Determining Pavement Damage Cost Attributed to Truck Traffic in Southwest Kansas

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ABSTRACT

The southwest Kansas region is one of the centers in the United States for the production of processed beef and related industries. Trucks utilized to support these industries cause noteworthy damages to the regional highway pavements. The objective of this research project was to determine the pavement damage cost of a typical highway section in southwest Kansas attributed to the truck traffic for the processed beef and related industries. To achieve the project objective, the researchers first collected pavement data from the Kansas Pavement Management Information System. Then, they estimated the truck vehicle miles traveled that were generated by the industries on the selected highway section. Finally, using these data, the researchers determined the damage cost in 2007 dollar value of the selected highway section associated with the industries. During data analysis, the researchers adopted a systematic pavement damage estimation procedure that incorporated a time-decay model and a traffic-related damage model developed by American Association of State Highway and Transportation Officials and used in the Highway Economic Requirements System. Results of the analysis indicated that the damage cost was as high as $1,727 per mile per year on the 41-mile highway section attributed to the beef and related industries. Outcomes of this research will help highway agents assess highway pavement maintenance needs and set up maintenance priorities. In addition, the analysis results will be valuable for the determination of reasonable user costs.

Key words: cost—damage—Kansas—pavement—truck
INTRODUCTION

Kansas is one of the leading states in the processed meat and related industries in the United States. It ranks first in number of cattle slaughtered nationwide, second in total number of cattle, and third in the number of cattle on feed and in red meat production by commercial slaughter plants in 2004 (USDA 2005). In Kansas, the southwest region plays a key role in the industries by having more than three hundred feed yards and several of the biggest meat processing plants in the nation. The processed meat and related industries use trucks as the dominant transportation mode, which speeds up highway pavement damage in the region and causes concerns including air pollution, fuel consumption, safety, and congestion.

Previously, the Kansas Department of Transportation (KDOT) initiated a research project to study the transportation modes used in the processed beef and related industries in the southwest Kansas region and their impacts on local and regional economies (Bai et al. 2007). The researchers of that project collected related transportation data and estimated truck vehicle miles traveled (VMT) generated by the industries in the region. It became particularly interesting for government agencies and the industries to determine the highway pavement damage costs associated with the VMT, which will be valuable for stakeholders to understand the highway pavement damage costs attributable to the processed beef and related industries and to promote the utilization of other transportation modes. The knowledge can be also used to assess highway pavement maintenance needs and to set up maintenance priorities. In addition, the analysis results will be valuable for the determination of reasonable user costs.

LITERATURE REVIEW

The highway pavement damage cost analysis required knowledge of various subjects, including the processed meat and related industries in southwest Kansas, highway maintenance theories and practices, heavy-vehicle impact on pavement damage, fundamentals of pavement management systems, and pavement performance/condition predictions. To date, various agencies and individuals have performed studies that involved estimation of highway damage associated with certain types of heavy vehicles. For instance, some researchers have studied the road damage costs due to abandoned short-line railroads (Babcock et al. 2003; Russell et al. 1996), changes in regulations governing truck weights and dimensions (Hajek et al. 1998), and proposed drawdown usage of major waterways (Lenzi et al. 1996). The authors did not find studies that analyzed pavement damage attributed to a certain type of industry, such as the processed beef industry.

Some of the popular models currently used fall in different categories based on the model development methodologies, including Bayesian models, probabilistic models, empirical models, mechanistic-empirical models, and mechanized models (AASHTO 2002). Among these, empirical models have been widely used in pavement damage studies because of their maturity and reasonable accuracy. Tolliver (2000) developed a cost estimation procedure that utilized empirical models relating the physical lives of pavements to truck-axle loads and environmental factors. These empirical models were originally developed from American Association of State Highway Officials (AASHO) road test data and later incorporated into the pavement design procedure developed by AASHTO and followed by many state Departments of Transportation (DOT) including KDOT. In addition, the equations and functions used in these models have also been embedded in the pavement deterioration model of Highway Economic Requirements System (HERS), a comprehensive highway performance model used by the Federal Highway Administration (FHWA) to develop testimony for Congress on the status of the nation’s highways and bridges (FHWA 2002). The data required for the analysis procedure were available in the Pavement Management Information System (PMIS) database managed by each state DOT.
PAVEMENT PERFORMANCE PREDICTION MODELS

Two types of deterioration models were utilized in this study: a time decay model and an equivalent single axle load (ESAL). The former addresses the pavement damage caused by environmental factors, and the latter analyzes the pavement damage due to truck traffic. These two models are briefly described below. A detailed description of the equations used in the models can be found in (Liu 2007).

Traffic-Related Pavement Damage Model

Calculation of ESAL Factor

The ratio of decline in pavement serviceability relative to the maximum tolerable decline in serviceability can be used as a damage index to measure pavement damage:

\[
\beta = \frac{P_I - P}{P_I - P_T} \left( \frac{N}{\tau} \right)^{\beta},
\]

where \( P_I \) = initial pavement serviceability rating, \( P_T \) = terminal pavement serviceability rating, \( P \) = current pavement serviceability rating, \( N \) = the number of passes of an axle group of specified weight and configuration (e.g., a single 18-kip axle), \( \tau \) = the number of axle passes at which the pavement reaches failure (i.e., the theoretical life of the pavement), and \( \beta \) = deterioration rate for a given axle.

For flexible pavements, the unknown parameter \( \beta \) in equation (1) can be estimated through regression equations developed based on AASHO road test data, as shown in equation (2). Using the single 18-kip axle as a reference axle, the parameters can then be computed, as shown in equation (3). Based on these parameters, equations (4) and (5) are derived to compute the equivalent rate of flexible pavement deterioration caused by a single axle load in comparison to an 18-kip axle load and by a tandem axle group.

\[
\beta = 0.4 + 0.081\left( \frac{L_1 + L_2}{SN + 1} \right)^{23} 1.39 \times 10^L_2 23,
\]

\[
\beta_{18} = 0.4 + 0.081\left( \frac{18 + 1}{SN + 1} \right)^{23} = 0.4 + \frac{1094}{(SN + 1)^{1.9}}.
\]

\[
\log_{10}(ESAL) = 4.79 \log_{10}\left( \frac{L_1 + 1}{18 + 1} \right) + \frac{G}{\beta_{18}} - \frac{G}{\beta},
\]

\[
\log_{10}(ESAL) = 4.79 \log_{10}\left( \frac{L_2 + 2}{18 + 1} \right) - 4.33 \log_{10}(2) + \frac{G}{\beta_{18}} - \frac{G}{\beta}.
\]

where \( L_1 \) = axle load in thousand pounds or kips, \( L_2 \) = axle type (1 for single, 2 for a tandem, and 3 for triple axles), \( SN \) = structural number of flexible pavement section, and \( \beta_{18} \) = deterioration rate for a single 18-kip axle load. In both equations (4) and (5),
The ESAL factor \( n \) is computed by taking the inverse logarithm of the appropriate expression, as shown in equation (7):

\[
n = 10^{\log_{10}(ESAL)}.
\]  

(7)

The above equations are derived for flexible pavements. For rigid pavements, equation (8) is used to convert rates of deterioration to rigid pavement ESAL for single axle loads, and equation (9) is utilized to compute the equivalent rate of pavement deterioration caused by a given tandem axle group. \( G \) is computed using equation (10), and \( n \) is computed using equation (11).

\[
\log_{10}(ESAL) = 4.62 \log_{10}\left(\frac{L_s + 1}{18 + 1}\right) + \frac{G}{\beta_{18}} - \frac{G}{\beta},
\]

(8)

\[
\log_{10}(ESAL) = 4.62 \log_{10}\left(\frac{L_s + 2}{18 + 1}\right) - 3.28 \log_{10}(2) + \frac{G}{\beta_{18}} - \frac{G}{\beta},
\]

(9)

\[
G = \log_{10}\left(\frac{P_L - P_T}{P_I - 1.5}\right),
\]

(10)

\[
n = 10^{\log_{10}(ESAL)}.
\]

(11)

**Calculation of ESAL Life**

The ESAL life of a pavement is the cumulative number of ESAL that the pavement can accommodate before it needs to be rehabilitated. The following equations were included in HERS and can be used to calculate the cumulative ESAL, or \( LGE \):

\[
LGE = XA + \frac{XG}{XB},
\]

(12)

\[
SNA = SN + \sqrt[6]{\frac{6}{SN}},
\]

(13)

\[
XB = 0.4 + \left(\frac{1.094}{SNA}\right)^{5.19},
\]

(14)

\[
XG = \log_{10}\left(\frac{P_L - P_T}{3.5}\right),
\]

(15)

\[
XA = 9.36 \log_{10}(SNA) - 0.2.
\]

(16)
where \( LGE \) = cumulative ESAL that a pavement section can accommodate before reaching its terminal serviceability rating (in logarithmic form), \( XB \) = rate at which a pavement’s life is consumed with the accumulation of ESAL, \( XG \) = pavement serviceability loss in terms of the maximum tolerable pavement Present Serviceability Rating (PSR) loss (from \( P_I \) to \( P_T \)), \( XA \) = theoretical life of newly constructed pavement in ESAL, and \( SNA \) = converted pavement structural number.

The actual life cycle of a flexible pavement is computed by taking the inverse logarithm of \( LGE \):

\[
ESALLifecycle = 10^{LGE}.
\]

(17)

For rigid pavements, the theoretical life is a function of the thickness of the concrete slab \( (d) \) and can be calculated using the following equations:

\[
ESALLifecycle = 10^{LGE},
\]

where

\[
XA = 7.35 \log_{10}(d + 1)0.06, \quad (19)
\]

\[
XB = 1 + \frac{16,240,000}{(d + 1)^{0.46}}, \quad (20)
\]

\[
XG = \log_{10}\left(\frac{P_I - P_T}{3.5}\right), \quad (21)
\]

\[
LGE = XA + \frac{XG}{XB}. \quad (22)
\]

**Time-Related Deterioration of Pavements**

As discussed in (Tolliver 2000), the decay rate due to environmental conditions can be estimated using the following equation:

\[
\delta = -\ln\left(\frac{P_T}{P_I}\right), \quad (23)
\]

where \( \delta \) = decay rate due to environmental losses, \( P_T \) = terminal PSR, \( P_I \) = initial PSR, and \( L \) = maximum feasible life of pavement section.

Given the decay rate, the PSR due to the environmental impact can be computed as

\[
P_{E} = P_I \times e^{-t\delta}, \quad (24)
\]

where \( P_{E} \) = PSR due to the environment impact and \( t \) = typical pavement performance period.
Calculation of Structural Numbers

For flexible pavements, the structural number, or $SN$, can be determined using equation (25) (Tolliver 2000):

$$SN = a_1 d_1 + a_1^* d_1^* + a_2 d_2 + a_3 d_3.$$  \hspace{1cm} (25)

The structural number for a composite pavement, particularly for asphalt concrete (AC) overlay of portland concrete cement (PCC) slab, can be calculated by equation (26) (AASHTO 1993):

$$SN = SN_{ol} + SN_{eff} = \sum a_{ol} d_{ol} + a_{eff} D_{eff} m_{eff},$$  \hspace{1cm} (26)

where $SN_{ol}$ = overlay structural number; $SN_{eff}$ = effective structural number of the existing slab pavement; $d_1$, $d_1^*$, $d_2$, $d_3$, and $d_{ol}$ = thickness of surface layer, base course, base layer, subbase layer, and overlay layer; $D_{eff}$ = thickness of fractured PCC slab layer (inches); $a_1$, $a_1^*$, $a_2$, $a_3$, $a_{ol}$, and $a_{eff}$ = layer coefficient; and $m_{eff}$ = drainage coefficients for a fractured PCC slab.

DATA COLLECTION

This project focused on the highway section of US 50/400 between Dodge City to Garden City, Kansas, one of the major highway sections carrying heavy truck traffic generated by the beef and related industries (Bai et al. 2007). Figure 1 shows the selected highway section, which was further divided into four pavement segments (PS) based on different pavement characteristics.

![Figure 1. Location of highway segment under study](image)

The estimation of highway pavement damage costs required several types of data, including truck parameters, pavement characteristics data, and pavement maintenance cost data. The previous study (Bai et al. 2007) showed that 3-S2 tractor-trailer combinations were the predominant truck used by the processed beef and related industries. In addition, 82% of the truck combinations on the nationwide highway system are 3-S2 trucks (USDOT 2000). Therefore, the 3-S2 model was used as the truck type for this study. This configuration has two axles on the semi-trailer and three axles on the tractor. It has a loading configuration of 10/35/35 meaning that the tractor unit applies a 10,000 pound load to the front axle, and each of two tandem axle groups under the trailer support 35,000 pounds of weight—a maximum legal gross vehicle weight (GVW) is 80,000 pounds. The pavement characteristics data of the four segments were collected from KDOT’s PMIS. KDOT also provided information about the recent maintenance costs for the four pavement segments. Table 1 describes each of the pavement segments and recent maintenance projects.
Table 1. US-50/400 pavement basic data in Finney County

<table>
<thead>
<tr>
<th>PS</th>
<th>Beginning Point</th>
<th>Ending Point</th>
<th>Length</th>
<th>Type</th>
<th>SN</th>
<th>Cost Data</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Year</td>
</tr>
<tr>
<td>1</td>
<td>1.4 km E Garden City</td>
<td>ECoL</td>
<td>16.3 km/10.13 mi</td>
<td>FDBIT</td>
<td>5.4</td>
<td>2005</td>
</tr>
<tr>
<td>2</td>
<td>WCoL</td>
<td>WCL</td>
<td>29.2 km/18.14 mi</td>
<td>PDBIT</td>
<td>3.05</td>
<td>1985</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Cimarron</td>
<td></td>
<td></td>
<td></td>
<td>1997</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2004</td>
</tr>
<tr>
<td>3</td>
<td>ECL Cimarron</td>
<td>ECoL</td>
<td>6.9 km/4.29 mi</td>
<td>FDBIT</td>
<td>N/A</td>
<td>1992</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2001</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1989</td>
</tr>
<tr>
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<td></td>
<td></td>
<td></td>
<td>1992</td>
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<td></td>
<td>1992</td>
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<td></td>
<td></td>
<td>2001</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2003</td>
</tr>
</tbody>
</table>

ECoL: East County Line; WCoL: West County Line; WCL/ECL Cimarron: West/East City Limits of Cimarron; FDBIT: full depth bituminous pavement; PDBIT: partial depth bituminous pavement; and COMP: composite pavement.

TRUCK VMT ASSOCIATED WITH THE PROCESSED BEEF AND RELATED INDUSTRIES

The study of pavement damage costs involved two critical steps: the estimation of truck VMT generated by the processed beef and related industries and the computation of the damage on the selected highway segments caused by truck VTM. The truck VMT was determined by Bai et al. (2007) in the following six categories:

- Transporting feeder cattle to feed yards in southwest Kansas
- Transporting feed grain to feed yards in southwest Kansas
- Transporting finished cattle to meat processing plants in southwest Kansas
- Transporting boxed beef to customers in the United States
- Transporting meat byproducts
- Transporting boxed beef to oversea market

To estimate the processed beef and related truck traffic in southwest Kansas, the origins and destinations of each shipment component were identified first. Based on the identified origins and destinations, the beef-related truck traffic was then distributed to the major highways in the southwest Kansas area using TransCAD software. Routes were selected based on shortest distance, giving priority to the principal highways. There were 369 feed yards within the 24 counties of the southwest Kansas region that served as major origins or destinations for shipments. To facilitate the analyses, the feed yards within each county were aggregated to a centroid on a principal highway located in the county considering factors such as feed yard sizes and distribution. The shipments generated by the industries from major highways to each individual feed yard used only local roadways, and thus, were not considered in the study. Figure 2 shows the procedure for estimating the total VMT generated by the processed beef and related industries, followed by the estimated truck VMT in Table 2 (Bai et al. 2007, Liu 2007).
Table 2. Total annual truck VMT on the studied pavement segments (one-way)

<table>
<thead>
<tr>
<th>PS</th>
<th>Shipment</th>
<th>Annual Truckloads per PS</th>
<th>Total Annual Truckloads</th>
<th>Annual VMT per PS</th>
<th>Total Annual VMT</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Feed cattle to feed yards</td>
<td>4,209</td>
<td>55,539</td>
<td>42,637</td>
<td>562,610</td>
</tr>
<tr>
<td></td>
<td>Finished cattle to meat processing facilities</td>
<td>41,044</td>
<td></td>
<td>415,776</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Boxed beef to U.S. customers</td>
<td>4,473</td>
<td></td>
<td>45,312</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Byproducts to export destinations</td>
<td>5,813</td>
<td></td>
<td>58,886</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Feed cattle to feed yards</td>
<td>4,209</td>
<td>55,539</td>
<td>76,351</td>
<td>1,007,477</td>
</tr>
<tr>
<td></td>
<td>Finished cattle to meat processing facilities</td>
<td>41,044</td>
<td></td>
<td>744,538</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Boxed beef to U.S. customers</td>
<td>4,473</td>
<td></td>
<td>81,140</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Byproducts to export destinations</td>
<td>5,813</td>
<td></td>
<td>105,448</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Feed cattle to feed yards</td>
<td>5,748</td>
<td>56,477</td>
<td>24,659</td>
<td>242,282</td>
</tr>
<tr>
<td></td>
<td>Finished cattle to meat processing facilities</td>
<td>40,443</td>
<td></td>
<td>173,500</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Boxed beef to U.S. customers</td>
<td>4,473</td>
<td></td>
<td>19,189</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Byproducts to export destinations</td>
<td>5,813</td>
<td></td>
<td>24,938</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Feed cattle to feed yards</td>
<td>5,748</td>
<td>56,477</td>
<td>49,259</td>
<td>484,006</td>
</tr>
<tr>
<td></td>
<td>Finished cattle to meat processing facilities</td>
<td>40,443</td>
<td></td>
<td>346,596</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Boxed beef to U.S. customers</td>
<td>4,473</td>
<td></td>
<td>38,334</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Byproducts to export destinations</td>
<td>5,813</td>
<td></td>
<td>49,817</td>
<td></td>
</tr>
</tbody>
</table>

DAMAGE ATTRIBUTED TO TRUCK TRAFFIC OF BEEF INDUSTRIES

Cost Estimation Procedure

Two types of deterioration models were utilized in this study: a time decay model and an ESAL, or pavement damage model. The former addresses pavement damage caused by environmental factors, and the latter analyzed the pavement damage due to truck traffic. The loss of pavement serviceability
attributed to the environmental factors was estimated first, and the rest of the serviceability loss was then assigned to truck axle loads. The total pavement damage cost associated with truck traffic generated by the processed beef and related industries was calculated in seven major steps (see Figure 3).

![Figure 3. Pavement damage cost analysis procedure](image)

**Calculation of ESAL Factors and Annual ESAL (Steps 1 and 2)**

To calculate the pavement damage costs due to trucks associated with processed beef and related industries, it was necessary to calculate ESAL factors for the study truck type and pavements. Pavement structural numbers are key inputs for the calculation of ESAL factors. The numbers for pavement segments 1 and 2 were obtained directly from KDOT PMIS system as 5.4 and 3.05. However, the structure numbers for segments 3 and 4 had to be computed based on their pavement structural information. PS 3 is a flexible pavement, which is a full-depth asphalt pavement without a base layer. The subbase layer of this pavement segment is the subgrade (natural soil). According to this information, the layer coefficients $a_i$ and $a_i^*$ were determined as 0.4 and 0.26, respectively, based on (Tolliver 2000). PS 4 is a composite pavement segment, which has a surface layer of 38 mm (1.5 in) Bituminous Mixtures (BM)-1T, a 151 mm (5.95 in) base course of hot mix asphalt (HMA), and a 178 mm (7.01 in) subbase layer of concrete pavement on the subgrade (natural soil). The layer coefficients $a_{oi}$, $a_{oi}^*$, and $a_{eff}$ for this pavement configuration were 0.4, 0.26, and 0.22, respectively (Liu 2007).

With the structural numbers known, the front axle ESAL factor was calculated first. For the 3-S2 trucks used in this study, the load applied to this axle was 10 kips. The initial and terminal PSR values of the study highway segments were 4.2 and 2.5, as used by KDOT for pavement management. A rear tandem axle ESAL factor for the 3-S2 truck was computed in the same manner as for the single axle, with a different load of 35 kips. The total ESAL factor value for a standard truck was the sum of the front single axle and two rear tandem axle groups ($\Sigma n$). The annual ESAL for each pavement segment was then computed as the truck ESAL factor multiplied by the estimated annual truck VMT generated by the processed beef and related industries. Notice that the VMT values used for this calculation reflected round trips of the truck traffic by doubling those in Table 2. According to Bai et al. (2007), the majority of the trucks generated by the processed beef and related industries would carry other freight on the way back to maximize their profits. The VMT generated by the returning truck traffic were assumed to be the same as...
the one-way values calculated above. The final results of the ESAL factors and annual ESAL generated by the processed beef and related industries are listed in Table 3.

Table 3. Calculation of ESAL factors and annual ESAL

<table>
<thead>
<tr>
<th>Pavement Segment</th>
<th>PS 1</th>
<th>PS 2</th>
<th>PS 3</th>
<th>PS 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>SN (equations 25 &amp; 26)</td>
<td>5.4</td>
<td>3.05</td>
<td>4</td>
<td>3.69</td>
</tr>
<tr>
<td>(P_I)</td>
<td>4.2</td>
<td>4.2</td>
<td>4.2</td>
<td>4.2</td>
</tr>
<tr>
<td>(P_T)</td>
<td>2.5</td>
<td>2.5</td>
<td>2.5</td>
<td>2.5</td>
</tr>
<tr>
<td>(L_1)</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>(L_2)</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>(\beta_3) (equation 3)</td>
<td>0.472</td>
<td>1.17</td>
<td>0.658</td>
<td>0.759</td>
</tr>
<tr>
<td>(\beta_2) (equation 2)</td>
<td>0.412</td>
<td>0.532</td>
<td>0.444</td>
<td>0.461</td>
</tr>
<tr>
<td>(\beta_4) (equation 2)</td>
<td>0.466</td>
<td>1.106</td>
<td>0.73</td>
<td></td>
</tr>
<tr>
<td>(\log_{10}(\text{ESAL})) (equation 4)</td>
<td>-1.076</td>
<td>-0.931</td>
<td>-0.99</td>
<td>-0.966</td>
</tr>
<tr>
<td>(G) (equation 6)</td>
<td>-0.201</td>
<td>-0.201</td>
<td>-0.201</td>
<td>-0.201</td>
</tr>
<tr>
<td>(n) (equation 7)</td>
<td>0.084</td>
<td>0.117</td>
<td>0.102</td>
<td>0.108</td>
</tr>
<tr>
<td>(\Delta t)</td>
<td>1.31</td>
<td>1.356</td>
<td>1.342</td>
<td>1.349</td>
</tr>
<tr>
<td>VMT</td>
<td>1,125,220</td>
<td>2,014,954</td>
<td>484,564</td>
<td>968,012</td>
</tr>
<tr>
<td>Annual ESAL</td>
<td>1,473,852</td>
<td>2,731,694</td>
<td>650,209</td>
<td>1,306,016</td>
</tr>
</tbody>
</table>

Determination of the Pavement ESAL Lives (Step 3)

The maximum life of a pavement was defined in terms of tolerable decline in PSR. The highway segments that were studied were designed by KDOT at an initial PSR of 4.2 and a terminal PSR of 2.5—a maximum tolerable decline in PSR of 1.7. The life of the studied pavement segments in terms of traffic, or ESAL life, was determined using this maximum tolerable PSR decline. ESAL life is the total number of axle passes that would cause the pavement to decline to its terminal PSR irrespective of the time involved. The results of this step are shown in Table 4.

Table 4. Calculation of Pavement ESAL Life

<table>
<thead>
<tr>
<th>Pavement Segment</th>
<th>PS 1</th>
<th>PS 2</th>
<th>PS 3</th>
<th>PS 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>SN (equations 25 &amp; 26)</td>
<td>5.4</td>
<td>3.05</td>
<td>4</td>
<td>3.69</td>
</tr>
<tr>
<td>(P_I)</td>
<td>4.2</td>
<td>4.2</td>
<td>4.2</td>
<td>4.2</td>
</tr>
<tr>
<td>(P_T)</td>
<td>2.5</td>
<td>2.5</td>
<td>2.5</td>
<td>2.5</td>
</tr>
<tr>
<td>(SNA) (equation 13)</td>
<td>6.454</td>
<td>4.453</td>
<td>5.225</td>
<td>4.965</td>
</tr>
<tr>
<td>(XA) (equation 16)</td>
<td>7.38</td>
<td>5.871</td>
<td>6.521</td>
<td>6.314</td>
</tr>
<tr>
<td>(XB) (equation 14)</td>
<td>3.71E+11</td>
<td>2.55E+12</td>
<td>1.11E+12</td>
<td>1.45E+12</td>
</tr>
<tr>
<td>(XG) (equation 15)</td>
<td>-0.314</td>
<td>-0.314</td>
<td>-0.314</td>
<td>-0.314</td>
</tr>
<tr>
<td>(LGE) (equation 12)</td>
<td>7.38</td>
<td>5.871</td>
<td>6.521</td>
<td>6.314</td>
</tr>
<tr>
<td>ESAL Life (equation 17)</td>
<td>2.40E+07</td>
<td>7.43E+05</td>
<td>3.32E+06</td>
<td>2.06E+06</td>
</tr>
<tr>
<td>(L)</td>
<td>30</td>
<td>30</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>(\delta) (equation 23)</td>
<td>0.008</td>
<td>0.008</td>
<td>0.008</td>
<td>0.008</td>
</tr>
<tr>
<td>(P_E) (equation 24)</td>
<td>3.78</td>
<td>3.78</td>
<td>3.78</td>
<td>3.78</td>
</tr>
</tbody>
</table>
Calculation of Annual per-Mile Maintenance Cost

The researchers first converted the maintenance data from KDOT to reflect annual per-mile maintenance cost in current dollars. In addition, although a maintenance project was performed in a specific year, the pavements actually decayed gradually. It was necessary to allocate the total maintenance costs to annual splits. Therefore, the researchers first converted the maintenance costs to the current 2007 dollar value, and then distributed the total project costs as annual per mile cost for each pavement segment.

Based on economic theories (Sullivan et al. 2003), the expense \( M_{t_i}^S \text{current}\) of a pavement maintenance activity in the activity year \( t_i \) on pavement segment \( S \) can be converted to the current 2007 dollar value \( M_{t_i}^S \) given an interest rate \( r \) by equation (27)

\[
M_{t_i}^S = M_{t_i}^S \text{current} \times (1 + r)^{2007-t_i} .
\]  

(27)

For this study, the interest rate was determined based on the Producer Price Index (PPI) data from 1981 to 2006 (USDL 2007). The average of the PPI change rate per year for construction materials and components is 2.68%, and the average of the PPI change rate per year for construction machinery and equipment is 2.62%. Therefore, 3% was used as the rounded average interest rate.

To compute average annual maintenance costs, it was necessary to determine the time period covered by each maintenance expense. In this study, the maintenance time period of each expense \( M_{t_i}^S \) was considered as the interval in years \( I_i \) between two contiguous maintenance activities. Using the constant dollar smoothing method, annual maintenance spending \( A^S_t \) at time \( t \) on a pavement segment was computed using equation (28)

\[
A^S_t = \frac{M_{t_i}^S}{I_i} \sum_{i} \frac{M_{t_i}^S}{t_{i+1} - t_i} .
\]  

(28)

According to the KDOT pavement management policy, the maximum feasible life of a pavement is 30 years. From KDOT’s latest Pavement Management System data (2007), the anticipated design life for full-depth asphalt pavement was 14 years before a maintenance action was needed. The anticipated life was six years before an action was needed after a light rehabilitation with any overlay less than 1.5 inches or surface recycle actions. The performance period of the studied pavement segments, in terms of the number of years after a new pavement segment is resurfaced, was considered as 14 years because none of the four segments had overlays less than 1.5 inches. Based on the information and equations described above, the researchers converted the maintenance costs to the 2007 value and then calculated the annual per-mile maintenance cost. The results of these calculations are summarized in Table 5.
Table 5. Maintenance costs in year 2007 value

<table>
<thead>
<tr>
<th>Pavement Segment</th>
<th>Year</th>
<th>Project</th>
<th>Previous Dollar ($)</th>
<th>2007 Dollar ($)</th>
<th>Cost/mile/year ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2005</td>
<td>K-6374-01</td>
<td>15,908,221</td>
<td>16,887,032</td>
<td>119,003</td>
</tr>
<tr>
<td></td>
<td>1985</td>
<td>K-1764-01</td>
<td>3,074,770</td>
<td>5,891,577</td>
<td>15,103</td>
</tr>
<tr>
<td></td>
<td>1997</td>
<td>K-6190-01</td>
<td>999,522</td>
<td>1,343,274</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2004</td>
<td>K-9324-01</td>
<td>1,653,059</td>
<td>1,806,342</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>1992</td>
<td>K-4038-01</td>
<td>1,685,548</td>
<td>2,626,029</td>
<td>35,651</td>
</tr>
<tr>
<td></td>
<td>2001</td>
<td>K-8146-01</td>
<td>746,771</td>
<td>891,684</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1981</td>
<td>K-1228-01</td>
<td>3,595,654</td>
<td>7,754,356</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1989</td>
<td>K-3643-01</td>
<td>272,433</td>
<td>463,799</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1992</td>
<td>K-4039-01</td>
<td>627,261</td>
<td>977,252</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1992</td>
<td>K-4609-01</td>
<td>448,390</td>
<td>698,577</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2001</td>
<td>K-8145-01</td>
<td>220,173</td>
<td>262,898</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2003</td>
<td>K-8145-02</td>
<td>1,730,826</td>
<td>1,948,060</td>
<td></td>
</tr>
</tbody>
</table>

Overall Average Annual Per-Mile Cost in 2007 Value $47,864

Per-ESAL Unit Cost and Total Cost Attributed to the Industries (Steps 4 to 7)

The annual per-mile maintenance expenditure for each of the segments calculated here was due to both environmental factors and truck traffic. It is necessary to identify the proportion of the pavement damage caused by truck traffic only. The PSR loss of each segment due to environmental factors for the design period of 14 years was determined using the time decay model (equations [23] and [24]), given KDOT’s policy for initial PSR of 4.2 and terminal PSR of 2.5, with a maximum feasible life of 30 years. As a result, the percent of the pavement maintenance costs due to truck traffic was estimated as 75%.

Thus, the average annual maintenance cost per mile of each pavement segment needs to be adjusted by a factor of 75% to isolate the damage solely attributed to truck traffic. Knowing the costs attributed to truck traffic, the unit cost per ESAL for each pavement segment was computed as the average per-mile maintenance cost divided by the ESAL life of the same segment. In addition, the total maintenance cost that is attributed to the truck traffic of the beef and related industries in the region was calculated as the per-axle cost multiplied by the total ESAL generated by the truck traffic associated with the industries.

Table 6 shows the calculated average annual per mile cost caused by heavy trucks and the unit cost per ESAL for each pavement segment. As listed in the table, the average annual maintenance cost on the study highway section that was due to the damage caused by truck traffic associated with the processed beef and related industries was estimated as $71,019, an average annual per-mile cost of $1,727.

Table 6. Average annual per-mile cost, per ESAL cost, and total cost attributed to the industries

<table>
<thead>
<tr>
<th>Pavement Segment</th>
<th>Segment Length (mi)</th>
<th>AAPMC1 ($)</th>
<th>Pavement ESAL Life</th>
<th>PEMC2 ($)</th>
<th>Annual ESAL3 ($)</th>
<th>Pavement Damage Cost4 ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10.13</td>
<td>89,252</td>
<td>23991498</td>
<td>0.004</td>
<td>1,473,852</td>
<td>5,483</td>
</tr>
<tr>
<td>2</td>
<td>18.14</td>
<td>11,328</td>
<td>743019</td>
<td>0.015</td>
<td>2,731,694</td>
<td>41,645</td>
</tr>
<tr>
<td>3</td>
<td>4.29</td>
<td>26,738</td>
<td>3319627</td>
<td>0.008</td>
<td>650,209</td>
<td>5,237</td>
</tr>
<tr>
<td>4</td>
<td>8.57</td>
<td>29,427</td>
<td>2060297</td>
<td>0.014</td>
<td>1,306,016</td>
<td>18,653</td>
</tr>
<tr>
<td>Total</td>
<td>41.13 mi</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>$71,019</td>
</tr>
</tbody>
</table>

1Average annual per-mile maintenance cost in 2007 dollar value that was caused by heavy trucks;
2Per-ESAL maintenance cost in 2007 dollar value
3The annual ESAL generated by the truck traffic of the processed beef and related industries
4Pavement damage cost in 2007 dollar value that was caused by the truck traffic associated with the processed beef and related industries.

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CONCLUSION

The southwest Kansas region plays a key role in the processed beef and related industries by having more than three hundred feed yards and several of the biggest meat processing plants in the nation. Traditionally, the industries have been primarily using heavy trucks (e.g., tractor-trailers) for transporting processed meat, meat byproducts, grain, and other related products. With the continuous growth of these industries, the truck traffic has become one of the major causes for the damage of the local highway network. This paper presents a study of the highway pavement damage cost attributed to the processed beef and related industries. The results of this study can be of particular interest to stakeholders including KDOT for better understanding highway damage sources and assessing highway user costs. The results can also be valuable for identifying and promoting more cost-effective transportation modes for the beef processing and related industries.

The researchers analyzed the damage of a pavement section on US 50/400 that was attributable to the heavy trucks of the southwest Kansas processed beef and related industries. In the study, the researchers used the truck VMT generated by the industries, and then determined the associated pavement damage costs using a systematic procedure that accommodated models developed by AASHTO and used in HERS. The analysis results showed that the total pavement damage cost on the 41-mile highway section was $71,019 per year, or $1,727 per mile per year, that was associated with processed beef and related industries in the region. If the same truck traffic were carried on other major highways in the region (1,835 miles), the total damage cost attributed to the processed meat and related industries would be as high as about $3.2 million per year.

It should be pointed out that a few factors may affect the accuracy of this study. In the analysis, the researchers assumed that all trucks carried standard loads. During the data collection, it was found that a nontrivial percentage of the trucks were overloaded to reduce the shipping costs, which would cause much more severe damage to highways. However, the accurate overloading information could not be obtained and thus the factor was not considered in this study. In addition, the study used the estimated truck VMT data from a previous research project because the actual counts of the truck traffic generated by the processed beef and related industries on the selected highway section were not available. For future studies, more reliable data should be used to increase the accuracy of analysis results.
ACKNOWLEDGEMENTS

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Liu, C. 2007. Analyzing Highway Damage Costs Attributed to Truck Traffic of Processed Beef and Related Industries in Southwest Kansas. Department of Civil, Environmental, and Architectural Engineering, the University of Kansas, Lawrence, Kansas. (thesis or dissertation)