Index for Estimating Road Vulnerability to Damage from Overweight Vehicles

Data Based on Geographic Information System

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One component of North Carolina's motor carrier enforcement program is focused on overweight trucks. The aim of this enforcement program is to protect the state's roadway infrastructure, and as such it is important to identify those facilities and roadway segments that are most susceptible to damage from overweight vehicles. For that purpose, a quantitative road vulnerability index (RVI) was developed. Vulnerability is expressed as a function of truck volume, pavement condition, and bridge condition. By weighting these factors, one can assign vulnerability values to road segments statewide. Vulnerable road segments are then mapped in the same geographic information system (GIS) environment used to capture and display motor carrier enforcement activities for overweight violations. In addition to providing information to aid in the spatial assignment of weight enforcement activities, the RVI uses GIS data as a useful tool for the visual analysis and integration of roadway maintenance and operations concerns across various divisions of the North Carolina Department of Transportation.

Federal funding for the FMCSA Motor Carrier Safety Assistance Program and FHWA-funded size and weight enforcement programs requires that state efforts be data driven. To that end, the Institute for Transportation Research and Education at North Carolina State University produces web-based decision support tools, web map products, and custom on-demand data analysis in support of both programs. These products and services are made available to the North Carolina State Highway Patrol's Motor Carrier Enforcement group to aid in its efforts to meet its defined goals. This paper outlines the creation of one of those support tools for the size and weight enforcement program. The goal of the size and weight program is to "preserve our Nation's infrastructure and to keep trucks and buses moving efficiently," as mandated by FHWA (*1*). The road vulnerability index (RVI) is part of a spatial decision support system being developed to support the size and weight enforcement group in its endeavor to reduce the impact of heavy trucks on critical road infrastructure.

FHWA estimates that truck traffic will more than double nationally during the next 20 years (*2*). In addition to an expected increase in truck traffic, the American Trucking Association has been advocating for larger, more productive trucks, in both size and weight (*3*). It is critical that state departments of transportation and their motor carrier enforcement components understand the relationship between truck size and truck weight to ensure that a state's infrastructure is not unduly damaged by these more productive vehicles and that their operation does not increase safety risks to other motorists.

Inasmuch as motor carrier enforcement resources (manpower) are limited, efforts need to be spatially targeted to areas of greatest concern. In the case of truck weight enforcement efforts, this means those roads and other facilities (such as bridges) that are most vulnerable need to be clearly identified. In the scope of this paper, vulnerability is defined as the susceptibility of pavement and bridge structural integrity to damage caused by oversize or overweight truck traffic. The development of a statewide RVI is responsive to the Motor Carrier Enforcement group's need for this level of spatial specificity.

The current version of the North Carolina RVI is composed of three indices: relative truck exposure index (RTEI), pavement condition rating index (PCRI), and bridge severity index (BSI). Each of these individual indices was derived from data included in several geographic information system (GIS) layers obtained from the North Carolina Department of Transportation (DOT). Experts in the pavement management unit, traffic survey group, and bridge management unit at the North Carolina DOT were consulted to ensure that the approach taken would result in the most accurate statewide map of vulnerable road segments.

The RVI is being developed to provide the ability to overlay the spatial attributes of weight enforcement activity with the spatial attributes of vulnerable road infrastructure. This overlay process will permit weight enforcement personnel to better plan for the effective deployment of limited personnel and the use of portable scale capabilities. These layers are currently deployed as web maps and will be included as part of a larger effort to develop a web-based spatial decision support system.

RVI MODEL DEVELOPMENT

As mentioned previously, three components currently make up the RVI:

- RTEI,
- PCRI, and
- BSI.

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Transportation Research Record: Journal of the Transportation Research Board, No. 2235, Transportation Research Board of the National Academies, Washington, D.C., 2011, pp. 1–8.
DOI: 10.3141/2235-01

Each of these indices was created separately, attached to the North Carolina DOT state-maintained road layer, and then combined to create the final RVI. This combination was accomplished with a variety of tools in Esri's ArcGIS desktop software and then automated with the use of the ArcGIS ModelBuilder. The RVI was computed with the formula below:

$$\text{RVI} = \frac{\alpha\text{RTEI} + \beta\text{PCRI} + \gamma\text{BSI}}{\alpha + \beta + \gamma} \quad (1)$$

where

α = weighting coefficient for component RTEI,
β = weighting coefficient for component PCRI, and
γ = weighting coefficient for component BSI.

Equation 1 was applied to the road network for the state of North Carolina. However, the figures displayed in this paper are a subset of that statewide output. To illustrate the approach, a representative geographic area has been chosen that includes the following counties: Guilford, Alamance, and Orange. The result illustrates what the size and weight enforcement group will use to aid in its enforcement planning. The methodology presented for this representative area may be applied to any geographic area.

The following sections provide a discussion of the major elements and integration of the RVI and a description of the way in which the baseline values of α, β, and γ will be determined.

Relative Truck Exposure Index

The RTEI is a measure of how vulnerable a road is judged to be in regard to the truck traffic that the road carries. Initially, only truck counts were used to determine the RTEI. However, given the large difference in magnitude between the volume of truck traffic on Interstates and that on more rural North Carolina routes, the Interstates were more likely to be vulnerable regardless of the other components of the RVI. Therefore, another method was needed to obtain a more accurate depiction of vulnerability. As a result the method that was chosen considered the ratio of truck counts to truck capacity. The RTEI was determined by taking a ratio of truck counts to truck capacity on a route in a county. The formula used to calculate the RTEI for all road segments in the database is

$$\text{RTEI} = \frac{T}{v_t} \quad (2)$$

where T is truck count and v_t is truck capacity.

Truck Counts

Truck counts were obtained from the traffic survey unit at the North Carolina DOT in the format of a GIS point shapefile. These points represent a "limited number of traffic monitoring stations and were collected on primary routes (Interstate, U.S. and North Carolina Highways)" (*4*). The count stations were located at points where the primary routes intersect with "state, county and certain urban boundaries" (*4*). The nature of these points limits the breadth of the network used in the RVI in that not all state routes in the state have a documented truck count. Any routes in the state that did not have an associated truck count station were removed from the final result. In the future, the North Carolina DOT will tag each road segment with an estimate of the truck traffic. At that time, the RVI will be recalculated to include those segments in the final vulnerability index.

Because of the location of the truck count stations, some routes in a county may not have a truck count station assigned to them. However, there may be a truck count station just across the county line. This factor led to defining primary and secondary truck count stations. If a truck count station was located inside a county boundary, it was defined as a primary truck count station. If a truck count station was located within one-half mile of a county boundary, it was defined as a secondary truck count station to allow for consistency along routes that cross county boundaries. There are instances in which multiple primary truck count stations exist for a route. In those cases, an average of the truck counts was taken. The only time that a secondary truck count station was used was if no primary truck count station could be identified.

Another factor taken into consideration was the designation(s) of routes. There are routes that have multiple route designations, where two routes meet and become coincident for some distance. This factor made it necessary to create multiple county–route fields to handle those cases in which a route has primary, secondary, and tertiary designations.

Truck Capacity

Equation 3 is the base formula used to determine the truck capacity and was obtained from the *Highway Capacity Manual* (*5*). Because trucks are the emphasis of this analysis, modifications to the passenger car equivalent flow rate formula were made. The formula to determine the passenger car equivalent flow rate is

$$v_p = \frac{V}{\text{PHF} * f_G * f_{\text{HV}}} \quad (3)$$

where

v_p = passenger car equivalent flow rate for peak 15-min period (pc/h),
V = demand volume for the full peak hour (veh/h),
PHF = peak hour factor,
f_G = grade adjustment factor, and
f_{HV} = heavy vehicle adjustment factor.

Assumptions were made to simplify Equation 3. Both the PHF and the grade adjustment factor (f_G) were assumed to be 1.0. The peak hour truck count was not known because the truck counts were collected during a 48-h period. Also, the grade of a road segment was not taken into consideration in this version of the RVI. The heavy vehicle adjustment factor, f_{HV}, becomes $1/E_T$ in Equation 4, assuming that the proportion of trucks and buses is 1.

Roads in North Carolina are classified into one of three categories: divided centerline (DCL), four-lane (4L), and two-lane (2L). The passenger car equivalent flow rates for each of these types of roads were obtained from the *Highway Capacity Manual* (*5*). The table below shows the flow rate for each type of road, assuming a Level of Service E (LOS E) and a free-flow speed of 60 mph. LOS E is defined as operating at capacity:

Road Category	v_p
2L	1,700
4L	2,200
DCL	2,400

The formula used to calculate the truck capacity is shown in Equation 4.

$$v_t = \frac{\lambda v_p}{E_T} * 24 \tag{4}$$

where

v_t = demand volume of trucks per day,
λ = number of lanes, and
E_T = passenger car equivalent for trucks.

The passenger car equivalent, E_T, is determined by the terrain on which the road was constructed. The table below shows the types of terrain and their corresponding passenger car equivalent factor:

Terrain	E_T
Level	1.5
Rolling	2.5
Mountainous	4.5

The type of terrain on which a road segment is constructed is contained in the road network shapefile obtained from the North Carolina DOT. Once the truck capacity was calculated, the RTEI was calculated with Equation 1.

The values of the RTEI are in the range [0.000156, 0.401016]. These values were scaled to a range of [0,100] with the following linear transformation:

$$100 - \frac{\text{RTEI}}{\max(\text{RTEI})} * 100$$

The transformation that was used places segments more vulnerable to truck traffic at the lower end of the scale. Figure 1 shows a map of the scaled RTEI for the three county examples. The classification scheme used in the map is based on standard deviations from the mean. The mean value of the scaled RTEI is 91.52 with a standard deviation of 12.51. For this figure and all subsequent figures, lower values correspond to more vulnerable road segments.

Pavement Condition Rating Index

The two pavement condition attributes that are considered to be highly correlated with the vulnerability of a road to overweight trucks are alligator cracking and rutting.

Alligator Cracking

The pavement management unit at the North Carolina DOT defines alligator cracking as "a load associated structural failure" (*6*). An example of alligator cracking is shown in Figure 2 (*6*).

Four fields in the pavement condition survey (PCS) layer were used to determine the overall alligator cracking score. They are ALGTR_NONE, ALGTR_LOW, ALGTR_MDRT, and ALGTR_HIGH. The method by which the alligator cracking component was calculated was obtained from the pavement management unit at the North Carolina DOT.

Rutting

Rutting is defined as having "a surface depression in the wheel path(s) or at the edge of pavement" (*6*). Figure 3 shows an example of rutting (*6*).

A field called RUT_CD in the PCS layer was used to calculate the rutting component. The table below shows how the rutting component was scored:

Rutting Code	*Score*
None (N)	100
Low (L)	90
Moderate (M)	40
Severe (S)	0

In addition to these two distresses, if an overall pavement rating is below 50, then multiple distresses are involved and the pavement

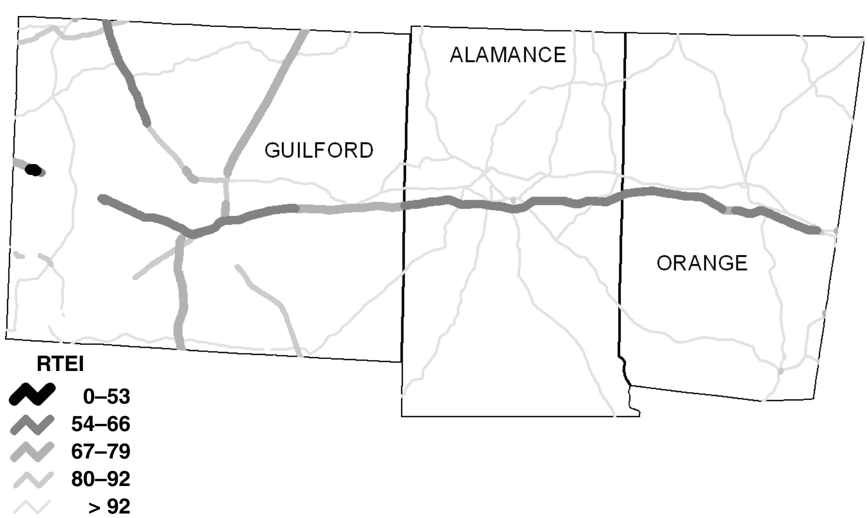

FIGURE 1 Examples of RTEI for three counties in North Carolina.

FIGURE 2 Example of severe alligator cracking.

is considered to be a problem. The overall pavement rating used was obtained from the North Carolina DOT PCS layer. The alligator cracking and rutting components were calculated on a scale of 0 to 100 and then weighted by the overall rating if it was less than or equal to 50. The following formula takes this factor into consideration and is applied to all road segments in the database:

$$\text{PCRI} = \begin{cases} \dfrac{A+R}{2} * \dfrac{\text{RTG}}{100} & \text{if RTG} \le 50 \\ \dfrac{A+R}{2} & \text{if RTG} > 50 \end{cases} \tag{5}$$

where

A = alligator cracking score, defined on a scale of 0 to 100;
R = rutting score, defined on a scale of 0 to 100; and
RTG = pavement condition rating calculated by North Carolina DOT, defined on a scale of 0 to 100.

Using the function above to calculate the PCRI results in a "discontinuity." For example, if two segments have similar alligator cracking and rutting scores and overall ratings on opposite sides of 50, the resulting PCRI for the two segments will be vastly different. This issue will be addressed at a future date. Figure 4 shows a map of the scaled PCRI for the three county areas. The classification scheme used in the symbology is the same as the one used in Figure 1. The mean PCRI value is 89.92, with a standard deviation of 20.76.

FIGURE 3 Example of severe rutting.

Bridge Severity Index

The BSI was calculated from two components found in the bridge GIS layer obtained from the North Carolina DOT. The first is whether a bridge is structurally deficient, functionally obsolete, or both. According to the bridge management unit at the North Carolina DOT, a bridge is "considered structurally deficient if significant load carrying elements are found to be in poor condition due to deterioration or the adequacy of the waterway opening provided by the bridge is determined to be extremely insufficient to point of causing intolerable traffic interruptions" (*7*). The bridge management unit defines a functionally obsolete bridge as "one that was built to standards that are not used today" (*7*). If a bridge is determined to be structurally deficient, it is given a value of 100. If a bridge is only functionally obsolete, it is given a value of 33. If a bridge is neither structurally deficient nor functionally obsolete, it is given a value of 0. The second component of the BSI is how far the bridge's posted weight is below 45 tons. The lower a bridge's posted weight, the more vulnerable it is to oversize or overweight trucks. The weight score was then transformed to a scale of 0 to 100 with the following formula: 100 $W_j/\max(W_j)$. A weighted average is then taken of the two components to obtain an individual bridge's bridge rating (BR).

$$\text{BR}_j = 0.2D_j + 0.8W_j \tag{6}$$

where

BR_j = bridge rating for bridge j, defined on a scale of 0 to 100;
D_j = bridge distress score for bridge j, defined on a scale of 0 to 100; and
W_j = weight score for bridge j, defined on a scale of 0 to 100.

The bridge distress value, D_j, and weighting used in calculating the BR were recommended by an expert with the bridge maintenance unit at the North Carolina DOT. Once the BR has been calculated for each bridge, BSI was calculated for each road segment. Once the data sets were in the proper format, the following formula was used to calculate the BSI for every road segment:

$$\text{BSI} = \max_j(\text{BR}) + \sum_{j \ne \max} \frac{\text{BR}_j}{10} \tag{7}$$

where

$\max_j(\text{BR})$ = maximum bridge rating for each segment;
BR_j = bridge rating j;
j = 1, . . . , n; and
n = number of bridges.

The formula used to calculate the BSI ensures that all bridges play a role in determining the vulnerability of a road segment while emphasizing the maximum bridge rating for that road segment as the most important factor. The BSI was then scaled with a transformation that was similar to that used for the RTEI:

$$100 - \frac{\text{BSI}}{\max(\text{BSI})} * 100 .$$

The result of this scaling is that lower values are considered to indicate more vulnerability than are higher values. Figure 5 shows a map

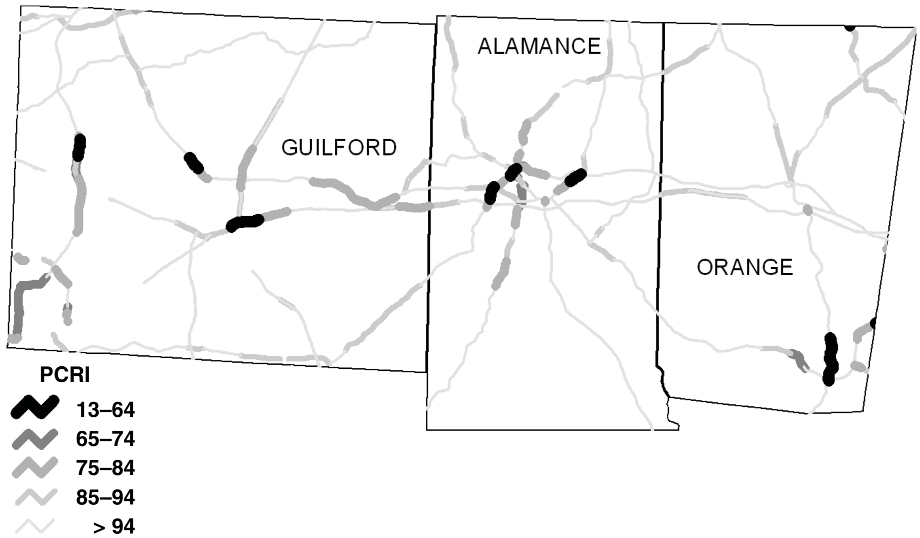

FIGURE 4 Examples of PCRI values for three counties in North Carolina.

of the scaled BSI for the three county areas. The classification is the same as in Figure 1, with a mean value of 89.06 and a standard deviation of 12.51.

Integration of Individual Components

Once each of the individual indices was calculated, they were combined by using the following formula and applied to each road segment:

$$\text{RVI} = \frac{\alpha\text{RTEI} + \beta\text{PCRI} + \gamma\text{BSI}}{\alpha + \beta + \gamma} \quad (8)$$

To begin, α, β, and γ were assumed to be 1. The initial RVI value that results from that assumption is shown in Figure 6. The mean value of the initial RVI is 90.22, with a standard deviation of 9.20. Lower values represent road segments that are more vulnerable to overweight trucks.

Baseline RVI

In the previous section, the initial RVI was calculated with the coefficients of each of the component indices assumed to be 1.0. Determining the relationship between each of the indices' coefficients is a matter of expert judgment. Before this relationship can be decided, any bias in the model needs to be removed. The baseline RVI will provide a starting point at which the three component indices contribute equally to the RVI. Once that is done, the coefficients can be modified from the baseline RVI on the basis of advice from experts in each of the three component fields.

To determine the bias in the model, a correlation analysis was performed. A paired correlation between each of the component indices and the overall RVI value was computed. Table 1 shows the results of this paired correlation analysis:

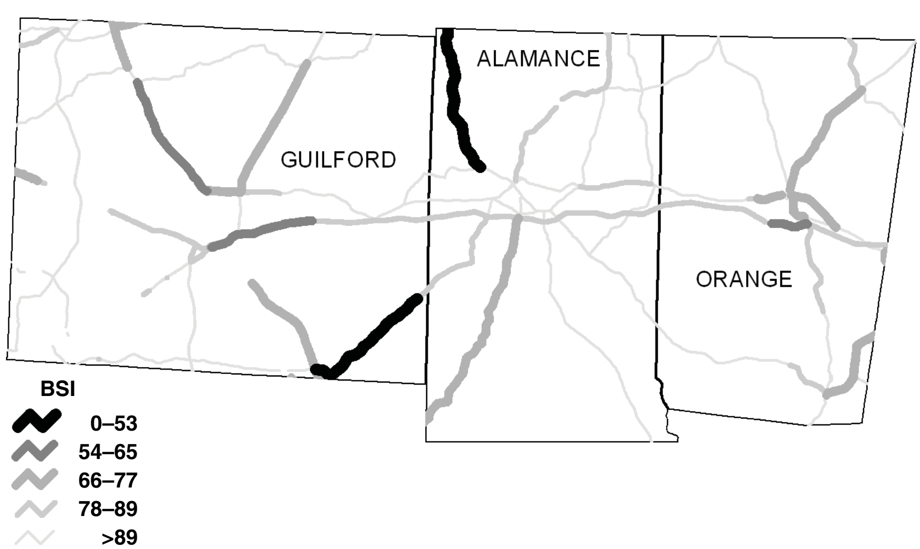

FIGURE 5 Examples of BSI values for three counties in North Carolina.

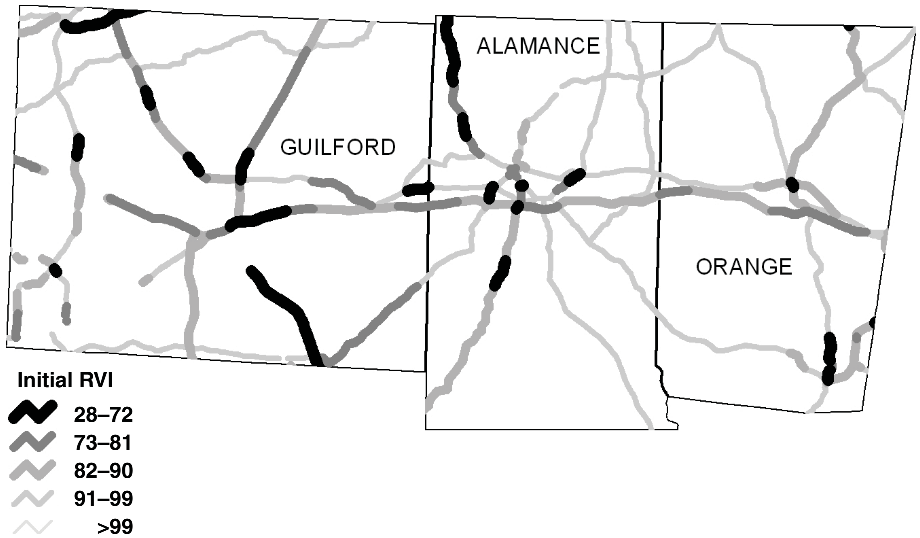

FIGURE 6 Examples of RVI values for three counties in North Carolina with $\alpha = \beta = \gamma = 1$.

From Table 1, the amount of variation in the RVI explained by each of the individual indices can be determined. Equation 9 shows the results of squaring the correlations found in Table 1.

$$R^2_{BSI} = .245$$
$$R^2_{RTEI} = .213$$
$$R^2_{PCRI} = .525 \quad (9)$$

where

R^2_{BSI} = variance in the RVI explained by the BSI,
R^2_{RTEI} = variance in the RVI explained by the RTEI, and
R^2_{PCRI} = variance in the RVI explained by the PCRI.

The percentages of the variation in the RVI explained by the BSI, RTEI, and PCRI are 24.5%, 21.3%, and 52.5%, respectively. To ensure that the variation in the RVI is equally explained by each of the indices, an optimization was performed to minimize the following:

$$\epsilon = (\rho_{BSI} - \rho_{RTEI})^2 + (\rho_{RTEI} - \rho_{PCRI})^2 \quad (10)$$

where

ϵ = variable that holds value of calculation on right side of equation,
ρ_{BSI} = correlation between RVI and BSI,
ρ_{RTEI} = correlation between RVI and RTEI, and
ρ_{PCRI} = correlation between RVI and PCRI.

TABLE 1 Paired Correlations Between BSI, RTEI, PCRI, and RVI

	BSI	RTEI	PCRI	RVI
BSI	1			
RTEI	0.088359	1		
PCRI	−0.00895	−0.07198	1	
RVI	0.495071	0.46147	0.724567	1

The baseline coefficients that result from minimizing Equation 10 are shown below:

$$\alpha = 1.14$$
$$\beta = 0.77$$
$$\gamma = 1.09 \quad (11)$$

If the baseline coefficients shown in Equation 11 are plugged into Equation 8, the baseline model is obtained.

$$\text{RVI} = \frac{1.14 * \text{RTEI} + 0.77 * \text{PCRI} + 1.09 * \text{BSI}}{3} \quad (12)$$

Now that the bias has been removed from the model, the coefficients can be modified to reflect the opinions of experts. Figure 7 shows a map of the baseline RVI, with a mean value of 90 and standard deviation of 8.54.

SENSITIVITY ANALYSIS

To see how stable the model was to small perturbations of the component indices, a sensitivity analysis was performed. For the sensitivity analysis, each of the component indices was perturbed by 5%. Results of the sensitivity analysis are shown in Table 2.

The RVI used to determine the sensitivity of the model was calculated by using the means of each of the component indices and is denoted as RVI_μ. When one looks at the percent differences between the RVI calculated as a result of perturbing one of the component indices and RVI_μ, the model appears to be fairly stable.

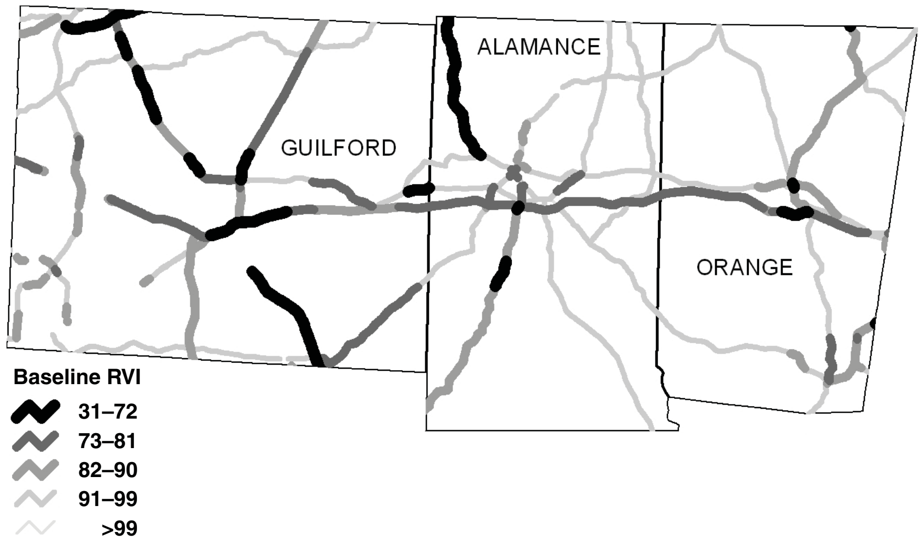

FIGURE 7 Examples of baseline RVI values for three counties in North Carolina.

CONCLUSIONS

Although the RVI remains in a very preliminary state of development and application, the value of the effort to this point is in having demonstrated how truck exposure data, pavement condition data, and data on the structural and functional attributes of bridges might be combined into a single index of road vulnerability. It is not the responsibility of motor carrier weight enforcement personnel to assess vulnerability but rather to direct their efforts in ways that might contribute to lessening the impact of overweight trucks on clearly vulnerable roads and facilities. The ability to map the RVI values of road segments statewide with a graphic GIS-based interface to these data provides the potential for improved weight enforcement planning.

Although this is only one piece of information, the size and weight enforcement group now has an additional tool that can help it in determining how best to allocate limited enforcement resources. Given these limited resources, the number of vulnerable road segments may need to be reduced. To do that, a minimum truck count threshold was determined on a troop-by-troop basis. For the troop that contains the three counties used in this paper, the minimum truck count threshold was determined to be 1,000. Figure 8 shows those road segments that are highly vulnerable (RVI ≤ 73) and also meet the minimum truck count threshold. A value of 73 represents the highest value in the lowest stratification using standard deviations from the mean.

TABLE 2 Sensitivity Analysis Using a Delta of 5%

	RTEI	PCRI	BSI	RVI	Percent Difference
μ	91.52	89.92	89.06	90.22	
$\mu_{[RTEI]}$ + 5%	96.10	89.92	89.06	91.95	1.93
$\mu_{[PCRI]}$ + 5%	91.52	94.42	89.06	91.37	1.28
$\mu_{[BSI]}$ + 5%	91.52	89.96	93.51	91.83	1.79

It remains unclear to what extent spatially targeting weight enforcement activities, in large part on the basis of bridge and pavement conditions, will provide a benefit to achieving enforcement goals that are more clearly driven by the presence of truck traffic (exposure). It is believed, however, that by adding measurable indices of bridge and pavement vulnerability to a measurable index of exposure, limited enforcement resources can more effectively be applied to the complementary goals of maximizing the number of vehicles weighed, the effects of monetary sanctions for being overweight, and the goal of infrastructure preservation. It remains to be determined whether the present GIS-based interface to these data will be of more benefit to those staff members in a state DOT having direct responsibility for the condition of the roadway infrastructure or to weight enforcement personnel in their efforts to preserve roadway infrastructure through enforcement methods.

LIMITATIONS

There are several limitations to the size of the resulting road network (i.e., number of routes and segments). For the RTEI, the network is limited to those segments that have an associated truck count station. Another limitation to the RTEI is the number of lanes, which is used to calculate the passenger car equivalent flow rate. There are road segments for which documentation for the number of lanes is either missing or in error. For the PCRI, there are segments that have no pavement condition rating information. These segments were removed from the final RVI network database.

FUTURE WORK

This is the first version of the RVI. One of the first things to be addressed is the manner in which the PCRI is weighted. The step function causes a discontinuity and needs to be addressed. Input from experts at the North Carolina DOT will be necessary to find an appropriate way to weigh the alligator cracking and rutting scores.

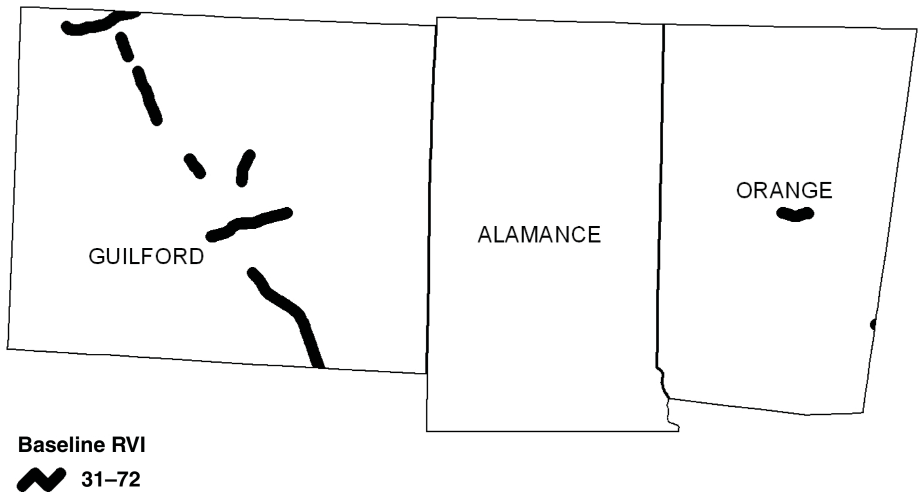

FIGURE 8 Example of baseline RVI values that also meet minimum truck count threshold for three counties in North Carolina.

Once the baseline RVI has been determined, a meeting with experts at the North Carolina DOT will take place to discuss what their opinions are on how the coefficients of the model should be modified to reflect the impact each of the individual components has on the RVI value. Additional information currently under consideration for adding to the RVI includes geometric design, lane width, and grade. The geometric design aspect will be especially important in the mountainous areas and will determine those roads in the state that do not have the minimum curvature for some classes of vehicles to traverse the road properly. In regard to lane width, that aspect becomes especially important if longer, “more productive” trucks become more prevalent. The narrower a lane is, the more likely it becomes that a truck will require the use of the shoulder to traverse a road segment. That factor will most likely have a greater impact in regard to smaller highways, so care will need to be taken to ensure that this factor does not overly influence the overall RVI. Last, including the grade factor will increase the accuracy of the truck capacity component of the RTEI.

ACKNOWLEDGMENTS

The research for this paper is part of an ongoing relationship with the size and weight enforcement group at the North Carolina State Highway Patrol. The authors thank Neil Mastin, Don Idol, and Kent Taylor at the North Carolina Department of Transportation for their contributions.

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The Maintenance and Operations Management Committee peer-reviewed this paper.