Proposed Methodology for Quantifying Roadside Tree Crash Risk

Christine E. Carrigan
RoadSafe, LLC
Box 312
12 Main Street
Canton, Maine 04221
Phone: 207 513 6057
e-mail: christine@roadsafellc.com

Ethan M. Ray
RoadSafe, LLC
545 E. Rancho Catalina Pl.
Oro Valley, AZ 85704
Phone: 207 891 7617
Email: ethan@roadsafellc.com

Malcolm H. Ray
RoadSafe, LLC
Box 312
12 Main Street
Canton, Maine 04221
Phone: 207 514 5474
e-mail: mac@roadsafellc.com

Submitted
November 15, 2018

Word count
Text = 3,872
Figures & Tables: 8 @ 250 words each = 2,500
Total number of words= 6,372

Paper prepared for consideration for presentation and publication at the 98th Annual Meeting of the Transportation Research Board, January 2019
Proposed Methodology for Quantifying Roadside Tree Crash Risk
Christine E. Carrigan, Ethan M. Ray, and Malcolm H. Ray

ABSTRACT

Collisions with trees have long held the dubious distinction of being the roadside object most frequently struck in fatal run-off-road collisions. While removing trees from the roadside has obvious roadside safety benefits, trees are an aesthetic feature of communities and a feature of the local road landscape. Balancing the risks associated with roadside trees and the appeal of verdant tree-lined local roadways involves identifying trees that pose the highest risk to motorists and shielding or removing only the most at-risk trees. This paper presents a tool that can be used by engineers to quantify the risk associated with roadside trees based on the density and location of the trees with respect to the travel way. This method allows engineers to quantify which location presents the most and least risk to the occupants of errant vehicles.
INTRODUCTION

According to the Fatality Analysis Reporting System (FARS), trees have been the most frequently struck fixed roadside object in fatal run-off-road crashes for every year since 1975, the year when the FARS data system was created. In the last 40 years, trees have accounted for between 27 and 38 percent of all fixed object run-off-road fatal crashes. For example, impacts with trees resulted in 2,585 fatal run-off-road crashes nationwide in 2016; 35 percent of the 7,194 fatal run-off-road fixed object crashes. Signs, luminaires and poles were the next most frequently struck objects with 1,364 fatal run-off-road crashes in 2016. Even a small improvement in reducing the frequency of roadside tree collisions has the potential for making a dramatic decrease in fixed-object run-off-road crash fatalities.

In 1984, Zegeer et al. describe the crash data and roadway data collection and statistical analysis that was used to develop a predictive model for the frequency of utility pole crashes. The authors developed a nomograph for predicting accident frequency with unshielded utility poles as a function of the ADT, pole offset and pole density. Although poles and trees are different features and the countermeasures available are different, the calculation of their risk is quite similar.

In 1986 the Guide to Management of Roadside Trees was published. This publication included a manual process for collecting roadway and roadside data and comparing the actual tree/vehicle crash rate to the expected rate. Using this method, if a roadway has a higher than expected crash rate it would be prioritized for treatment.

Highway designers generally rely on established design standards as a means for producing designs with the lowest practical risk. Most State DOT design standards use rules-of-thumb that are simple to apply and require little detailed knowledge of a specific project area. For example, the 2011 AASHTO Roadside Design Guide (RDG) provides clearzone recommendations in Table 3-1 which would suggest the minimum offset for trees. This guidance suggests a roadway with a design speed of 55 mi/hr, average annual daily traffic (AADT) of 1,000 vehicles/day and 1:6 or flatter foreslopes have an area clear of fixed objects that is at least 16 feet (ft). The clearzone guidance does not indicate exactly what the risk is, and the designer has no way of knowing how much safer a 20-ft wide clearzone might be. In many practical situations, it may not be possible to provide the recommended 16-ft of clearzone. The designer has no means of assessing the relative risk trade-offs of, for example, a 12-ft clearzone in comparison to the recommended 16-ft.

In addition to design standards used by highway planners and designers, there are many statistical models which have been developed to predict where roadside encroachments or crashes may occur. Some of these models have been used for decades in the RDG and some were recently developed for the third version of the Roadside Safety Analysis Program (RSAPv3) and a future update to the Highway Safety Manual (HSM). Unlike the simple clearzone guidelines, statistical models of crash frequency quantify the frequency and severity of crashes so the designer can explicitly compare the risk of one alternative to another. Some of these recently developed statistical models have been compiled here into a single procedure specifically aimed at evaluating tree crash risk that can be used by roadside designers during planning, design, and maintenance in conjunction with established design standards. The following procedure considers estimating the risk of a fatal or serious injury crash based on the density of trees on the roadside, the offset from the travel way, the operational characteristics of the roadway and the roadway geometry.
BACKGROUND

Historically, two methods have been used to estimate the frequency and severity of crashes: the crash-based method and the encroachment-based method. Crash-based methods estimate the frequency of crashes of a particular severity by developing statistical models based on observed data. Such models, as commonly found in the Highway Safety Manual (HSM), include a safety performance function (SPF) and an assortment of crash modification factors (CMF) that adjust the frequency based on particular characteristics of the highway and traffic. (7) Encroachment-based methods have been used in roadside safety since the 1970s. (8-10) Both methods typically use a regression model with the crash or encroachment frequency as the dependent variable and highway characteristics (e.g., traffic volume, curvature, grade, etc.) as the explanatory variables. The encroachment-based method, however, divides each event into three conditional probabilities: 1) the probability of leaving the road, 2) the probability of striking an object given the vehicles has encroached onto the roadside and 3) the probability of a particular severity of crash given the vehicle strikes a roadside object. Each conditional probability is separately modelled, and the product provides an estimate of risk.

This basic approach is the foundation of several computer programs, the most recent of which is RSAPv3. (5) Recent research in several projects have further improved theencroachment model and the encroachment adjustment factors used in the encroachment-based method as will be discussed below. (6; 11-13) Other recent research has developed methods to treat the trajectory characteristics as statistical properties that can be analyzed using survival analysis; this avoids the very time consuming explicit trajectory simulations needed in prior computer programs. (11)

Given this background and assuming the terrain between the edge of the roadway and the face of the trees is relatively flat and traversable, tree collisions can be estimated with the following encroachment-based conditional probability model described above but using slightly different notation than contained in the RSAP Engineers Manual (14):

\[
\text{OUTCOME}_{Sj} = \text{ENCRT} \cdot \text{EAF}_S \cdot P_{\text{OFFSET TREE}} j \cdot P_{\text{OUTCOME TREE}} \cdot \left[ \frac{\text{PSL}^3}{65^3} \right]
\]

where:

\( \text{OUTCOME}_{Sj} \) = The expected annual number of fatal or serious injury tree crashes on road segment \( s \) for alternative \( j \).

\( \text{ENCRT} \) = The expected annual number of encroachments on a base segment based on the AADT (See Figure 1 or Equation 2a or 2b).

\( \text{EAF}_S \) = Highway characteristic encroachment adjustment factors for the highway segment of interest (See Table 2).

\( P_{\text{OFFSET TREE}} j \) = The conditional probability that a vehicle will strike a tree given the vehicle encroaches on the roadside based on the lateral offset of the trees from the travel way and the spacing of trees (Figure 2).

\( \text{PSL} \) = Posted speed limit on the highway segment in mi/hr.

\( P_{\text{OUTCOME TREE}} \) = The condition probability of a fatal or serious injury tree crash given a tree crash occurs.
METHODOLOGY – DETAILS OF THE RISK ANALYSIS TOOL

Equation 1 is the basis of the following three-step methodology for assessing tree crash risk as shown in Table 1. The three steps are 1) segment the roadway into homogeneous sections; 2) estimate the annual frequency of fatal and serious injury (KA) crashes for existing conditions; 3) estimate the annual frequency of KA crashes for each design alternative or mitigation strategy under consideration. Worksheets that facilitate the computation process are presented at the end of this paper in Table 3 through Table 5.

### Table 1. Assessment Process

<table>
<thead>
<tr>
<th>Find:</th>
<th>The average annual frequency of serious injury and fatal crashes with unshielded trees for existing conditions (i.e., OUTCOME &lt;sub&gt;S0&lt;/sub&gt;) and compare to the average annual frequency of serious injury and fatal crashes with unshielded trees for each alternative condition (i.e., OUTCOME &lt;sub&gt;Sj&lt;/sub&gt;).</th>
</tr>
</thead>
<tbody>
<tr>
<td>Given:</td>
<td>The following traffic and site characteristics for each approach direction where trees are exposed to approaching traffic:</td>
</tr>
<tr>
<td></td>
<td>• The highway type (i.e., divided and undivided).</td>
</tr>
<tr>
<td></td>
<td>• Site-specific geometric conditions (e.g., curvature, grade, number of lanes, lane width, etc.) and the posted speed limit by direction.</td>
</tr>
<tr>
<td></td>
<td>• Bi-directional average annual daily traffic (AADT) in vehicles/day.</td>
</tr>
<tr>
<td></td>
<td>• Average perpendicular distance in feet from the edge of the travel for each direction of travel to the face of the trees or tree line and the average distance between trees.</td>
</tr>
</tbody>
</table>

### Procedure:

1) Segment the roadway of interest into homogeneous sections and determine each segment length in miles (L).

2) Calculate average annual frequency of serious injury and fatal tree collisions for existing conditions (OUTCOME <sub>S0</sub>).
   a) Determine the average tree spacing by segment edge. Determine the average perpendicular distance in feet to the face of the trees by edge and direction.
   b) Use Table 2 to find the segment-specific encroachment adjustment factor for each approach direction, EAF<sub>S</sub>. Note that for horizontal curves and grade the adjustment will be different for each direction of travel.
   c) Use Figure 1 to estimate number of base annual encroachments (ENCR<sub>T</sub>) by direction.
   d) Use Figure 2 to estimate the probability of a crash given an encroachment by direction ($P_{OFFSET\_TREE\_j}$).
   e) $P_{OUTCOME\_TREE}$ for a KA crash is equal to 0.0576.
   f) Calculate the estimated average annual frequency of fatal and serious injury crashes with n unshielded trees by direction, then sum to find the result for each edge where:

\[
OUTCOME_{S0} = \sum_{j=1}^{n} ENCR_T \cdot EAF_S \cdot P_{OFFSET\_TREE\_j} \cdot P_{OUTCOME\_TREE} \cdot \frac{PSL^3}{65^3}
\]

3) Calculate the average annual frequency of fatal and serious injury crashes for each alternative j. If annual frequency is acceptable, no further action is required. If annual frequency is not acceptable, return to step 2a, modify the tree spacing or offset and continue through step 3 to evaluate if the alternative is more desirable than the original.
Step 1 – Segment the Roadway

The first step in assessing roadside tree risk is to divide the roadway into homogeneous segments. For purposes of these analyses, a homogeneous road segment is one where all the following characteristics do not change within the segment:

- Highway type (i.e., divided, undivided, one-way).
- AADT
- Lane width
- Radius of horizontal curve
- Number of through lanes
- Posted speed limit
- Grade (excluding vertical curvature)
- Average perpendicular distance to trees change 5 feet or less.

Restricting the analysis to homogeneous segments is an important step because the characteristics that define a segment are key predictors of the encroachment frequency. For example, vehicles are more likely to leave the travel way on the outside of a horizontal curve than a tangent section, so the segment needs to be limited to the horizontal curve.

This method, as in the HSM method, distinguishes between intersection related crashes and segment related crashes. The data in this procedure was developed based on segment related crashes only and therefore, intersections are ignored (i.e., intersections do not cause a new segment). A roadway segment is defined as beginning and ending where there is a change in any of the characteristics listed above. Roadway characteristics can be entered into Table 3 – Worksheet A.

Step 2 - Calculate Frequency of KA Tree Collisions for Existing Conditions

The second step involves calculating the frequency of KA tree crashes for each edge of each of the homogeneous segments using the characteristics of the existing conditions at the site. This step involves following six sub-steps.

Step 2a – Determine Existing or Alternate Conditions

Determine the average tree spacing by segment edge. Also determine the average perpendicular distance in feet to the face of the trees by edge and direction.

Step 2b – Encroachment Adjustment Factors

The state-of-the-practice in highway safety for developing encroachment adjustment factors is to use observational cross-sectional models to estimate the variable coefficients using a negative binomial regression model. A negative binomial regression model of the edge crashes was estimated for both divided and undivided highways during NCHRP 17-54.\(^6\) NCHRP 22-12(03) compiled additional encroachment adjustment factors developed under previous research efforts.\(^13\)

Table 2 is a compilation of available encroachment adjustment factors and can be used to determine appropriate adjustments with respect to each approach direction. Details of the development of each of the adjustment factors can be found in the cited reports. The total adjustment for the segment (EAF\(_S\)) is found by multiply all of the individual adjustments together. EAF\(_S\) should be calculated for each direction of approach for each segment. This part of the process is simplified using Table 4 – Worksheet B.
Table 2. Site Specific Adjustment Factors (EAFi).(6; 13)

<table>
<thead>
<tr>
<th>Average Lane Width (ft)</th>
<th>Undiv</th>
<th>Div</th>
<th>No. of Lanes</th>
<th>Undiv</th>
<th>Div</th>
<th>Posted Speed Limit</th>
<th>Undiv</th>
<th>Div</th>
</tr>
</thead>
<tbody>
<tr>
<td>≤ 9</td>
<td>1.50</td>
<td>1.25</td>
<td>1</td>
<td>1.00</td>
<td>1.00</td>
<td>&lt; 65</td>
<td>1.42</td>
<td>1.18</td>
</tr>
<tr>
<td>10</td>
<td>1.30</td>
<td>1.15</td>
<td>2</td>
<td>0.76</td>
<td>1.00</td>
<td>≥ 65</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>11</td>
<td>1.05</td>
<td>1.03</td>
<td>≥ 3</td>
<td>0.76</td>
<td>0.91</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>≥ 12</td>
<td>1.00</td>
<td>1.00</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>AR Horizontal Curve Radius (ft) †</th>
<th>All Highway Types</th>
<th>TR Horizontal Curve Radius (ft) †</th>
<th>All Highway Types</th>
<th>Segment Grade ††</th>
<th>All Highway Types</th>
</tr>
</thead>
<tbody>
<tr>
<td>AR &gt; 10,000</td>
<td>1.00</td>
<td>TR &gt; 10,000</td>
<td>1.00</td>
<td>-6 ≥ G</td>
<td>2.00</td>
</tr>
<tr>
<td>10,000 ≥ AR &gt; 432</td>
<td>e^(474.4/AR)</td>
<td>10,000 ≥ TR &gt; 432</td>
<td>e^(173.6/TR)</td>
<td>-6 &lt; G &lt; -2</td>
<td>0.5-(G/4)</td>
</tr>
<tr>
<td>432 ≥ AR &gt; 0</td>
<td>3.00</td>
<td>432 ≥ TR &gt; 0</td>
<td>1.50</td>
<td>-2 ≤ G</td>
<td>1.00</td>
</tr>
</tbody>
</table>

† The horizontal curve radius may either curve away (AR) from the trees under consideration or toward them (TR). When the driver is turning the wheel of the vehicle away from the tree, the AR adjustments shall be used. When the driver is turning the steering wheel toward the tree, the TR adjustment should be used. This adjustment must be considered for each direction of travel where an encroaching vehicle could approach the tree. See thumbnails below for further clarification.

†† The grade approaching the tree must be considered for each direction of travel. Positive grades indicate an uphill grade and negative values indicate a downhill grade. Uphill, flat and slightly downhill grades have an adjustment of 1.

**Step 2c – Frequency of Base Encroachments**

The most recent collection of encroachment data was undertaken in 1978 in five Canadian provinces by Cooper and his colleagues.(15) Cooper used field investigation teams to periodically search highways for tracks and other evidence of vehicles encroaching onto the roadside. The teams collected apparent encroachments which Cooper used to develop a relationship to predict encroachments as a function of highway and traffic characteristics. The original data collected by Cooper was remodeled again in NCHRP 22-27 when updating RSAPv3.(5)

The variable ENCR_T represents the number of vehicles that are expected to depart an edge of a highway and enter the roadside or median as a function of the two-way total traffic volume (AADT). ENCR_T is the number of encroachments on a base segment of the highway where a base segment, based on Cooper, is assumed to have the following characteristics:
• Straight (i.e., tangent) road segment.
• Flat (i.e., ± 3 percent grade) road segment.
• 12-ft wide lanes.
• One lane in each direction for undivided roadways and two lanes in each direction for divided highways.
• Zero major access points/mi.
• Posted speed limit of 65 mi/hr
• Generally flat terrain (i.e., as per the Highway Capacity Manual (16)).

Models are available that incorporate heavy vehicles, but heavy vehicles have been ignored in this methodology for three reasons: 1) it is believed that the occupants of passenger vehicles are at greater risk than drivers/occupants of heavy vehicles during tree crashes, 2) excluding the adjustments for heavy vehicles is a more conservative approach when estimating frequency of crashes, and 3) heavy vehicles are beyond the scope of this paper.

The ENCR\textsubscript{T} model from RSAPv3 based on the Copper data in terms of encroachments per million vehicle miles travelled is provided in Figure 1. The expected encroachments from one edge per million vehicle-miles travelled were modeled, recognizing that there are four possible encroachment directions on any segment: primary right (PR), primary left (PL), opposing right (OR) and opposing left (OL). The solid lines in Figure 1 indicate the range of AADT values for which the data were collected; 1,000 to 12,903 vehicles/day for two-lane undivided highways and 5,954 to 44,930 vehicles/day for four-lane divided highways. The dotted lines are extrapolations.

The equations are then converted to a frequency by multiplying by the million vehicle miles of travelled for the segment as shown in Equation 2a and Equation 2b. (14)
Step 2d – Probability of a Tree Crash Given an Encroachment ($P_{OFFSET TREE_j}$)

NCHRP 17-54 recently simulated encroachment trajectories and developed a statistical model to represent the conditional probability of striking narrow fixed objects such as trees on crash given the vehicle leaves the roadway. The density and offset to the fixed objects are the independent variables of the equation. Figure 2 is a graphical representation of Equation 3, developed under NCHRP 17-54 (6) and adopted to the needs of this paper to represent the relationship found between $P_{OFFSET TREE_j}$, which is the average tree offset ($OFFSET_i$) and tree spacing ($SPACING_i$):

$$P_{OFFSET TREE_j} = \frac{e^{-0.0281 OFFSET_i + 0.0047 DENSITY_i - 2.202}}{1 + e^{-0.0281 OFFSET_i + 0.0047 DENSITY_i - 2.202}}$$

Figure 2. $P_{OFFSET TREE_j}$ by Offset and Spacing.
Step 2e – Probability of a Fatal or Severe Injury Crash with Tree ($P_{OUTCOME\ TREE}$)

$P_{OUTCOME\ TREE\ j}$ is the probability at a base posted speed limit of 65 mi/hr and adjusted within Equation 1 for the actual posted speed limit using a method proposed by Ray and Carrigan. The conditional probability of a tree crash resulting in a fatal or serious injury is 0.0576 based on crash data collected in Washington state. ($5; 18$) $P_{OUTCOME\ TREE}$ is equal to 0.0576.

Step 2f – Annual Frequency of Injury Collision ($OUTCOME_{S0}$)

All the components of Equation 1 have been determined in the previous sub-steps so the frequency of fatal and serious injury tree crashes on the segment of interest can now be calculated by multiplying each component together. This step can be completed using Table 5 – Worksheet C. The individual $OUTCOME_{S0}$ values for the direction are added together to calculate the frequency of fatal and serious injury tree crashes by edge for undivided roadways. The values are not added for divided roadways.

Step 3 – Calculate Frequency of KA Tree Collisions for Each Alternative

Calculate $OUTCOME_{S_j}$ for each alternative under evaluation. If the final value of $OUTCOME_{S0}$ is acceptable for the agency, then nothing further needs to be done. If the final $OUTCOME_{S0}$ is not acceptable to the agency, then return to Step 2a and modify the roadside by increasing offset or decreasing number of trees (both of which would be accomplished by tree removal) and re-calculating the remaining steps. Mitigation strategies for reducing crash risk are outlined in the 2011 RDG and NCHRP Report 500 Volume 3 (A Guide for Addressing Collisions with Trees in Hazardous Locations). ($4; 19$) Jurisdictions may choose to establish an acceptable level of risk and determine if alternatives meet that level or not while considering factors including cost, ease of implementation, timeline for implementation, etc.

EXAMPLE PROBLEM

An example regarding the redesign of approximately one mile of road is presented here as a way to demonstrate use of the methodology. The highway is a two-lane undivided rural collector in New England. The road is primarily residential in nature with both horizontal and vertical curves, tangents, and sight obstructions. Beyond the edge of travel, there are trees, small street signs and mail boxes. The roadway features for the 0.091-mile-long segment of interest are presented in Table 3. This roadway is a typical rural collector for the region, however, the crash rate is double the state crash rate and the road has experienced several injury and fatal run-off-road crashes in the last five years prompting the local agency to examine alternative treatments. The series of photographs in Figure 3 illustrates the general character of the road.

The worksheets provided in this section are designed to assist users in the data gathering and risk calculation steps. Yellow highlighted areas denote user input fields.
Figure 3. Example roadway looking in the primary direction (left) and opposing direction (right).

Table 3. Example Problem: Worksheet A – General Information

<table>
<thead>
<tr>
<th>General Information</th>
<th>Location Information</th>
</tr>
</thead>
<tbody>
<tr>
<td>Analyst</td>
<td>Roadway</td>
</tr>
<tr>
<td>Agency</td>
<td>Location</td>
</tr>
<tr>
<td>Date performed</td>
<td>Jurisdiction</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Input Data</th>
<th>Base Condition</th>
<th>PL</th>
<th>PR</th>
<th>OL</th>
<th>OR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Divided, undivided or one-way</td>
<td>D</td>
<td>U</td>
<td>O</td>
<td>Undivided</td>
<td></td>
</tr>
<tr>
<td>Segment length (mi)</td>
<td>--</td>
<td>0.091</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AADT</td>
<td>--</td>
<td>7000</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of access points</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Lane width (ft)</td>
<td>≥12</td>
<td>12</td>
<td>12</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>Radius of curvature (ft)</td>
<td>&gt;1000</td>
<td>Tangent</td>
<td>Tangent</td>
<td>Tangent</td>
<td></td>
</tr>
<tr>
<td>Number of lanes (in one direction)</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Posted speed limit (mi/hr)</td>
<td>≥65</td>
<td>45</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Grade</td>
<td>≤-2</td>
<td>-4</td>
<td>-4</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Tree spacing (ft)</td>
<td>--</td>
<td>10</td>
<td>50</td>
<td>50</td>
<td>10</td>
</tr>
<tr>
<td>Offset to face of tree or trees (ft)</td>
<td>--</td>
<td>10</td>
<td>30</td>
<td>30</td>
<td>10</td>
</tr>
</tbody>
</table>

Table 4. Example Problem: Worksheet B – Encroachment Adjustment Factors

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>PL</td>
<td>1.00</td>
<td>1.00</td>
<td>1.42</td>
<td>1.00</td>
<td>1.50</td>
<td>2.13</td>
</tr>
<tr>
<td>PR</td>
<td>1.00</td>
<td>1.00</td>
<td>1.42</td>
<td>1.00</td>
<td>1.50</td>
<td>2.13</td>
</tr>
<tr>
<td>OL</td>
<td>1.00</td>
<td>1.00</td>
<td>1.42</td>
<td>1.00</td>
<td>1.00</td>
<td>1.42</td>
</tr>
<tr>
<td>OR</td>
<td>1.00</td>
<td>1.00</td>
<td>1.42</td>
<td>1.00</td>
<td>1.00</td>
<td>1.42</td>
</tr>
</tbody>
</table>

Table 5. Example Problem: Worksheet C – Risk Calculation

<table>
<thead>
<tr>
<th>Direction</th>
<th>Base Encroachments (per Million Vehicle-Miles Traveled)</th>
<th>Encroachment Adjustment Factor</th>
<th>Probability of Tree Crash Given an Encroachment</th>
<th>Probability of Fatal or Serious Injury Given a Crash with a Tree</th>
</tr>
</thead>
<tbody>
<tr>
<td>ENCR</td>
<td>EAF$_S$</td>
<td>$P_{OFFSET\ TREE}^I$</td>
<td>$P_{OUTCOME\ TREE}^I$</td>
<td></td>
</tr>
<tr>
<td>See Equation 2a or 2b</td>
<td>[6] from Worksheet B</td>
<td>Figure 2</td>
<td></td>
<td>Given for KA</td>
</tr>
<tr>
<td>PL</td>
<td>0.056</td>
<td>2.13</td>
<td>0.50</td>
<td>0.0576</td>
</tr>
<tr>
<td>PR</td>
<td>0.056</td>
<td>2.13</td>
<td>0.07</td>
<td>0.0576</td>
</tr>
<tr>
<td>OL</td>
<td>0.056</td>
<td>1.42</td>
<td>0.07</td>
<td>0.0576</td>
</tr>
<tr>
<td>OR</td>
<td>0.056</td>
<td>1.42</td>
<td>0.50</td>
<td>0.0576</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Direction</th>
<th>Avg. Annual Frequency of KA Crash with an Unshielded Tree for Each Direction</th>
<th>Avg. Annual Frequency of KA Crash with an Unshielded Tree Each Edge (Undivided Only)</th>
</tr>
</thead>
<tbody>
<tr>
<td>OUTCOME</td>
<td>$S_0$</td>
<td>$S_0$</td>
</tr>
<tr>
<td>See Note 1 &amp; Note 2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PL</td>
<td>0.000114</td>
<td>[5] PL + [5] OR</td>
</tr>
<tr>
<td>PR</td>
<td>0.00016</td>
<td>[5] OR</td>
</tr>
<tr>
<td>OL</td>
<td>0.00011</td>
<td>[5] PR + [5] OL</td>
</tr>
<tr>
<td>OR</td>
<td>0.000076</td>
<td></td>
</tr>
</tbody>
</table>

Note 1: $OUTCOME_{S_0} = [1] \times [2] \times [3] \times [4] \times \frac{PSL^2}{6.5^3}$

Note 2: If divided, column [5] is end of process. If undivided, use column [6].

The one-mile section of road of concern is segmented into homogeneous section and the remainder of this example concerns one particular segment. The opposing right edge (i.e., PL+OR) of the 0.091-mile segment is expected to have 0.00190 KA crashes/mi/year and the primary right edge (i.e., PR+OL) of the segment is expected to have 0.00027 KA crashes/mi/year. Both values account for vehicles traveling in the primary and opposing directions of travel. Since the opposing right edge has a larger frequency of KA tree crashes, the engineer may decide to focus efforts to reduce tree crashes on that edge.

The 1984 Zegeer nomograph for utility pole accident frequency offers another way to calculate risk.

The Zegeer method is slightly different since it is for utility poles and the “density” of poles can be much less than the “density” of trees. In order to apply the example problem to the 1984 Zegeer nomograph an assumption will be made that the density of trees is 70 trees per mile (i.e. 75-ft spacing). Using this assumption, we calculate a risk of 0.79 accidents/mi/year on the opposing right edge and 0.39 accidents/mi/year on the primary right edge. The Zegeer nomograph predicts all crashes whereas this method is focused only on KA crashes, so the two methods are not directly comparable. While the two methods are not numerically comparable, they do indicate the same trend, the opposing right side of the road has higher risk and would be the obvious choice to focus redesign efforts on if the risk was determined by the jurisdiction to be too high.

As discussed throughout this paper with respect to Zegeer’s nomograph, utility poles and trees are similar, and some assumptions can be made regarding the probably of interaction with these similar features during ROR crashes. In a paper published in the Transportation Research Circular E-C220, Carrigan established an acceptable risk target for different jurisdictions. For State roadways in Washington, “the existing risk of a fatal or incapacitating injury crash with a utility pole… incapacitating + Fatal Utility Pole crashes/mi/yr [+] 0.0010.” (20, pg. 188) If the
local transportation agency used an acceptance criteria of 0.0010 KA crashes/mi/year and lower
as suggested by Carrigan, then the primary right edge would not need to be altered or treated
whereas the opposing right edge should be examined for better alternatives. A mitigation
strategy for the opposing right edge might include increasing the spacing from 10 to 20 ft by
cutting every other tree. Re-running the method with this new alternative for the opposing right
dge alternative would result in a risk of 0.00085 KA crashes/mi/year which would satisfy the
acceptance criterion.

CONCLUSION

The procedure outlined in this paper can be used by engineers to quantify the risk of fatal
and serious injury crashes with roadside trees. The risk of existing trees and trees lines can be
evaluated and then compared to alternative designs. This technique allows engineers to consider
planting new trees where the crash risk is not increased while also removing the most at-risk
trees such that lower risk trees can remain thus fulfilling their aesthetic function. Future efforts
in this area should include the consideration of roadside slopes, tree size, and risk reduction
benefits of shielding.

AUTHOR CONTRIBUTION STATEMENT

The authors confirm contribution to the paper as follows: study conception and design: C.
Carrigan, M. Ray; data collection: C. Carrigan; analysis and interpretation of results: C.
Carrigan, M. Ray, E. Ray; draft manuscript preparation: E. Ray, C. Carrigan, M. Ray. All
authors reviewed the results and approved the final version of the manuscript.

REFERENCES


