HIGHWAY DAMAGE DUE TO MOVEMENT OF WIND TURBINE COMPONENTS

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ABSTRACT

This paper proposes a methodology for assessing the damage imposed by the movement of wind turbine components on Texas’s highway infrastructure. The pavement damage associated with traffic resulting from site preparation was omitted from the scope of this study because reliable data characterizing the construction traffic were not available. The damage to the pavement structure was estimated using three primary distresses: rutting, longitudinal, and alligator cracking. In addition, the impact on the ride quality was also estimated. Pavement damage was evaluated using the Mechanistic Empirical Pavement Design Guide (MEPDG). The methodology adopted involved calculating the pavement distress due to the combined effect of the wind turbine and the design traffic relative to the design traffic only. This ensures that biases in the distress predictions obtained from the MEPDG will cancel each other out in each of the two scenarios. For the roughness estimate, the difference between the damage value due to the combined traffic and the design traffic only was evaluated and deemed as the damage indicator. The researchers observed that the increased pavement damage in the case of national highways was roughly 0.3 and 4 per cent irrespective of the distress mechanism. However, the pavement damage on state highways had a much more serious impact. The researchers observed that the relative damage imposed on the pavement structure from a roughness perspective was minimal. The additional damage imposed by the wind turbine truck traffic will translate into a reduction in pavement service life estimated at 9 per cent.

1. INTRODUCTION

Over the last decade, the wind energy sector has become a growing part of the Texas’s energy sector. Currently wind turbines generating 35,603 MW of wind energy are installed in the U.S., of which 27.3 per cent are installed in Texas (AWEA, 2009). In Texas, most of the development has occurred in the Competitive Renewable Energy Zones identified by the Public Utility Commission of Texas (PUCT). These areas were defined as having the highest potential for wind energy generation in the state.

Much of the wind energy industry development been driven by federal and state incentives. For example, in Texas, the Renewable Portfolio Standard obliges electricity retailers serving open markets to purchase a portion of their electricity from renewable energy sources. Incentives from the federal government include a production tax credit (PTC) of 2.1 cents/kilowatt-hour for commercial wind farm developers (Wiser, 2001). Furthermore, wind energy advocates are currently promoting a National Renewable Electricity Standard (RES), which would ensure that 25 per cent of the U.S. electricity demand is met by renewable energy sources by 2025 (AWEA, 2010a).
As government incentives continue to drive wind energy investments, the U.S. wind manufacturing sector has grown substantially. In 2004, domestically manufactured components provided for less than 25 per cent of total installed wind capacity. At the start of 2010, 50 per cent of the wind turbines installed in U.S. were manufactured domestically (AWEA, 2010b). The level of investment in the U.S. wind industry is thus also reflected in the number of manufacturing facilities that have opened in the past several years. In 2008, for example, the U.S. Department of Energy reported that 37 manufacturing facilities were producing various wind turbine components (USDE, 2010). Currently 67 manufacturing facilities are operating in the U.S., and plans for the construction of 20 new facilities were announced in early 2010. Texas is witnessing an unprecedented growth in wind power development. Wind farm development generates traffic to move wind turbine components. Determining the impact of this additional traffic on Texas’s highway infrastructure is therefore essential.

2. TRANSPORTATION OF WIND TURBINE COMPONENTS

Data from the Oversize-Overweight (OS/OW) database showed that on an annual basis, anywhere from 13,000 to 20,000 permits are issued to the wind energy industry for moving wind turbine components on Texas roads. In general, a wind turbine requires between 8 and 10 OS/OW permits to move components from the point of origin to the wind farm site (i.e., 1 permit for the nacelle, 1 permit for the rotor hub, 3 permits for the blades, and 3 to 5 permits for the tower). Thus, Texas facilitates the movement of about 1,300 to 2,500 wind turbines per year on its transportation network.

The OS/OW database was used to identify the routes vehicles used in hauling components from origin to destination. Furthermore, analysis of the OS/OW database provided the research team with an understanding of which roadway facilities are most impacted by the wind sector and the average distance of haul. This analysis showed that on an annual basis approximately 25 to 30 per cent of wind turbine traffic originates in the bordering states of Arkansas, Louisiana, New Mexico, and Oklahoma—the bulk of which enters the state from New Mexico and Oklahoma. Furthermore, most wind turbine components enter through the ports of Houston, Galveston, Corpus Christi, Beaumont, and Freeport. Approximately 42 per cent of all permits issued to the industry originate from these five ports. In-state manufacturing facilities also generate wind activity. Particularly, two manufacturing plants owned by Trinity Structural Towers in Fort Worth and Coleman are the origins of 15 to 20 per cent of permits issued to the industry. A similar analysis was conducted for route destinations. The study found that 26 to 42 per cent of permits issued to the wind industry terminate in the bordering states. In-state destinations accounted for 58 to 74 per cent of the issued permits.

The next step in the analysis required determining the types of roadway facilities impacted by the movement of wind turbine components. Drawing a random sample of 97 records from the 2009 OS/OW database, and plotting each record’s route in Google Maps, provided a representative distribution of roadway facilities used in the transportation of wind turbine components, as well as the average distance of haul. The total vehicle-miles traveled (VMT) for the 97-record sample was 63,102.1 kms. Facility usage as a percentage of total VMT is illustrated in Figure 1.

Figure 1 shows that most of the VMT occurs on national facilities such as the Interstate (IH) (49.2 per cent) and the US Highway (27.4 per cent) system. For the IH, most of the VMT occurred on IH-10 (41.8 per cent), IH-20 (18.2 per cent), and IH-45 (18.8 per cent).
Farm-to-market (FM) roads facilitated only about 3.5 per cent of total VMT. FM roads typically serve as the final link in the distribution network.

The average haul distance in Texas was 669.7 kms (standard deviation: 355.4 kms). Figure 2 illustrates the distribution for haul distances, indicating that, other than a few peaks at 80 (50 miles), 161 (100 miles), and 1208 (750 miles) km, the distribution takes on a normal shape with a mean centered around 725 km.

Truck transportation is currently the most pragmatic mode to deliver wind turbine components. The biggest advantage that trucks have over rail is the ability to deliver components directly to the construction site (AWEA, 2010b). Because most wind development sites are in remote rural locations, often they are accessible only by road. Even if the components were to be shipped by rail, a leg of the journey would still have to be made by truck.
3. **STUDY GOAL AND METHODOLOGY**

This paper focuses on the impacts imposed by transporting wind turbine components on the Texas highway infrastructure. The methodology presented in this paper aims to quantify the infrastructure damage incurred in terms of key distress mechanisms such as rutting and fatigue cracking. In addition, the paper attempts to quantify the impact of the additional traffic on roughness scores.

The FM road network in Texas is large, therefore, an understanding of the damage imposed by wind related traffic could be argued to be equally important. However, Figure 1 shows that the wind turbine trucks are a mere 4 per cent of the total FM VMT. Thus, estimating the pavement damage on IH, US, and State Highways ensures that 93 per cent of the wind turbine component-related damage is accounted for.

To quantify the damage due to wind turbine component movement, pavement sections were located along the corridors through which the wind turbine components are routed. To calculate the additional damage due to turbine transportation, determining the expected traffic on these pavement sections along with their material and structural designs is essential. In addition, the proper characterization of the truck traffic required for moving the components requires knowledge of the expected number of wind turbines to be installed in a given year. The following sections discuss each of these aspects.

3.1 **Calculation of the Traffic Generated due to Movement of Wind Turbine Components**

The American Wind Energy Association (AWEA) provides quarterly reports on U.S. wind energy projects, including detailed information on the number of wind turbines that were installed between 2000 and 2009. According to the OS/OW database, the installation of one wind turbine generates nine OS/OW truck trips. These two data sources were used to calculate the total amount of turbine-related truck traffic moving daily on the Texas network (see Figure 3). Wind turbine components are routed through different corridors to reach their destinations. Thus, evaluating the impact due to this additional truck traffic requires determining the wind traffic that will traverse a particular pavement section.

Ninety seven records from the OS-OW database were extracted through random sampling and analyzed to visualize the routes used to move these OS/OW wind loads. For each of the pavement sections, the percentage of wind traffic that would travel that section by considering how many of the routes included the section. After that, determining the annual average daily turbine-related truck traffic seen by a particular pavement section is then possible.
Figure 3: Average daily traffic generated by movement of turbine components (AWEA, 2010c; AWEA, 2010d).

3.2 Design Traffic

Design traffic refers to the expected truck traffic volume that the pavement is designed for. The Texas Department of Transportation (TxDOT) maintains network-level traffic volume information for its entire highway network in the Pavement Management Information System (PMIS) database. The 20-year cumulative standard axle count data included in PMIS was used to calculate the annual average daily design truck volume. To simplify the problem, the design truck type was assumed to consist of two standard 82 kN axles. Figure 4 shows the design truck count obtained for each of the IH sections.

Figure 4: Design traffic for IH sections from Texas PMIS database.
3.3 Structural and Material Information

TxDOT includes the design details of recently approved construction contracts in an intranet database, “Plans Online.” This database provides detailed structural information and information on the material design for a given project (Figure 5). Plans Online designs were used as the structural designs for the pavement sections. The design also provided information on the material used for the construction of a given structural layer. For example, in the case of a surface layer, the design will clearly state whether a fine surface mix like a dense grade PG76-22 Type-D was used or if a relatively coarse dense graded mix like the PG76-22 Type-C was used. This information in most cases was used to determine the typical gradation, binder content, and the air voids for the given mix from TxDOT’s Specification (TxDOT, 2004).

3.4 Analysis and Calculation of Damage

The damage due to the movement of the wind turbine components was calculated using the MEPDG, developed as part of the National Cooperative Highway Research Program (NCHRP) Projects 1-37A and 1-40D. In this method, pavement responses are calculated using a multi-layer linear elastic approach (ARA, 2004). These pavement responses are then related to field distresses using transfer functions. However, modeling a pavement section using the MEPDG requires detailed information about the pavement’s structure, materials, and expected load. The previous sections explained how this information was obtained in order to enable the research team to model these sections.

Figure 5: Structural details of IH-10 in Orange County.
Wind power investments are a function of several factors, including government incentives in the form of tax breaks, mandates authorized by state and federal legislation, and an increasing environmental awareness. These and other factors make the determination of the exact number of wind turbine installations in a given year quite uncertain. To account for this uncertainty, two additional scenarios were modeled for any given pavement section. The first scenario assumed the pavement being subjected to turbine-related traffic volume is one standard deviation higher (+SD) than the expected traffic (Figure 4) and the second scenario assumed a wind traffic volume that is one standard deviation lower (-SD) than the expected value. Thus, the three scenarios provide a robust estimate of the pavement response by accounting for the uncertainties of Texas wind power development.

4. MAIN FINDINGS

4.1 Additional Damage Imposed by Movement of Wind Turbine Components

Using the transfer functions in the MEPDG without calibrating to local conditions implies that the distress predictions will be systematically biased. To account for the bias in the predictions, the additional damage due to the movement of the wind-related trucks was calculated as a ratio of the damage due to the cumulative effect of the wind and design traffic relative to the effect of the design traffic only. Calculating a ratio will result in the bias term in the numerator as well in the denominator canceling each other out. Therefore, in a situation where the additional damage due to the wind turbine traffic is negligible, the damage ratio will be approximately equal to one. Thus, the damage parameter for rutting, longitudinal cracking and alligator cracking is as given in Equation 1.

\[ DP = \frac{\text{Damage due to Wind Traffic} + \text{Design Traffic}}{\text{Damage due to Design Traffic}} \] (1)

where, \( DP \) = Damage Parameter for a particular distress.

Figure 6 provides the damage parameter for US Highway sections from a rutting perspective. Figure 6 indicates that the additional damage imposed by the movement of the wind components on US Highways is about 5 per cent. For IH and State Highways (SH), the damage was 1 and 8 per cent, respectively. Similar trends were observed with respect to the other two distress mechanisms, i.e., longitudinal and alligator cracking. The damage parameters computed for IH sections from an alligator cracking perspective are provided in Figure 7.

Figure 7 suggests the additional damage imposed by the movement of wind turbine components is less than 1 per cent for IH sections over a 20-year service life. However, the lower functional road classes, such as US and SH, witnessed a gradual increase in the damage parameters.

The increase in the damage parameters can be attributed to two factors. Firstly, the higher functional classes (i.e. IH) are designed to carry higher daily truck traffic volumes compared to the lower functional classes. This design difference results in greater relative damage imposed by the design traffic with respect to the damage caused by the wind traffic; therefore, the net damage ratio will reduce. Second, the higher functional classes are designed to carry higher traffic volumes and therefore their structural capacity is much higher than that of the lower classifications. The additional wind turbine truck traffic thus has a very low impact on the pavement structure of the higher functional classes as compared to the lower ones. On the contrary, most wind turbine components are hauled a significant distance over IH relative to US and SH. Thus, the pavement structure of the US
and SH limits the distances over which the wind turbine-related truck traffic can be moved on these lower functional classes without imposing substantial damage.

Figure 6: Damage parameter for rutting for US highway sections after 20 years.

Figure 7: Damage parameter with alligator cracking IH sections after 20 years.
In terms of roughness, the additional damage due to the movement of wind turbines was assessed differently. The roughness transfer function is additive and is defined as the sum of all other distress types, including the ones measured above and transverse cracking. Therefore, the approach consists of calculating the difference between the roughness predicted due to the combined effect of the wind turbine and design traffic and that computed due to the effect of the design traffic only. As the transfer function is additive, computing the difference of two roughness scores will cancel out the bias in the predictions. The damage parameter from a roughness standpoint is defined in Equation 2.

\[ DP = \text{Rough due to Wind and Design Traffic} - \text{Rough due to Design Traffic} \quad (2) \]

Figure 8 presents the damage parameter for US sections from a roughness perspective. It suggests that the damage increases when moving from a higher to a lower functional class of highway. Table 1 summarizes the damage parameters as computed for each distress mechanisms and the roughness scores for each of the three functional highway classes.

The results presented in Table 1 show that the damage indicators start increasing in general when moving from a higher to lower functional road classes. However, in this context, the financial and economic impacts of these indicators may not necessarily show the same trend, as the cost of constructing one lane mile of IH is higher than that of US or SH. Even then, it is still important to note the extent of damage imposed by the movement of wind turbine components and the resulting reduction in the service life of the pavement.

As highlighted in the previous discussion, the VMT incurred by the wind turbine truck traffic occurs mostly on the higher functional highway classifications. The VMT by highway functional class was illustrated in Figure 1. To estimate the overall impact of the OS/OW truck traffic associated with wind energy development in Texas, the individual functional class damage factors can be weighed by the proportion of the total VMT that is traversed on the given functional class.

![Figure 8: Damage parameter for roughness for US sections after 20 years.](image)
Table 1: Damage Parameters and Distress Mechanisms.

<table>
<thead>
<tr>
<th>Distress Mechanism</th>
<th>Facility Type</th>
<th>One Std. Dev. Lower</th>
<th>Expected Traffic</th>
<th>One Std. Dev. Higher</th>
</tr>
</thead>
<tbody>
<tr>
<td>Longitudinal Cracking</td>
<td>IH</td>
<td>0.1</td>
<td>0.3</td>
<td>0.4</td>
</tr>
<tr>
<td>(per cent)</td>
<td>US</td>
<td>0.2</td>
<td>2.3</td>
<td>4.4</td>
</tr>
<tr>
<td></td>
<td>SH</td>
<td>32</td>
<td>58</td>
<td>144</td>
</tr>
<tr>
<td>Alligator Cracking</td>
<td>IH</td>
<td>0.1</td>
<td>0.2</td>
<td>0.4</td>
</tr>
<tr>
<td>(per cent)</td>
<td>US</td>
<td>0.1</td>
<td>4.1</td>
<td>4.4</td>
</tr>
<tr>
<td></td>
<td>SH</td>
<td>1.0</td>
<td>4.1</td>
<td>7.4</td>
</tr>
<tr>
<td>Rutting</td>
<td>IH</td>
<td>0.2</td>
<td>0.4</td>
<td>0.7</td>
</tr>
<tr>
<td>(per cent)</td>
<td>US</td>
<td>0.3</td>
<td>4.8</td>
<td>8.1</td>
</tr>
<tr>
<td></td>
<td>SH</td>
<td>1.7</td>
<td>7.6</td>
<td>11.8</td>
</tr>
<tr>
<td>Roughness</td>
<td>IH</td>
<td>0.1</td>
<td>0.2</td>
<td>0.3</td>
</tr>
<tr>
<td>(inches/mile)</td>
<td>US</td>
<td>0.6</td>
<td>1.2</td>
<td>1.8</td>
</tr>
<tr>
<td></td>
<td>SH</td>
<td>0.6</td>
<td>1.3</td>
<td>1.9</td>
</tr>
</tbody>
</table>

Table 2 provides the overall impact scores associated with OS/OW wind turbine truck traffic on the Texas network with respect to each of the three distress mechanisms (rutting, longitudinal cracking, and alligator cracking) as well as the impact on roughness.

Table 2: Overall Impact on Highway Infrastructure due to Wind Turbine Truck Traffic.

<table>
<thead>
<tr>
<th>Distress Type</th>
<th>Impact on IH</th>
<th>Impact on US</th>
<th>Impact on SH</th>
<th>Overall Impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>Longitudinal Cracking</td>
<td>0.3 per cent</td>
<td>2.3 per cent</td>
<td>58 per cent</td>
<td>+11.4 per cent</td>
</tr>
<tr>
<td>Alligator Cracking</td>
<td>0.2 per cent</td>
<td>4.1 per cent</td>
<td>4.1 per cent</td>
<td>+2.1 per cent</td>
</tr>
<tr>
<td>Rutting</td>
<td>0.4 per cent</td>
<td>4.8 per cent</td>
<td>7.6 per cent</td>
<td>+3.0 per cent</td>
</tr>
<tr>
<td>Roughness</td>
<td>0.003 m/km</td>
<td>0.019 m/km</td>
<td>0.021 m/km</td>
<td>+0.011 m/km</td>
</tr>
</tbody>
</table>

The data presented in Table 2 indicates that the damaging effects of the OS/OW wind turbine truck traffic are more serious from a longitudinal cracking perspective than from an alligator cracking or rutting. The results also indicate that the traffic's effect on roughness measure is minor.

4.2 Impact on Service Life of Pavements

The design life for flexible pavements in Texas is 20 years. At the end of this period, the structure will reach a terminal distress level at which point it would require rehabilitation. The difference in the time period to reach the terminal distress level due to the design traffic, and due to the combined effect of the design and wind turbine truck traffic, reflects the reduction in the service life due to wind energy development (see Figure 9).

The reduction in the service life of the pavement sections were evaluated from a rutting perspective. Figure 10 illustrates the reduction in service life for the US Highway sections due to the movement of wind turbine components.

On average, the reduction in the service life of pavements due to movement of wind turbine components on IH, US, and SH were 1.9, 15.2, and 20.2 per cent, respectively. A weighted average of the service life reduction was calculated based on the VMT proportion traversed on each highway class. Thus, the overall reduction in the service life of pavements due to the wind turbine truck traffic was estimated at 9.1 per cent.
5. CONCLUSIONS

This paper presents a methodology for estimating damage to the Texas highway network due to the movement of wind turbine components. The procedure entails the usage of the recently developed MEPDG for estimating pavement damage with respect to three primary distress mechanisms, i.e., rutting, longitudinal cracking, and alligator cracking. In addition, the extent of damage on the pavement structure from a roughness perspective was also estimated. The truck volumes associated with transporting wind turbine components was obtained from estimates provided by the AWEA. TxDOT’s OS/OW database was used to identify the major corridors for the movement of this traffic. Pavement damage was
assessed on sections that were located along these routes on IH, US, and SH. However, no pavement section was sampled from FM roads because they represented a relatively small share of the VMT incurred by the wind turbine truck traffic.

The results presented in general show that the wind turbine truck traffic is likely to impose greater damage to the pavement structure when moving from higher to lower functional classes. This outcome is primarily due to the lower classes of highways, especially state highways, not being designed to carry heavy traffic volumes or axle loads. The evidence suggests that most of the wind turbine truck traffic traverses on higher functional classes, partly because the pavement structure of the lower functional classes limits the distances that these trucks can traverse on them. The results indicate that the additional damage due to wind turbine component transportation on IH and US highway sections is about 0.3 and 4 per cent higher respectively, irrespective of the distress mechanism. However, in the case of SH highways, the results indicate that the movement of the wind turbine truck traffic will result in a 58 per cent increase in longitudinal cracking, which implies that it will reduce the service life of the pavement by 37 per cent. Also observed was that the impact on the roughness scores was minimal for all three types of functional classes.

In terms of the overall impact of the OS/OW wind turbine truck traffic, the study established that the additional damage imposed was 2 and 3 per cent for alligator cracking and rutting, respectively. However, from a longitudinal cracking perspective, the additional damage imposed was almost 11 per cent higher relative to the damage imposed by the design traffic. As far as the roughness measure was concerned, the OS/OW wind turbine truck traffic contributed an additional 0.011 m/km over a 20-year analysis period.

The additional damage imposed by the truck traffic associated with wind energy development will result in a reduction in the service life of the pavements. Assuming that the pavements were constructed to reach their terminal distress values at the end of the analysis period, given the design traffic, the time to reach the same terminal distress value was calculated due to the combined effect of the design traffic and the wind turbine truck traffic. The results from this study suggest that the reduction in the service life of the highway infrastructure due to movement of wind turbine components is about 9 per cent.

6. REFERENCES
