path south of Amarillo, while the relaxation of the second bridge vertical clearance modifies the blue path, as well as the

[9] Approximate location of bridges (latitude, longitude): Bridge 1:35.192631, -101.742325; bridge 2: 32.390984, -99.725218; and Bridge 3: 31.079177, -102.360319.

purple path, close to Abilene. Additionally, the relaxation of the third bridge modifies the blue path toward the west of Texas and the orange path that ends close to Acuña. The total composite score is 23% lower than the total composite score of the base scenario, indicating that an investment in upgrading those three bridges can lead to a significant saving in terms of distance traveled, number of turns, and pavement damage—three key elements that all the stakeholders involved (manufacturers, shippers, public authorities, and the general public) would like to minimize.

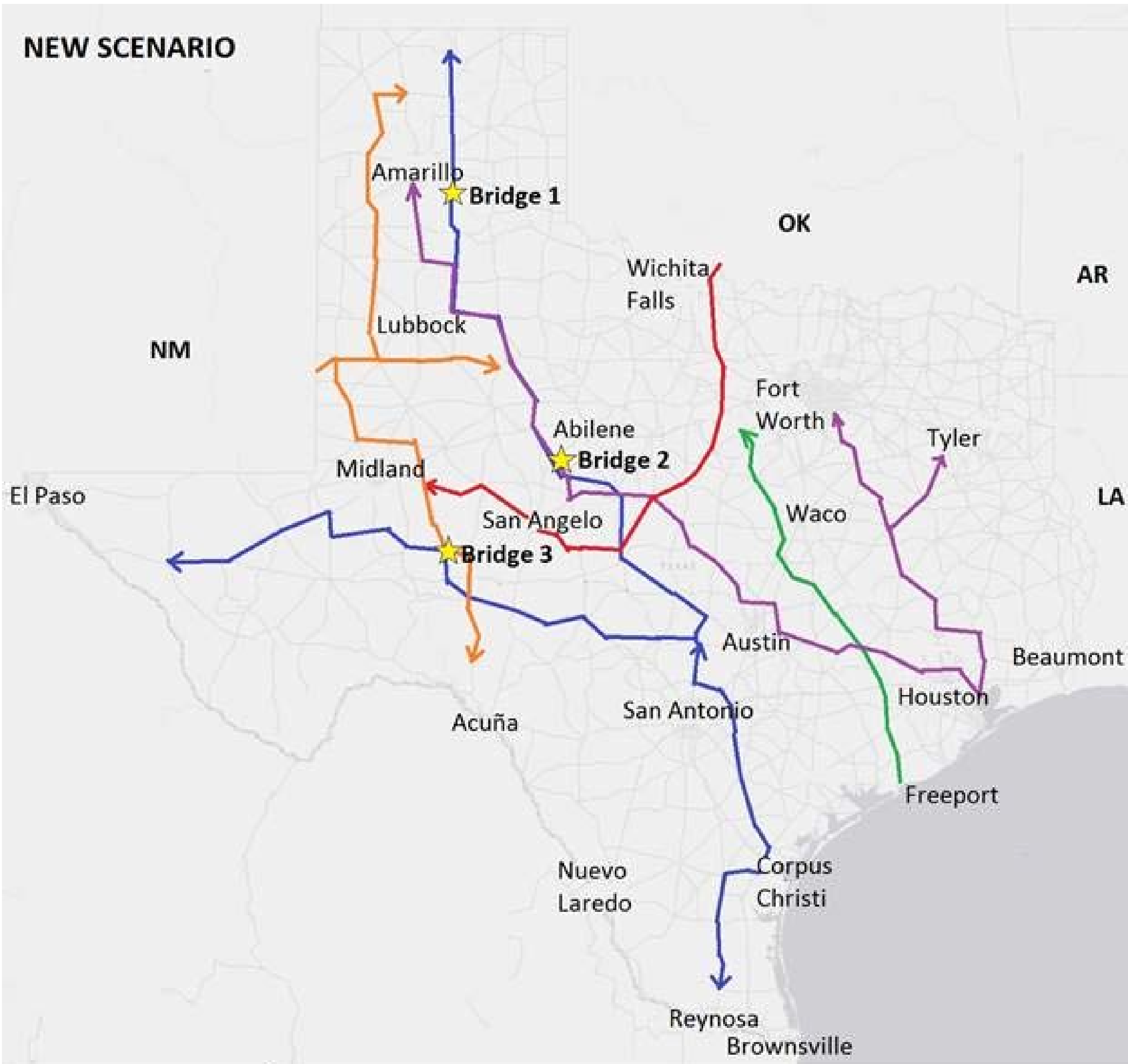


Figure 5.3: Route plan for scenario A

Many other scenarios may also be considered and evaluated using the tool developed. As a last example, we replicated the prediction process to create a new scenario, Scenario B, in which the size of the turbine (and the associated trucks) is 10% bigger than our assumption (following the predictions of several studies that have proposed even bigger turbines in the future) for the years 2020 to 2025. The new route plan for Scenario B is presented in Figure 5.4. The paths are slightly different from those presented in the base case scenario, with a significant difference for those paths that start or end outside of Texas (see the red and purple paths toward the east side of Texas and the orange path toward the west side of the state). The total composite score of Scenario B is 15% higher than the total composite score of the base case scenario.

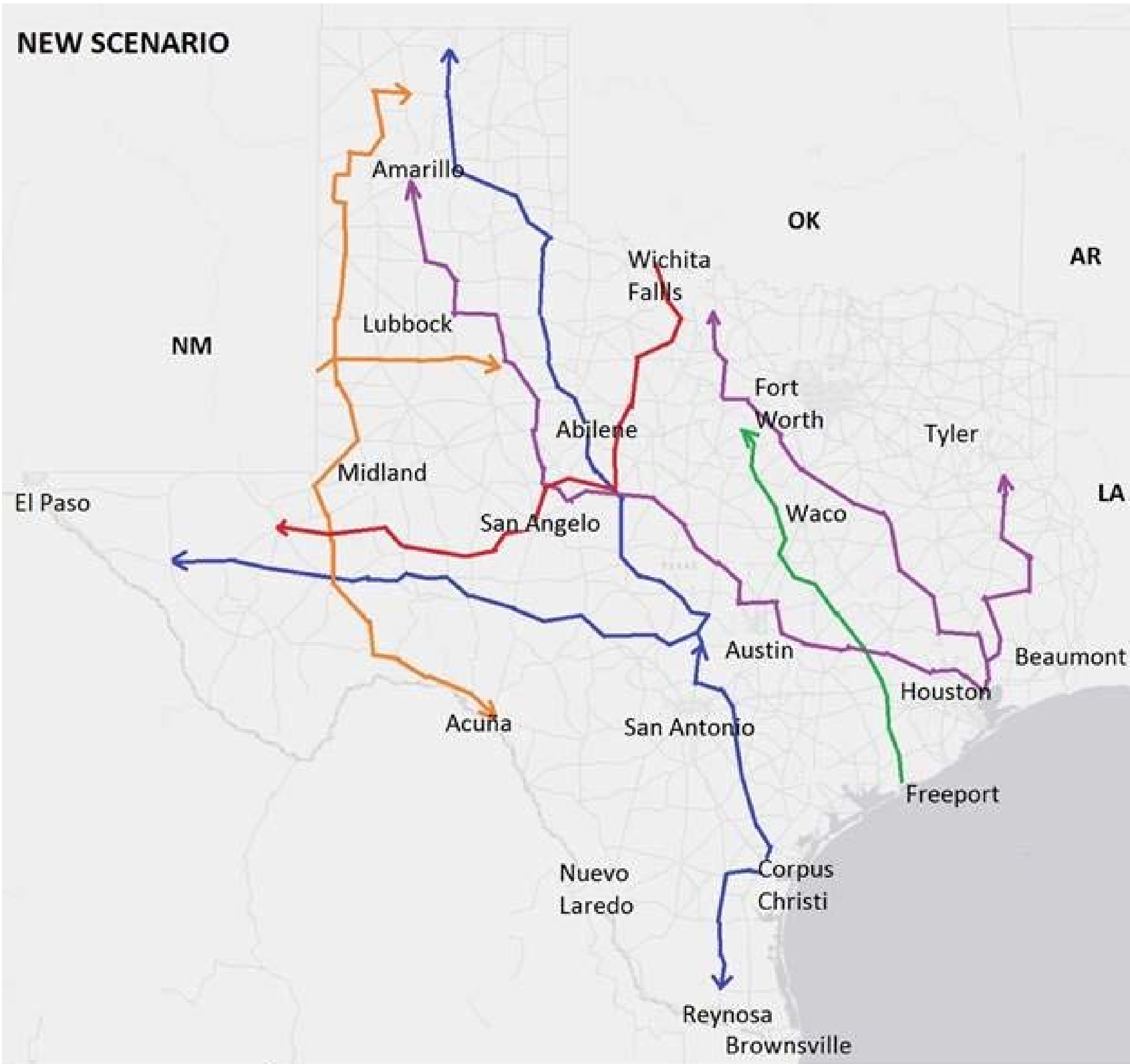


Figure 5.4: Route plan for scenario B

Table 5.1: Most used section of highways in our route plan (2016 to 2025)

Highway name	Section beginning	Section ending	Number of trucks
US-83	US-180	US-62	2,848
I-10	US-277	US-163	1,680
I-27	TX-70	I-40	1,520
US-385	US-380	TX-354	1,520
US-380	TX-214	TX-208	1,408

Chapter 6. Training Workshop in the Use of the Planning Tool

In close association with TxDOT, the research team organized a three-hour workshop to present the following in a cascading process of inter-related dimensions: (1) the most likely wind farm locations and their production capacities; (2) the nature and size of wind turbine components corresponding to the estimated production capacities of wind farms; (3) the routing paths for the wind turbine components; and (4) the truck movement patterns corresponding to the routing paths, as well as recommendations for investing in additional transportation infrastructure to facilitate the movement of wind turbine components. The research team provided instruction in the use of the corridor-based planning tool to plan for future construction of wind farms and the transportation of wind turbine components. The workshop's PowerPoint presentations are provided as this project's second product (0-6850-P2).

The workshop was held at the CTR offices on Tuesday, August 9, 2016, from 9:00 a.m. to noon. TxDOT Project Manager Wade Odell was present; other attendees included TxDOT representatives Jennifer Bierman, Michelle Conkle, Sondra Johnson, and Travis Scruggs. The research team presented the features and uses of the software and performed a detailed demonstration of the tool.

Most of the participants expressed positive feedback about the tool and indicated willingness to use the tool to improve their operations and predict the future needs of their riders. However, several comments and concerns were voiced during the workshop, which will be addressed by the research team. Three of the suggestions involved improving the tool's user interface, which were giving route validation after a route is generated, changing the format that the vehicle height is input into the system, and labeling the roads that are on the generated route. Also, attendees requested a list of the top-ten most travelled routes in the route plans, in order to focus on the maintenance of these segments. These comments and suggestions were incorporated into an updated version of the tool (provided to TxDOT as 0-6850-P1).

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Appendix A: Market Segmentation Model Results

Category	**West Texas – Low WPC**		**West Texas – High WPC**		**North Texas**		**Panhandle**		**Central Texas**	
Variable	Coeff.	t-stat	Coeff.	t-stat	Coeff.	t-stat	Coeff.	t-stat	Coeff.	t-stat
Constant	-11.238	-1.04	29.372	1.54	-10.617	-0.62	-8.819	-0.68	4.078	0.38
$GDP_{t,t-1}$	2.527	2.43	-5.108	-2.63	2.202	2.78	1.834	2.85	0.846	2.49
$Dlines_{q,t}$-$Dlines_{q,t-1}$	-0.101	-2.26	-0.055	-2.44	-0.200	2.32	-0.220	-2.19	-0.010	-2.43
RPS_t	4.985	2.61	-12.286	-2.85	11.118	2.85	22.768	2.29	6.670	2.82
Adjusted R square	0.203		0.220		0.260		0.240		0.250	

Appendix B: Single Linear Regression with Segmentation Variables Model Results

Variable	Coeff.	t-stat
Constant	-6.116	-0.83
$GDP_{t,t-1}$	1.151	2.14
$Dlines_{q,t}$-$Dlines_{q,t-1}$	-0.670	-2.32
RPS_t	10.623	2.27
Dummy West Texas – Low WPC	-3.809	2.63
Dummy West Texas – High WPC	-6.012	2.58
Dummy North Texas	-0.400	2.15
Dummy Panhandle	7.589	3.29
Adjusted R square	0.250	

Appendix C: Final Specification Model Results

Variable	Coeff.	t-stat
Constant	-4.336	-0.52
$GDP_{t,t-1}$	0.958	2.82
$Dlines_{q,t}$-$Dlines_{q,t-1}$	-0.100	-2.86
RPS_t	8.915	2.42
Dummy West Texas – Low WPC	-4.537	-2.69
Dummy West Texas – High WPC	-6.793	-2.58
Dummy North Texas	-0.464	-2.16
Dummy Panhandle	9.196	3.37
$w_{q,t-1,t-2}$	-0.227	-3.01
$w_{q,t-1,t-2}$ interacted with: Dummy non-Central Texas	0.057	1.99
Adjusted R square	0.32	

Appendix D: Project Survey

Following is the text of the actual survey used in this task.

Texas Transportation Planning for Future Renewable Energy Projects

This survey is part of an initiative of the Texas Department of Transportation to better accommodate the future growth of wind farms and the use of renewable energy in the state of Texas. Your company is being contacted and asked to fill this questionnaire in order to help analyze the critical issues regarding the infrastructure for the transportation of oversize and overweight loads, specifically wind turbine components.

The Center for Transportation Research at the University of Texas at Austin, and the Texas Department of Transportation appreciate your collaboration and time.

Company name:
Name of contact person:
Phone and e-mail:
Date:

Questions

Characterization of the Company

1. Which components of wind turbines do you transport? What are the usual dimensions?
2. How many deliveries do you do per year? (or per month?)
3. What is your fleet size? What type of vehicles do you use? What are their dimensions?
4. What are the usual origin or destination cities or towns for shipping wind turbine components in Texas?

Infrastructure and Service

5. Does your company face issue regarding height-width clearance and weight limit on Texas' road network? What are the issues? Could you please give examples?
6. Do drivers face physical obstacles such as bridges, tunnels, tightly bending roads, etc., in their routes in spite of having a route plan and permit from the Texas Permitting and Routing Optimization System (TxPROS)? How do they overcome these challenges?
7. Do you think there is a shortage of skilled drivers to transport wind turbine components or other oversize loads? Does it affect your services?
8. Have you experienced any changes in dimensions of the wind turbine components you transport? If yes, how did it affect your fleet?

Regulation Issues

9. What issues does your company face in obtaining a transportation permit from the Texas Department of Motor Vehicles (TxDMV) to transport wind turbine components?
10. Is there a wait period from your desired schedule of transportation to the actual schedule?

11. Is it difficult for your company to employ escort vehicles for transportation of wind turbine components? Are escort vehicles required for all components or only a few specific parts? Are they required for the entire trip or only certain segments of the trip?
12. Does your company face any issues with the varying permit rules of different states for transportation of oversized and overweight loads on roads? Could you provide some examples?

Any Other Comments

13. If there are some issues that were not covered by this questionnaire and you believe that they are relevant for an improvement in the infrastructure for the transportation of wind turbine components, please provide your comments below.

Appendix E: Contacted Companies

Company name	Person contacted	Email address	Phone number	Website	Date contacted	Response
Lone Star Transportation	Tex Robbins (President), David Ferebee, Davida White	Sales@lonestar-llc.com; Tex.Robbins@lonestar-llc.com (President); David.Ferebee@lonestar-llc.com; davida.white@lonestar-llc.com	1-800-541-8271, (281) 590-9200	https://www.lonestar-llc.com/wind.html	June 10, 16, 17; July 6, 15	Interviewed David Ferebee
Daseke (parent company of Lonestar)	General company email, online form, Greg Hirsch	info@daseke.com; siefkes@siefkespetit.com; Greg@daseke.com	972-248-0412	http://www.daseke.com/about-daseke-dallas/	June 16	Connected to Tex Robbins, President of Lone Star Transportation
BNSF Logistics	Robert Sutton (Senior Vice President of US Projects & Rail Service), Nicolle Plummer (Marketing Coordinator), Dan Curtis, online form	Robert.Sutton@bnsflogistics.com; nicolle.plummer@bnsflogistics.com; Dan.Curtis@bnsflogistics.com	1-855-476-9365	http://www.bnsflogistics.com/our-people/leadership/	June 16, 24	Interviewed Robert Sutton
Mammoet USA	Online form, Amanda Lunsford (Tendering and Back Office Manager), Wayne Smith (Account Manager)	Amanda.Lunsford@mammoet.com; Wayne.Smith@mammoet.com	281-595-2715	http://www.mammoet.com/	July 15, 20, 27, 29	Wayne Smith stated over the phone that Mammoet deals mostly with wind turbine components in a controlled environment such as port facilities, and not with their transportation.

Company name	Person contacted	Email address	Phone number	Website	Date contacted	Response
Landstar	General company email, online form, Jay Folladori (Vice President Heavy Specialized Services)	corpcomm@landstar.com; gwhitcher@landstar.com; info@landstartrucking.com; jfolladori@landstar.com	800-872-9400; 904-398-9400	http://www.landstar.com/certifications; http://www.landstartrucking.com/contact-us	June 16; july14, 22, 27	Got connected to Jay Folladori, but no response from him.
Siemens	Online form, general company email for energy, Kendra Sestile, Sally Chope (Head of Siemens Wind Power Onshore Americas Transportation department)	support.energy@siemens.com; usa.800siemens.us@siemens.com; kendra.sestile@siemens.com; sally.chope@siemens.com	+49 180 524 70-00	http://www.energy.siemens.com/hq/en/renewable-energy/wind-power/	July 2, 8, 13, 15, 22, 27	Kendra Sestile responded with Sally Chope's email, but no response from Sally Chope.
DHL - Renewable Energy Solutions	General company email for renewable energy, online form, Robert Mintz (Senior Manager of Communications)	renewable.energy@dhl.com; CustomerService@dhl.com; Robert.Mintz@dhl.com	1-800-225-5345	http://www.dhl.com/en/logistics/freight_transportation/renewable_energy.html#.VYCnYBbmJps	June 16, 18, 24; July 8	Got connected to Robert Mintz, but no response from him.

Company name	Person contacted	Email address	Phone number	Website	Date contacted	Response
Anderson Trucking Service	Alan, David, Bruce, Jake, Mark, Shane, Scottt, Eric, and online form	alanre@atsinc.com; TheHerald@atsinc.com; davidme@atsinc.com; kimball@atsinc.com; bruceto@atsinc.com; jakelo@atsinc.com; joannaju@atsinc.com; markke@atsinc.com; shaneke@atsinc.com; scottan@atsinc.com; ericma@ats-inc.com; jackjo@atsinc.com; patricfu@atsinc.com; tracyhe@atsinc.com	320-255-7400	http://www.atsinc.com/projects/	June 2, 17, 24; July 8, 14, 29, 30	No response
Daily Express	Mark Eyer; David Rilee; Mike Howard (Vice President Sales), Matt Ray	Mark Eyer (meyer@dailyexp.com); drilee@dailyexp.com; tlong@dailyexp.com; mhoward@dailyexp.com; mrea@dailyexp.com	800-726-7711	http://www.dailyexp.com/windenergy.html; http://www.dailyexp.com/contactsales.html	June 10, 17, 24; July 15, 22, 27	No response
General Electric	Online form, Nikolas Noel (Media contact listed on company website); Michael Ebner (Logistics Quality & EHS Manager)	nikolas.noel@ge.com; michaelC.ebner@ge.com	+1 518 385 6090; +1 678 844 6084	https://renewables.gepower.com/wind-energy.html	July 9, 15, 22, 27, August 4	Called by Michael Ebner, requested email with Google doc survey—no response yet.
Texas Trucking Association	Ann and general company email	info@texastrucking.com; ann@texastrucking.com	(800) 727-7135	http://www.texastrucking.com/TXTA/About_Us/TXTA/About.aspx?hkey=ac1edc45-a749-4ff4-933e-b38768bed248	June 4, 16, 17, 22	No response

Company name	Person contacted	Email address	Phone number	Website	Date contacted	Response
Texas Association of Structural Movers	General company email	jmccullough@assnmgmt.com	(512) 454-8626	http://www.texashousemovers.com/	June 4, 16	Do not transport wind turbines.
TII - Transport Investments Inc. - American Wind Transport Group, LLC	Douglas B. McAdams (President); David Hartman (Vice President of Operations)	dnhartman@transportinvestments.com; dbmcadams@transportinvestments.com	334-229-9668	http://transportinvestments.com/wind.php	June 8, 17	No response
Energy Transportation, Inc.	General company email; online form	info@energytran.com; dmcglade@energytran.com	800.653.2336	http://www.energytran.com/	June 16, 24	No response
Oehlerking Hauling Inc.	General company email	info@oehlerkinghauling.com; dispatch@oehlerkinghauling.com	+1 301-274-3803	http://www.oehlerkinghauling.com/smartEnergy.htm	June 16	No response
Integrated Wind Energy Services LLC	General company email	info@integratedwind.net	573-332-7575	http://www.integratedwind.net/Wind.aspx	July 14	No response
Nooteboom	General company email, Johan van de Water (Manager Communications & PR)	info@nooteboom.com; j.vd.water@nooteboom.com	+310246488864	http://www.nooteboomgroup.com/nooteboom/en/our_products/transport_segments/windmill_transport/	July 14	No response
Badger Transport Inc.	Al Johnson (President)	al.johnson@badgertransportinc.com	1-715-823-5426	http://www.badgertransportinc.com/contact/	July 15	No response
Dad's Transportation LLC	Online form	-	218-841-0013	http://dadstransportation.com/index.html	July 15	No response
Trinity Structural Towers, Inc.	General company email; President Kerry Cole	trinity.towers@trin.net, Kerry.Cole@trin.net	214-631-4420	http://www.trinitytowers.com/	June 24	Responded with manufacturer contact suggestions.

Company name	Person contacted	Email address	Phone number	Website	Date contacted	Response
Alstom	Timothy Brown (Vice President Communications Renewable Power); Andy Geissbuehler (GM of Alstom Wind in NA)	timothy.s.brown@power.alstom.com; andy.geissbuehler@power.alstom.com	(806) 381-2493	http://www.alstom.com/microsites/power/products-services/renewables/wind-power/	June 24, July 15, 30, August 4	Tim Brown responded with email of Andy Geissbuehler; no response from Mr. Geissbuehler yet.
Vestas	Piper Baron (Marketing and Communication Manager); Maria Iredale (Director for Project Transportation in Americas	pibrn@vestas.com; mholt@vestas.com	+1 503 327 2319	http://www.vestas.com/	July 2, 9, 24, 27, 28	Interviewed Maria Iredale
Nordex	General company email	NordexUSA@nordex-online.com	(312) 386-4100	http://www.nordex-online.com/en/	July 2, 24	No response
Gamesa	General company email	media@gamesacorp.com	+34 944 03 73 52	http://www.gamesacorp.com/en/	July 2, 24	No response
Acciona	Press room; Sustainability	gabinetedeprensa@acciona.es; responsabilidadcorporativa@acciona.es	+34 91 663 28 50	http://www.acciona.com/	July 2, 15	No response

Appendix F: Interviews

F.1. Interview with Lone Star Transportation

Company name	Lone Star Transportation
Date	19-Jun-15
Name of contact person	David Ferebee
Phone	817-306-1000
E-mail	david.ferebee@lonestar-llc.com
Which components of wind turbines do you transport? What are the usual dimensions?	All
How many deliveries do you do per year? (or per month?)	Depends on the number of wind projects being developed in a particular year. We have delivered up to 10,000 loads in one year.
What is your fleet size? What type of vehicles do you use? What are their dimensions?	700 trucks and numerous types of trailers; varying dimensions.
Does your company face issues regarding height-width clearance and weight limit on Texas' road network? What are the issues? Could you please give examples?	No. We work closely with TX to plan and secure routing clearances. Construction can change routing in the middle of a project that causes interruptions.
Do your drivers face physical obstacles such as bridges, tunnels, tightly bending roads, etc., in their routes in spite of having a route plan and permit from the Texas Permitting and Routing Optimization System (TxPROS)? How do they overcome these challenges?	No, we survey the route prior to submitting to TXPROS; thus we know we can negotiate the route with said components.
Do you think there is a shortage of skilled drivers to transport wind turbine components or other oversize loads? Does it affect your services?	No, it does not affect our services or planning as we only commit to what our capacity allows for.

Have you experienced any changes in dimensions of the wind turbine components you transport? If yes, how did it affect your fleet?	Yes, we are constantly modifying or purchasing new equipment to accommodate the components as they increase in size, but they are getting to a point where they are not transportable over the road.
What issues does your company face in obtaining a transportation permit from the Texas Department of Motor Vehicles (TxDMV) to transport wind turbine components?	None
Is there a wait period from your desired schedule of transportation to the actual schedule?	No, we work with the OEM [original equipment manufacturer] and are in tune to the schedules.
Is it difficult for your company to employ escort vehicles for transportation of wind turbine components? Are escort vehicles required for all components or only a few specific parts? And are they required for the entire trip or only certain segments of the trip?	Depending on the market conditions, escorts can be difficult to secure. Each state and route have different requirements as to when they are actually required.
Does your company face any issues with the varying permit rules of different states for transportation of oversized and overweight loads on roads? Could you provide some examples?	Not necessarily problems, but we do have to plan for each state's different requirements when planning equipment for a particular component.
If there are some issues that were not covered by this questionnaire and you believe that they are relevant for an improvement in the infrastructure for the transportation of wind turbine components, please provide your comments below.	
What are the usual origin or destination cities or towns for shipping wind turbine components in Texas?	Varies depending on project locations and which OEM we are working for.

Could you please give examples of wind turbine components your company transports and examples of their dimensions?	We move blades, nacelles, rotors, and tower sections. They vary on size and weight depending on the manufacturer and the size of nacelle being installed.
Could you give examples of types and dimensions of trailers that your company uses to transport wind turbine components?	We use most every type trailer in our fleet for wind loads. As a reference, one of our trailer cards is attached with dimensions. [See Figure F1.]
Could you provide examples of origin and destination cities or towns for shipment of wind turbine components in Texas?	That list would just be endless as we have done many, many wind projects in Texas. About the only area we have not done wind projects in is East Texas—say, I45 and east.
You had mentioned in the survey that wind turbine components are increasing in size over time; could you please give examples of the larger, and the older dimensions?	Again, this depends on the manufacturer and what the customer orders. One might reference that the first wind blades here in the US were about 13 meters long; the ones we move now are up to 60 meters long.

Types and dimensions of Lone Star Transportation's trailers are shown in Figure F.1.

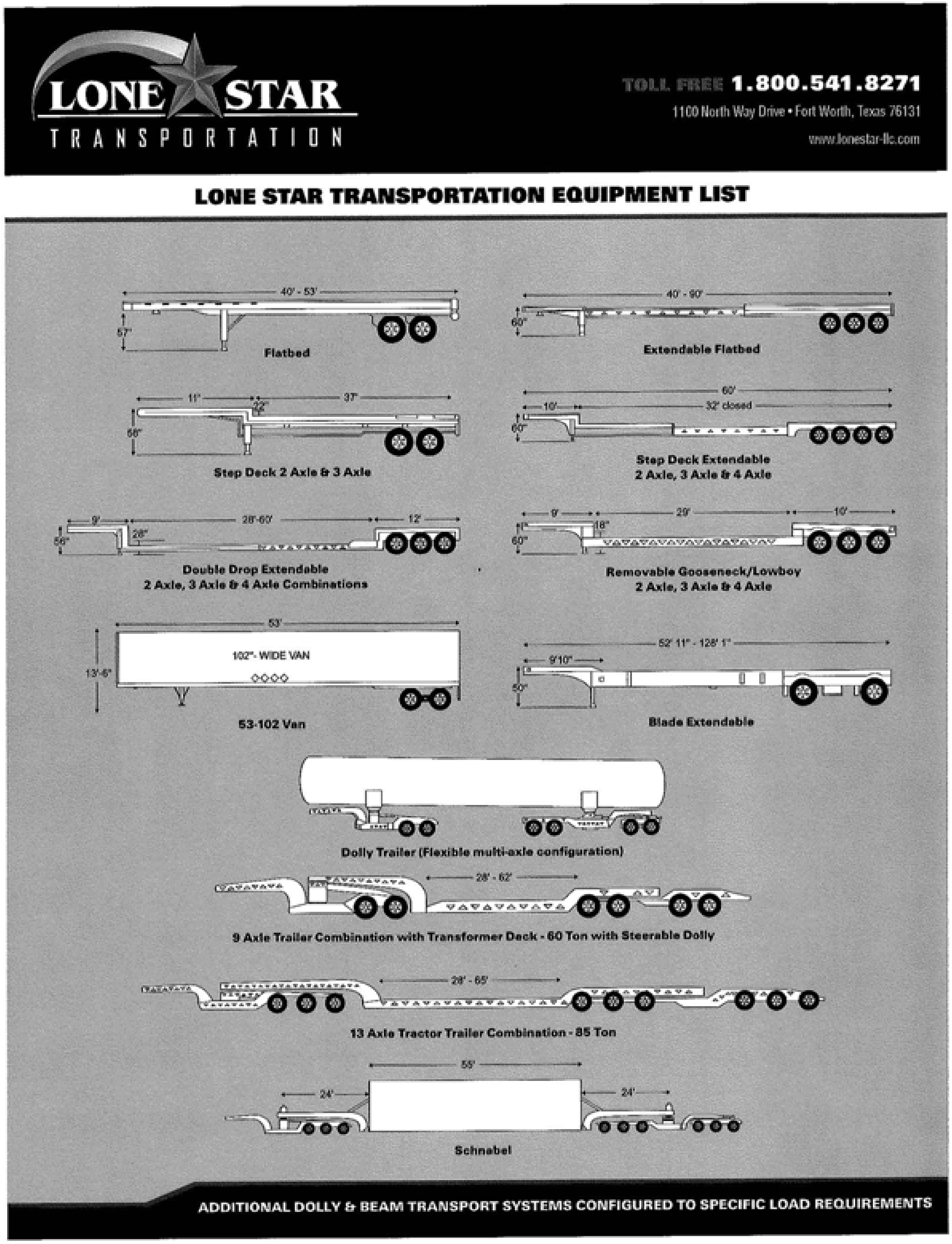

Figure F.1: Lone Star Transportation's equipment list

F.2. Interview with BNSF Logistics

Company name	BNSF Logistics
Date	7/1/2015
Name of contact person	Robert Sutton
Phone	479-203-5443
E-mail	robert.sutton@bnsflogistics.com
Which components of wind turbines do you transport? What are the usual dimensions?	BNSF Logistics coordinates the movement of nacelles, hubs, tower sections, and blades for a variety of manufacturers. The dimensions vary by manufacturer and the specifics for each particular wind farm. In general today we are seeing blades that are mostly moving in the 48m to 57m range.
How many deliveries do you do per year? (or per month?)	This will be dependent on the year as the industry fluctuates in accordance with national policy tied to the production tax credit. However, we expect to handle several thousand components in 2015 and 2016 with many of these either terminating in Texas or moving through Texas for other locations.
What is your fleet size? What type of vehicles do you use? What are their dimensions?	BNSF Logistics as a non-asset based third party logistics firm does not own tractors or trailers. Our core in the wind space is coordinating the movement of wind components on the various railroads and managing the transload of those components at our transload sites. For Texas most of our transload operations currently are focused in West Texas.
Does your company face issues regarding height-width clearance and weight limit on Texas' road network? What are the issues? Could you please give examples?	With BNSF Logistics primarily focusing on rail movement of wind components, we do not experience as many challenges as the actual asset based carriers. However, as components continue to get bigger, especially looking at the weight of the nacelles and the length of the blades, the challenges continue to mount when looking at routes that will work to safely move the components. We have seen in some limited instances municipalities that are unwilling for the large components to move through their communities as well.

Do your drivers face physical obstacles such as bridges, tunnels, tightly bending roads, etc., in their routes in spite of having a route plan and permit from the Texas Permitting and Routing Optimization System (TxPROS)? How do they overcome these challenges?	We typically do not have unforeseen challenges as this is part of the route survey process to determine any pinch points, tight turns, bridges with weight limits, low clearances, etc., that would impede the movement of the freight. The most common unforeseen challenge relates to municipalities that will not allow traffic to move through their communities even after a permit has been issued based on the approved route.
Do you think there is a shortage of skilled drivers to transport wind turbine components or other oversize loads? Does it affect your services?	The size and weight of the components create unique challenges for drivers. Hiring of skilled drivers and retention of those drivers is paramount to ensure safety of these cargoes and definitely we are seeing a shortage in this type of driver. With an aging driver population this issue will only continue to get more challenging in the coming years.
Have you experienced any changes in dimensions of the wind turbine components you transport? If yes, how did it affect your fleet?	Yes, the components continue to get heavier and larger in general. Nacelles continue to get heavier as the output of the machines increase. The biggest changes we have seen recently is associated with the length and curvature of the blades. It was only recently that most blades were around the 42m to 45m length and now we are seeing these most commonly be in the 55m to 58m range with a number of OEM's looking at blades moving into the 62m to 65m range in the next couple of years. At these lengths, old equipment becomes obsolete or must be retrofitted to handle these longer lengths.
What issues does your company face in obtaining a transportation permit from the Texas Department of Motor Vehicles (TxDMV) to transport wind turbine components?	N/A

Is there a wait period from your desired schedule of transportation to the actual schedule?	The schedule changes are often based upon the work being done at the wind farm and/or the manufacturing schedules of the OEM's. Often a plan is presented prior to the start of the project and then equipment needs are determined based upon the expected schedule. When changes occur, it can require additional equipment to be committed or in some cases equipment to be moved to other projects due to delays.
Is it difficult for your company to employ escort vehicles for transportation of wind turbine components? Are escort vehicles required for all components or only a few specific parts? And are they required for the entire trip or only certain segments of the trip?	N/A
Does your company face any issues with the varying permit rules of different states for transportation of oversized and overweight loads on roads? Could you provide some examples?	Since most of the wind components we coordinate use rail as the primary means for intrastate transportation, this has not been a major issue for us.
If there are some issues that were not covered by this questionnaire and you believe that they are relevant for an improvement in the infrastructure for the transportation of wind turbine components, please provide your comments below.	

What are the usual origin or destination cities or towns for shipping wind turbine components in Texas?	For Texas, most of the components currently are moving into West Texas for wind farm installations in that region. In regards to origins for domestically manufactured and/or sourced components, these would all originate outside of the state and are dependent on the OEM and their manufacturing locations. However, for import freight—primarily this is blades and towers—we see these coming into the gulf ports such as Galveston, Houston, and Corpus Christi. There are some instances of nacelles and hubs being imported as well but that is less common.

F.3. Phone Interview with Vestas Americas (paraphrased responses)

Company name	Vestas
Date	7/28/2015
Name of contact person	Maria Iredale
Phone	503-327-2319
E-mail	mholt@vestas.com
Which components of wind turbines do you transport? What are the usual dimensions?	My role is to transport the main components. Towers: widest in diameter are up to 14’9”. Blades: longest are up to 57.5m, but a model with 62m blades will be available this year. Hubs, nacelles (heaviest): up 75 tons (13 axle), but there is a push to super load on a 19 axle. The majority are moved on rail.
How many deliveries do you do per year? (or per month?)	Everything at some point is going to go on a truck. This year we will deliver about 1500 turbines. Multiply that by eight for each component.
What is your fleet size? What type of vehicles do you use? What are their dimensions?	We do not have our own fleet. (Note: could not divulge which carrier services Vestas uses.)
Does your company face issues regarding height-width clearance and weight limit on Texas' road network? What are the issues? Could you please give examples?	Texas is one of the friendliest with permitting and escort perspectives—it’s my favorite state to deliver wind into. There are no major issues I can think of.
Do your drivers face physical obstacles such as bridges, tunnels, tightly bending roads, etc., in their routes in spite of having a route plan and permit from the Texas Permitting and Routing Optimization System (TxPROS)? How do they overcome these challenges?	There may be issues with tunnels, bridges, etc., on a project, but there’s never been a problem with getting a reroute. We always got our delivery to the site.

Do you think there is a shortage of skilled drivers to transport wind turbine components or other oversize loads? Does it affect your services?	Yes, I do. I know there is. I have been in situations where I had the equipment but not the driver. Requires a lot of levels of expertise and certifications. Driver retention is a problem. Drivers will be very, very important, especially since this year is a PTC year (renewable electricity production tax credits issued).
Have you experienced any changes in dimensions of the wind turbine components you transport? If yes, how did it affect your fleet?	They tend to get bigger, heavier, and longer every year, pushing the envelope. However, Vestas is on the forefront of railing. We only truck in local areas if possible, although this is not always possible. (If there is proper communication, the designers will not design something too large to transport.)
What issues does your company face in obtaining a transportation permit from the Texas Department of Motor Vehicles (TxDMV) to transport wind turbine components?	Carriers are responsible for pulling the permits; it seems pretty efficient. We have received few problems and complaints from carriers obtaining permits.
Is there a wait period from your desired schedule of transportation to the actual schedule?	In Texas, you can deliver and install year round. There's a lot of flexibility. We typically do not have much trouble with the site being ready in time for us to deliver. We typically meet contracted delivery without too much trouble.
Is it difficult for your company to employ escort vehicles for transportation of wind turbine components? Are escort vehicles required for all components or only a few specific parts? And are they required for the entire trip or only certain segments of the trip?	There's no shortage of escorts in Texas. Typically, they are needed on all parts, but it depends on the mark of the turbine. The number of escorts needed varies by state: 1, 2, 3, 4, etc.
Does your company face any issues with the varying permit rules of different states for transportation of oversized and overweight loads on roads? Could you provide some examples?	Yes. Some states, especially in the northeast, have the older infrastructure. It's harder to get permits with the winding, skinny roads. In wide open Texas, this is not a problem.

If there are some issues that were not covered by this questionnaire and you believe that they are relevant for an improvement in the infrastructure for the transportation of wind turbine components, please provide your comments below.	N/A
What are the usual origin or destination cities or towns for shipping wind turbine components in Texas?	We have manufacturing facilities in Colorado: nacelle, blade, and tower factories. We also have overseas factories—we deliver to Houston, Corpus Christi, Brownsville, and Beaumont and move the components from there. (Note: respondent could not say what percentage of deliveries comes from Colorado or overseas.)

Appendix G: Number of Wind Turbines Manufactured by Each Company and Turbine Model

Company	**Total**/Split	Company	**Total**/Split
BHD	**10**	**Sany**	**5**
FL1000	10	SE8720	5
Bonus	**214**	**Siemens**	**844**
B62_1300	214	MK2	35
China Creative Wind	**17**	SWT2.3_101	87
Model unknown	17	SWT2.3_93	722
Clipper	**174**	**Suzlon**	**164**
C96	174	S64	96
DeWind	**21**	S88	66
D8.2	21	S95	1
ECO	**1**	S97	1
86	1	**Vestas**	**894**
Gamesa	**180**	V100_1.8	169
G87	180	V47	412
GE	**3078**	V66	8
1.5S	232	V80_1.8	67
1.5SLE	2331	V82	164
1.5XLE	417	V90_1.8	1
1.85_87	98	V90_3.0	73
Mitsubishi	**1356**	**Zond**	**40**
MWT1000	197	Z50	40
MWT1000A	844	**Northern Power Systems**	**3**
MWT92_2.4	315	NW100	3
NEG Micon	**107**	**Samsung**	**3**
NM48_700	107	2.5MW	3
Nordex	**12**		
N100	12		

Appendix H: Western Regional Permit Oversize/Overweight Restrictions for Texas

Following are the Texas restrictions that other WASHTO states must include for multi-state permits that involve routes through Texas.

For Travel on the Following Highways:

US59, US69, US77, US83, US84, US87, US287, US290, SH46, LP289, LP337 Contact Texas.

IH10 12' Width At the TX-NM line (both directions)

IH10
10' Width
70' Length

Turning IH10E To SE.LP375N; IH10W To SE.LP375S; Se.LP375N To IH10W; And In El Paso. Contact Texas For Detour

IH10 12' Width

N & S Frontage Roads: Between FM3351 (MP550) and Boerne Stage Rd in San Antonio. Boerne Stage Rd is located approximately ¾ mile south of FM3351.

IH10 12' Width

12' max width on the EFR and WFR between NW.LP1604 and Huebner Rd in San Antonio. Huebner Rd is located approximately ¼ mile south of N.LP345.

IH10
On and Off
Ramps Closed

All EB and WB Exit and Entrance Ramps between SP53 and Huebner Rd in San Antonio are closed. Huebner Rd is located approximately ¼ mile south of N.LP345.

IH10
No permits at
U-Turn

EB to WB U-Turn at Huebner Rd in San Antonio: No permits on the EB to WB U-Turn at Huebner Rd. Huebner Rd is located approximately ¼ mile south of N.LP345.

IH10
12'width
80' Length

San Antonio: Cloverleaf @ W.IH10/LP1604. Use The Following Detours:IH10E To LP1604E: IH10E, LP1604W, La Cantera (W Of IH10) X-Under, LP1604E.
IH10W To LP1604W: IH10W, La Cantera (N Of LP1604) X-Under, IH10E, LP1604w
N.LP1604E To IH10W: LP1604E, IH10E, SP53 X-Over, IH10W.
N.LP1604W To IH10E: LP1604W, IH10W, La Cantera (North Of LP1604) XUnder, IH10E Or LP1604W, La Cantera (W Of IH10) X-Under LP1604E, IH10E

IH10 Houston

Inside of IH610: Must Use IH610 To Detour Around Houston. Loads Starting Or Stopping Inside IH160, Contact Texas For Detour

IH10
NFR & SFR
No Permits MP 851 To MP853: W.US90 To N.US69, Beaumont Area

IH20 No Weight

No weight traveling W-Bound over FM1219 (MP73): Detour: IH20-Ramp off at

MP73-Ramp on after FM1219
IH20
12' Width
85' Length
&/Or 59' Trl
Roscoe: On The NFR And SFR Between 1/4 Mile West Of FM608 And 1/4 Mile East Of FM608. 12' Max Width, 85' Max Length, And/Or 59' Max Trailer Length
IH20
12' Width
85' Length
59' trailer length
12' max width, 14' max height, 85' max length, and/or 59' max trailer length on the ML, NFR, and SFR between CR Moore Field Rd and W.BI20 in Big Spring. CR Moore Field Rd is located approximately 1 ½ miles east of FM2599.
IH20
No Width
No Height &/Or
85' Length
On NFR And SFR In Abilene, Between BU83 To SL322
IH20 No Width North Frontage Road: From SH183 To SP465 (Fort Worth Area)
IH20NFR No Permits MP394: Over The Brazos River Truss Bridge, Millsap Area
IH27, US87,
LP289
Lubbock
All Loads Must Remain On IH27/US87 Through Lubbock Or Use LP289 Around Lubbock. Other Highways Inside The LP289 May Be Used Only For Loads With An Origin Or Destination Inside Of LP289.
IH27 No Permit No permits on the EFR and WFR between S.BI27 in Plainview and SH194.
IH27
No Width
No Weight
No width and/or no weight between S.BI27 in Plainview and SH194.
IH27 100' Length
100' max length and all vehicles must have no less than 18" of ground clearance on the WFR at the railroad crossing just north of SH194. This is a permanent restriction.
IH30 9' Width
NFR: W-bound near Royce City: From FM551 (MP77A) to FM548 (MP73)
SFR: E-bound near Royce City: From FM551 (MP77A) to FM548 (MP73)
IH30 No Permits
NFR: E-bound near Royce City: From FM548 (MP73) to FM551 (MP77A)
SFR: W-bound near Royce City: From FM551 (MP77A) to FM548 (MP73)
IH30 No Travel
No Travel Thru Downtown FT Worth Or Dallas Without Approval. Stopping Or Starting IH820 Ft Worth Contact Texas For Detour. Stopping Or Starting LP12 Dallas Contact Texas For Detour.
IH35
EFR & WFR
No Permits No Width From FM51 To Just South Of US82 In Gainesville
IH35EFR No Permits No Permits From N.LP340 In Waco To Lincoln City RD In Elm Mott
IH35 WFR 10' Width From Berger Rd To FM1237 (In Temple)
IH35WFR 10' Width N.Bu77 In Lacy Lakeview To N.LP340, Waco
IH35 &

N.BU77
Turns No Permits For Turns: To Or From IH35 & N.Bu77, Lacy Lakeview
IH35 10' Width
10' max width and/or 90' max length on the WFR between FM1858 and FM3149. Between Elm Mott and West, North of Waco.
IH35 No permits
No permits on the EFR between S.FM2268 and Stagecoach Rd/Robertson Rd in Salado. Stagecoach Rd/Robertson Rd is located approximately 1 mile north of S.FM2268.
IH35 13' 6" height
NBound at Stagecoach Rd/Robertson Rd in Salado. Stagecoach Rd/Robertson Rd is located approximately 1 mile north of S.FM2268.
IH35 No permits No permits on the WFR between N.FM2268 and FM2843 in the Salado area.
IH35 11' Width
11' max width on the EFR between Shanklin Rd and LP121 in Belton. Shanklin Rd is located approximately 1 ¼ miles south of LP121.
IH35 No Permits
No permits on the WFR between Big Elm Rd and 1 mile south of Big Elm Rd in Troy. Big Elm Rd is located approximately 2 ½ miles north of FM935.
IH35 10' Width
10' max width on the WFR between Berger Rd in Temple and FM1237.
Berger Rd is located approximately 1 mile north of N.LP363
IH35 13'6" Height Max Height Under FM935 – Troy (To Detour Ramp Off/Ramp On)
IH35 80' Length MP315: For All Turns To Or From IH35 Frontage Roads & FM107/SH7 In Eddy.
IH35
Austin:
See Details
Length And/Or Weight Only Or Not Over 13'6" High Travel Thru Austin On IH35 Must Use Inside Lower Level Lane . ***Detour For Austin Is: NB…IH35N, SH71E, US183N, IH35N….Vice Versa For SB Travel.***
IH35
12' Width &/or
80' Length
NB Exit ramp to FM3009 (MP175) in Schertz: 12' Width and/or 80' Length.
IH35
San Antonio:
See Details
Must Use LP1604 On North & East Side Or IH410 On East & South Sides To Detour Around San Antonio. For Loads Stopping Or Starting Inside LP1604 Contact Texas For Detour
IH35 12' Width between FM2790 and S.IH410, both directions (south San Antonio area)
IH35
11' Width &
150' length
No permitted turns:
• IH35 NB to NE.LP1604 NW, • IH35 NB to NE.LP1604 SE, • IH35 SB to NE.LP1604 NW, • IH35 SB to NE.LP1604 SE, • NE.LP1604 NW to IH35 SB
• NE.LP1604 SE to IH35 SB
IH35 Weights All Overweight Loads Must Have Load Zoned Axle Weight Distribution When Making Turns IH35SB To N.LP20, Laredo
IH35 Weights
All overweight loads must have load zoned axle weight distribution when making the following turns at this junction: Laredo. Axle Weights Are: 22,500

Single, 20,700 Tandem, 18,000 Triple, 15,750 Quad
IH35 NB To N.US83 NB, IH35 NB To IH35 SB, IH35 SB To N.US83 NB, US83 SB To N.IH35 NB, US83 SB To N.IH35 SB

IH35E See Details

Must Use IH635, And IH20 Route Around Dallas
For Travel On The West Side Of Dallas Using LP12 & SP408 LP12 10'Wide And 14' Tall Only

IH35E 10' Width MP399A To MP391: FM329 To FM876, Waxahachie Area

IH35W See Details

Must Use IH820 To Route Around Fort Worth. Loads Starting Or Stopping Inside IH820 Contact Texas For Detour

IH35W 10' Width

10' max width on the ML, EFR, and WFR between Meacham Blvd and Fossil Creek Blvd in Fort Worth. Meacham Blvd is located approximately 1 mile south of N.IH820. Fossil Creek Blvd is located approximately ½ mile north of N.IH820.

IH35W
No Turn
Around

In Fort Worth: Loads Cannot Travel IH35W NB To IH35W SB @ N.US287.

IH37NB No Permits

No Permits On The Entrance And Exit Ramps Between Carbon Plant Rd And FM3386, Corpus Christi.

IH37
EFR & WFR
Weight

4000 Lbs (Four Thousand) Single Axle On IH37 EFR And WFR From ¼ Mile North Of Ripple Rd (The "8" FR U-Turns) To The Nueces/San Patricio County Line. Ripple Rd Is Located Approximately ¾ Mile
North Of S.US77 In Calallen, North Of Corpus Christi

IH40 12' Width Into and Out of New Mexico.

IH40 12' Width MP96 To MP112: 12' Width From Conway (SH207) To Groom (FM295)

IH40NFR No Permits

No Permits On The NFR From FM295 To Where The NFR Ends West Of CR Weatherly Rd In Conway. CR Weatherly Rd Is Located Approximately 3 ¼ Miles East Of SH207

IH40 FRS No Permits

MP121 To MP124: No Permits On IH40 NFR And SFR From W.SH90 To E.SH70 Where It Is Double Signed With IH40, Jericho Area

IH45 No Access Traveling IH45 NB To FM489 EB Or WB In Freestone County, Near Dew

IH45 No Length No Length Exiting From The IH45 NB/SB Ml's To EB/WB FM977

IH45WFR 100' Long WFR: From SH7 To US79 & From FM977 To OSR

IH45 12' Width N-Bound between the Walker/Madison County line and SH21(MP142).

IH45 12' Width Northbound Between N.FM1374 And SH30 In Huntsville

IH45 10' Width East Frontage Rd, From SH30 To N.SH75 In Huntsville.

IH45 No Width MP178 To MP180: No Width In Buffalo Area

IH45 See Details

NB To S.LP336 In Conroe Must Take Exit #84
SB To S.LP336 In Conroe Must Take Exit #85
NB/SB To N.LP336 In Conroe Must Take Exit #88

IH45
EFR & WFR
13' Width

13’ Max Width On The EFR And WFR From S.LP336 To FM830 Where The Frontage Roads Exist, Conroe

IH45 No Permits

No permits on the N-bound exit ramp to Creighton Rd in Conroe. Creighton Rd is located 1 mile south of Loop 336.

IH45 No Width MP94: No Width Turns At FM1097, Willis

IH45

Houston:

See Details

Must Use IH610 To Detour Around Houston Loads Starting Or Stopping Inside IH610 Contact Texas For Detour

IH410 No Permits No Permit On Or Inside IH410 In San Antonio. Contact Texas For Detour

IH610 See Details

For Loads Stopping Or Starting Inside IH610 Around Houston: Contact Texas For Detour

IH610 No Permits On The NFR Between SP261 and US290 In Houston.

IH610 No Permits On SFR Between W.TC Jester and Ella Blvd. Heading East, Houston

IH610 No Permits EFR & WFR Between US59 and FM1093 In Houston.

IH635 10’ Width Dallas: Between IH35E and US75, North Dallas Area.

E.IH820 No Permits Traveling IH820NB To SH121SB, Fort Worth

N.IH820 100’ Length IH820 / SH199 Turning To Or From Making Left Turns

IH820 10’ Width

10' max width on the ML, NFR, and SFR between Mark IV Parkway and S.SH121 in Fort Worth. Mark IV Parkway is located approximately ¼ mile west of N.IH35W. This also affects SH121/SH183 where they are double signed with IH820.

US59 13’ 6” Height

S-Bound Max Height Between

Appendix I: Western Regional Vehicle Weight Table

Maximum load in pounds carried on any group of two or more consecutive axles

Distance*	2 axles	3 axles	4 axles	5 axles	6 axles	7 axles	8 axles	9 axles	10 axles
4	43,000	—	—	—	—	—	—	—	—
5	43,000	—	—	—	—	—	—	—	—
6	43,000	—	—	—	—	—	—	—	—
7	43,000	—	—	—	—	—	—	—	—
8	43,000	53,000	—	—	—	—	—	—	—
9	43,000	53,000	—	—	—	—	—	—	—
10	43,000	53,000	—	—	—	—	—	—	—
11	—	53,000	—	—	—	—	—	—	—
12	—	53,000	70,000	—	—	—	—	—	—
13	—	53,000	70,900	—	—	—	—	—	—
14	—	64,500	71,900	—	—	—	—	—	—
15	—	—	72,800	—	—	—	—	—	—
16	—	—	73,700	81,200	—	—	—	—	—
17	—	—	74,700	82,100	—	—	—	—	—
18	—	—	75,600	83,000	—	—	—	—	—
19	—	—	76,500	83,300	—	—	—	—	—
20	—	—	77,500	87,400	—	—	—	—	—
21	—	—	78,400	85,600	—	—	—	—	—
22	—	—	79,300	86,500	—	—	—	—	—
23	—	—	80,300	87,300	—	—	—	—	—
24	—	—	81,200	88,200	—	—	—	—	—
25	—	—	82,100	89,100	—	—	—	—	—
26	—	—	83,100	90,000	—	—	—	—	—
27	—	—	84,000	90,800	—	—	—	—	—
28	—	—	84,900	97,200	99,100	—	—	—	—
29	—	—	85,900	92,600	100,000	—	—	—	—
30	—	—	86,000	93,400	100,800	—	—	—	—
31	—	—	—	94,300	101,600	—	—	—	—
32	—	—	—	95,200	102,500	—	—	—	—
33	—	—	—	96,100	103,300	—	—	—	—
34	—	—	—	97,000	104,200	—	—	—	—
35	—	—	—	97,800	105,000	—	—	—	—
36	—	—	—	98,700	105,800	—	—	—	—
37	—	—	—	99,600	106,700	—	—	—	—
38	—	—	—	100,500	107,500	—	—	—	—
39	—	—	—	101,300	108,400	—	—	—	—
40	—	—	—	102,200	109,200	—	—	—	—
41	—	—	—	103,100	110,000	—	—	—	—
42	—	—	—	104,000	110,900	—	—	—	—
43	—	—	—	104,800	111,700	—	—	—	—
44	—	—	—	105,700	112,600	—	—	—	—
45	—	—	—	106,600	113,400	—	—	—	—
46	—	—	—	107,500	114,200	121,600	—	—	—
47	—	—	—	—	115,100	122,400	—	—	—
48	—	—	—	—	115,900	123,200	—	—	—
49	—	—	—	—	116,800	124,000	—	—	—
50	—	—	—	—	117,600	124,800	—	—	—
51	—	—	—	—	118,400	125,700	—	—	—
52	—	—	—	—	119,300	126,500	—	—	—
53	—	—	—	—	120,100	127,300	—	—	—
54	—	—	—	—	121,000	128,100	135,600	143,300	151,200
55	—	—	—	—	121,800	128,900	136,400	144,100	152,000
56	—	—	—	—	122,600	129,700	137,200	144,900	152,800
57	—	—	—	—	123,500	130,600	138,000	145,700	153,500
58	—	—	—	—	124,300	131,400	138,800	146,500	154,300
59	—	—	—	—	125,200	132,200	139,600	147,300	155,100
60	—	—	—	—	—	—	140,400	148,100	155,900
61	—	—	—	—	—	—	141,200	148,800	156,600
62	—	—	—	—	—	—	142,000	149,600	157,400
63	—	—	—	—	—	—	142,800	150,400	158,200
64	—	—	—	—	—	—	143,600	151,200	159,000
65	—	—	—	—	—	—	144,400	152,000	159,800
66	—	—	—	—	—	—	145,200	152,800	160,000
67	—	—	—	—	—	—	146,000	153,600	—
68	—	—	—	—	—	—	146,800	154,400	—
69	—	—	—	—	—	—	147,600	155,100	—
70	—	—	—	—	—	—	148,400	155,900	—
71	—	—	—	—	—	—	149,200	156,700	—
72	—	—	—	—	—	—	150,000	157,500	—
73	—	—	—	—	—	—	150,800	158,300	—
74	—	—	—	—	—	—	151,600	159,100	—
75	—	—	—	—	—	—	152,400	159,900	—
76	—	—	—	—	—	—	153,200	160,000	—
77	—	—	—	—	—	—	154,000	—	—
78	—	—	—	—	—	—	154,800	—	—
79	—	—	—	—	—	—	155,600	—	—
80	—	—	—	—	—	—	156,400	—	—
81	—	—	—	—	—	—	157,200	—	—
82	—	—	—	—	—	—	158,000	—	—
83	—	—	—	—	—	—	158,800	—	—
84	—	—	—	—	—	—	159,600	—	—
85	—	—	—	—	—	—	160,000	—	—

Appendix J: Detailed Route Plan (Base Scenario)

Blue line 1 (Corpus Christi to Reynosa): I-37N, US-77 S, US-281, I-69C.

Blue line 2 (Corpus Christi to North of San Antonio): US-181, TX-123, TX-46, US-281.

*Blue line 3 (North of San Antonio to North of Amarillo):*US-281, TX-71, US-283, US-84, US-277, US-83, US-62, US-287, TX-207, TX-136.

Blue line 4 (North of San Antonio to El Paso): I-10, TX-163, TX-137, US-190, I-10.

Green line (Freeport to Fort Worth): TX-36, TX-35, TX-60, TX-36, US-190, TX-217, TX-6, TX-174.

Red line (Wichita Falls to Midland): TX-148, US-281, US-377, US-37, TX-158.

*Orange line 1 (New Mexico to North of Amarillo):*US-82, US-380, US-385, US-87.

*Orange line 2 (New Mexico to East of Lubbock):*US-82, US-380.

Orange line 3 (New Mexico to Acuña): US-82, TX-214, US-385, TX-176, TX-137, TX-163.

*Purple line 1 (Houston to Amarillo):*TX-330, I-10, TX-8, US-290, TX-95, TX-29, US-183, US-84, US-67, TX-158, US-272, TX-70, TX-208, US-82, US-62, TX-70, I-27.

Purple line 2 (Houston to Fort Worth): TX-146, TX-105, I-45.

*Purple line 3 (Houston to Tyler):*TX-146, TX-105, I-45, US-79, TX-155.