Pavement Friction in a Program to Reduce Wet Weather Traffic Accidents at the Network Level

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Pavement Friction in a Program to Reduce Wet Weather Traffic Accidents at the Network Level

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Approximately 20% of all traffic accidents occur in wet weather conditions. Pavement surface problems, such as lack of skid resistance, probably contributed to a portion of those vehicle accidents on wet pavements. An approach for reducing wet weather accidents was developed. The main feature of the proposed approach is that it uses data from both automated accident and skid data files. The contents of both skid number (SN) and accident files were studied. The related parameters in the skid file were selected, including the skid number, and a group of accident parameters was defined. The skid and accident files were merged to allow for developing a program that identifies "high-risk" locations for treatment. Such locations are expected not only to have high wet weather accidents but also to have experienced a critical number of wet weather accidents. An example is used to illustrate the functionality and effectiveness of the proposed approach and the associated computer program. Accident history was obtained on approximately 500 rural two-lane highway sections over a 3-year period. The total traffic accidents involved was approximately 36,000. A criterion to estimate possible risks was developed, and a system of priority ratings, based on economic analysis, was established to assist in the process of selecting slippery highway sections for maintenance, permitting available funds to be allocated optimally.

In the United States, the most accepted method for measuring skid resistance is the locked wheel trailer method in accordance with the ASTM Method E-274. The result of the test is reported as skid number (SN) SN40, if the speed of the test trailer is 40 mph. There is a high level of complication in defining skid resistance of a pavement immediately after construction [SN40 (0)] and at time *t* after construction [SN40 (*t*)]. SN40 (0) is dependent on pavement variables (mix design variables and initial surface characteristics). SN40 (*t*) depends on two main variables: SN40 (0) and the characteristics of surface texture at time *t,* which are a function of other time-dependent variables such as traffic (*1*). Maintaining adequate skid resistance has been one of the most difficult responsibilities of highway agencies, because skid resistance is a highly variable characteristic and one that is affected by both tire and pavement as well as by environmental factors.

Most U.S. agencies collect friction data but do not report the data as part of a pavement management system (PMS). Agencies regard friction data as being related to specific program areas such as wet weather accident reduction and material evaluation. Friction data are usually collected along with other pavement condition data such as distress, roughness, and structural data. Most states store friction data on mainframes and PCs and can retrieve friction data from a number of storage media (*2*). Although surface friction data are important to pavement managers, particularly as a stand-alone "trigger" for maintenance or rehabilitation, few agencies collect such data on a networkwide basis. Instead, they evaluate only those sections that indicate a possible low SN (*3*).

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STUDY OBJECTIVES

The study objectives are as follows:

1. Develop a criterion to estimate possible risks or skidding accident potential.
2. Establish a system of priority ratings, based on economic analysis, to assist in selecting slippery sites—which are most prone to wet weather accidents—for resurfacing.
3. Prepare a computer program designed to assist in developing strategies aimed at wet weather accident reduction.

STUDY APPROACH

The study approach for reducing wet weather accidents can be explained in three parts: first, development of skid resistance information; second, treatment of accident information; third, development of a safety improvement program. A general flow diagram of the study approach is shown in Figure 1. This study is intended to illustrate an approach and is not an actual investigation or evaluation.

Skid Data

A number of states have a regular program in which SN measurements are made at a large number of locations. Routes are usually divided into "sections," which are variable in length. Each section is defined by pavement and traffic characteristics, which are essentially uniform. SN measurements along with a number of other parameters are reported on and organized in computer files, which also show averages of SN along a section and within a county. Of most importance to this work is the information on SN measurements. A series of SN measurements is usually taken on each section. An average value along with the number of tests and the standard deviation are

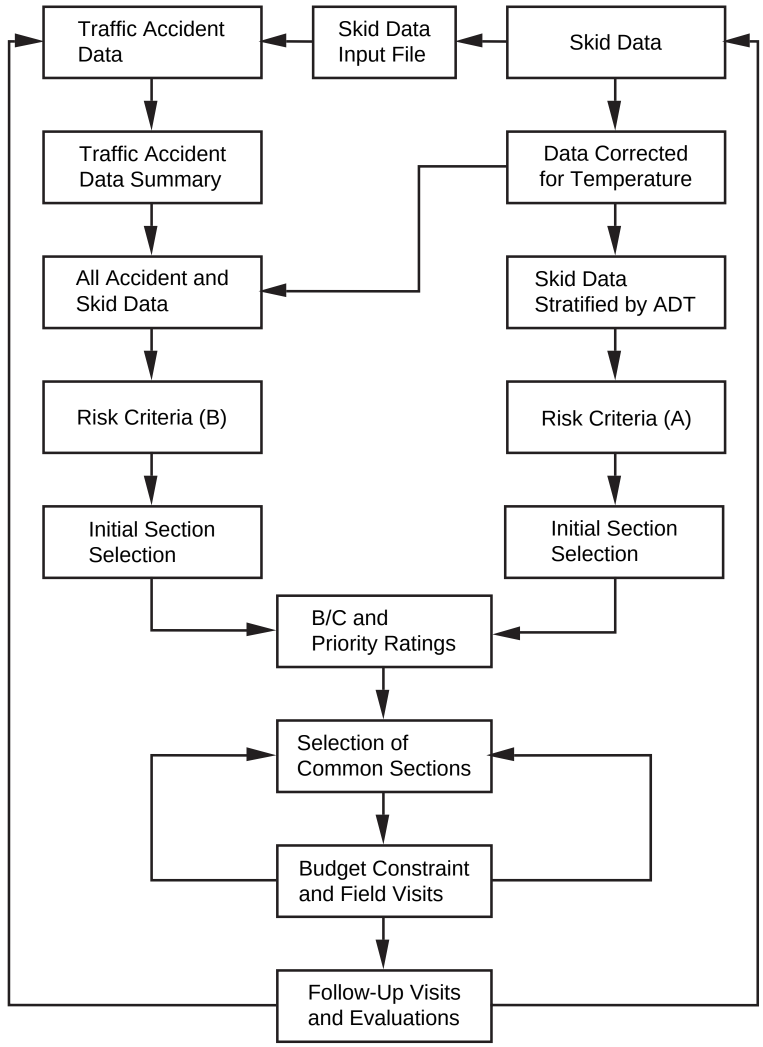

FIGURE 1 General flowchart of study approach.

recorded. The minimum and maximum SN values also are recorded for each section. The variables considered to be of primary importance are location-related data (county, route, district, beginning log, ending log, and section length), average daily traffic (ADT) data, weather data (temperature), and skid data (section average).

Skid resistance varies considerably within a short period of time because of environmental changes. Temperature change is one the significant variables affecting short-term changes. The correction for temperature is expected to make SN data more reliable for use in further analysis by controlling this major source of variability. The availability of air temperature in the SN file allows for correcting SN measurements for air temperature variation during tests. It is to be expected that very high temperatures tend to reduce pavement friction (*4*). Correcting SN for seasonal variation, especially temperature, was studied by a number of researchers (*5–9*). Air temperature, pavement temperature, Julian calendar date, dry spell factor, and rainfall quantity were among the variables used to correct friction measurements. One model corrects SN for test air temperature deviation from a standard temperature (70°F) as in Equation 1 (*4*). After reading the raw SN data, Equation 1 may be used to adjust SN data for test temperature variation.

$$\mathrm{SN}_c = \mathrm{SN} + (0.15 \times T - 10.5) \tag{1}$$

where

SN_c = corrected section average skid number,
SN = observed section average skid number, and
T = air temperature in °F at the time of SN measurement.

Traffic volume is the most influential variable affecting the performance of pavement surface over time. One way to account for the effect of traffic variability is to stratify the data by the traffic volumes or ADT groups. The study approach suggested stratifying the SN data by the three ADT categories: low with volumes of less than 2,000, medium with volumes between 2,000 and 4,000, and high with volumes of at least 4,000 vehicles per day.

Risk Criterion A Based on SN Data

Risk Criterion A assumes the availability of a policy regarding critical levels of SN. In many states, such critical or minimum friction requirements are based on research findings. However, only a handful of states reported having pavement friction requirements for new pavement construction (*5*). SN40 with ribbed tire (SN40R) minimum requirement for new construction varied from 30 to 45. More than 40 states reported performing skid testing on a regular basis and using the results in their pavement management system. Only 11 states indicated having an intervention level for friction. The range for SN40R was 28 to 41 for interstates, 25 to 35 for primary roads, and 22 to 35 for secondary roads (*5*). Another survey gave a wide range of skid number requirements for directing attention to corrective rehabilitation from 20 to 43 (*10*). The most common minimum skid number reported was 35 for five states. The variation in friction testing devices and testing tires may explain the large range in intervention levels, especially the extreme values.

The proposed approach uses specified critical levels of SN or models that can predict the potential for wet pavement accidents of a given section with a certain level of skid resistance. The risk can be defined by the expected rate of occurrence of wet weather accidents. Let EWA be the expected number of wet weather accidents per mile per year for a given SN_c. For each SN data set (stratified by ADT), available models can be used to estimate EWA with SN_c as the independent variable. Criterion A states that a section is at risk if EWA exceeds a given critical level. Let EWA_{cr} be the critical number of wet weather accidents/mile/year that sites would merit further attention. This criterion selects sections for further investigation if $EWA > EWA_{cr}$. This is the first component of risk because it selects sections for further consideration only on the basis of skid number (SN_c). In other words, any of those selected sections may or may not have actually experienced wet weather accidents, but they simply exhibited a relatively high potential for wet weather accidents.

Risk Criterion B Based on Traffic Accident Data

This risk criterion is determined by the actual experience of a given section with respect to wet weather accidents over a period of time. The following accident measures are defined:

A_d = dry weather accidents during the analysis period,
A_w = wet weather accidents during the analysis period,
A_t = total accidents during the analysis period,

$$A_{wt} = \text{rate of wet weather accidents} = \frac{A_w}{A_t} \times 100\% \qquad (2)$$

$$A_{wmy} = \text{number of wet weather accidents per mile per year} = \frac{A_w}{N \times \text{SL}} \qquad (3)$$

where N is the period over which accident history is obtained in years and SL = section length in miles.

$$A_{wmvy} = \text{wet weather accidents/million vehicle miles/year} = \frac{A_w \times 10^6}{\text{AVM} \times N} \qquad (4)$$

where

$$\text{AVM} = \text{annual vehicle miles} = \text{ADT} \times 365 \times \text{SL} \qquad (5)$$

To obtain such accident information from the state accident file, an input file is needed. This file must contain the following variables: county, route, beginning log, ending log, and the period of time over which accident history is required. With the exception of the last parameter, which is specified by the user, the other parameters can be provided by skid data file. Therefore, an input file that has these parameters can be created from the skid file to extract accident history from the traffic accident file. The desired period of accident history (from–to) must be specified.

The variables in the accident file that are of primary importance with respect to wet pavement accidents are as follows: county, route, log point, and road conditions (dry or wet). The variable "log point" represents the exact location of an accident, which is a point on a section between its beginning and ending log. Traffic accident data can be summarized by calculating the frequency of accidents for each level of road condition. That is, for a given section, this summary will give the number of accidents that occurred on each pavement section, on dry pavement, wet pavement, and so forth. Accidents occurring on wet and dry pavements are of primary importance to this study. The step of calculating accident measures or rate must wait until the two files (accident summary and skid data) are merged, because such accident measures are functions of variables from both SN and accident files, as given in Equations 2 to 5.

This risk criterion is very important because decisions made are on the basis of actual accident experience. Thus, it is suggested that at least three accident measures (A_{wt}, A_{wmy}, and A_{wmvy}) be considered in the decision making for this criterion. Accident rates are preferred for use in this criterion over accident frequencies because rates take into account other variables such as section length, study period, and volume of traffic. Critical levels for each of these measures are to be specified by the state agency. Acceptable levels of wet weather accidents that a state might reasonably allow and above which sections should be considered for further treatment is a difficult issue to resolve. Many researchers attempted to determine such critical levels through statistical analysis of accident data. Most studies recommended critical values for SN but not for wet weather accidents. This question is also hard to answer because a zero wet accident rate is an ideal, but it is unfortunately an unattainable ideal. This is a sensitive issue that requires public officials to draw a line between what is considered relatively safe and what is not. This decision will drastically affect the number of sections selected for further treatment and the cost of associated maintenance activities.

The Risk Criterion B selects a section for further evaluation if actual accident rates are equal to or greater than the specified critical (maximum) values. Common sections may be found from the sections selected on the basis of both Criteria A and B and indicate that such sections not only are expected to have high wet weather accidents but also have already experienced a critical number of wet weather accidents in the past. Such sections are considered high risk and, as a result, will be given higher priorities for corrective action.

Benefit–Cost Analysis and Priority Ratings

Benefits can be estimated from the expected savings because of anticipated reduction of wet weather accidents on resurfacing. Rural projects resurfaced because of a large number of wet weather accidents have been observed to show a clear reduction of wet pavement accidents after resurfacing. In one study, resurfaced sections exhibited an immediate reduction in wet pavement accidents ranging from 15% to 70% and probably averaging more than 20% over the life of the project (*11*). Consequently, wet weather accident reduction can be an important result of a resurfacing project.

Because of resurfacing, it is expected that wet weather accidents should decrease but will not necessarily become zero. This is because not all wet weather accidents are related to skid resistance of the pavement. This means that some minimum parameter of acceptability of wet weather accident rate will have to be specified. Let this parameter be EWA_{min} in Criterion A and $AWMY_{min}$ in Criterion B. A zero value may overestimate the expected benefits. A reasonable estimation of the minimum value also can be obtained using skid number after resurfacing and accident models that can predict wet weather accidents as a function of skid number if available. The benefits can be estimated as follows:

$$\text{Abenefits}(\text{ABN}) = \text{NARA} \times \text{AAC}_{\text{yr}} \quad (6)$$

where

Abenefits = benefits ($) from the expected savings because of anticipated reduction of wet weather accidents after resurfacing for a section selected by Criterion A,
NARA = anticipated reduction in wet weather accidents because of resurfacing for a section selected by Criterion A as defined in Equation 7, and
AAC_{yr} = average total accident cost in a given year.

$$\text{NARA} = \text{EWA} - \text{EWA}_{\text{min}} \quad (7)$$

$$\text{Bbenefits}(\text{BBN}) = \text{NARB} \times \text{AAC}_{\text{yr}} \quad (8)$$

where Bbenefits are the benefits ($) from the expected savings because of anticipated reduction of wet weather accidents after resurfacing for a section selected by Criterion B, and NARB is the anticipated reduction in wet weather accidents because of resurfacing for a section selected by Criterion B as defined in Equation 9.

$$\text{NARB} = \text{AWMY} - \text{AWMY}_{\text{min}} \quad (9)$$

The reason the expected benefits are different for Criteria A and B is that the anticipated reduction of wet weather accidents after resurfacing for a given section depends on the criterion used. Criterion A predicts wet weather accidents mainly as a function of SN, whereas Criterion B uses actual section history of wet weather accidents. A study developed methods leading to estimates of accident costs that can be used directly with state accident data as follows (*12*):

$$\text{AAC} = (\text{average direct accident cost}) + (\text{average indirect accident cost}) \quad (10)$$

where direct costs ($) are property damage, medical, legal, and funeral costs and indirect costs ($) are administrative costs and human capital costs (lost productivity).

The average accident cost can be updated to a current year by applying appropriate cost indices to the direct and indirect costs as in Equation 11:

$$\text{AAC}_{\text{yr}} = 15.04 \times \text{CPI}_{\text{yr}} + 120.3 \times \text{IAHE}_{\text{yr}} \quad (11)$$

where CPI_{yr} is the consumer price index in a given year (average) and $IAHE_{yr}$ is the index of hourly earnings in a given year.

Conversely, the cost of resurfacing can be estimated by knowing the amount of material (surface course) needed. The amount of material is a function of section length, road width, and the thickness of the surface course. Both the present cost per mile and the annual resurfacing cost (ARC) per mile can be estimated using input or default values for minimum overlay thickness and resurfacing unit cost. The thickness of overlay may change as a function of ADT, depending on the agency practices with respect to overlays. That is, for heavily traveled roads, the minimum overlay thickness may be higher than the minimum thickness of an overlay for lightly traveled roads. To calculate the benefit to cost ratios (*B/C*), the present cost needs to be converted to annual cost, because the benefit has been estimated on an annual basis. This requires an estimate of the expected performance period of the resurfaced pavement. Benefit–cost ratios are defined as follows in Equations 12 and 13:

$$(B/C)_a = \text{Abenefit/cost of resurfacing} = \frac{\text{NARA} \times \text{AAC}_{\text{yr}}}{\text{ARC}} \quad (12)$$

where $(B/C)_a$ = benefit to cost ratio for a section selected by Criterion A, and ARC = annual resurfacing cost/mile.

$$(B/C)_b = \text{Bbenefit/cost of resurfacing} = \frac{\text{NARB} \times \text{AAC}_{\text{yr}}}{\text{ARC}} \quad (13)$$

where $(B/C)_b$ is the benefit to cost ratio for a section selected by Criterion B.

Resurfacing is used as an example for achieving adequate skid resistance, provided attention is given to mix design variables in the design of that project. However, other measures to restore skid resistance have been used by many states, and these measures can replace resurfacing. Another parameter can be defined to prioritize selected sections based not only on *B/C* ratios but also on traffic volumes and SN levels. The resulting parameter is called priority rating (PR) and is defined as in Equations 14 and 15.

$$\text{PR}_a = \left[\frac{(B/C)a \times \text{ADT}}{100 \times \text{SN}_c}\right] \quad (14)$$

where PR_a is the priority rating for a section selected by Criterion A.

$$\text{PR}_b = \left[\frac{(B/C)b \times \text{ADT}}{100 \times \text{SN}_c}\right] \quad (15)$$

where PR_b is the priority rating for a section selected by Criterion B.

Even though ADT and SN were considered in the process leading to *B/C* ratios, it may be appropriate to give higher priorities to sections with high traffic volumes and low skid numbers. Using the parameter PR, selected pavement sections can be arranged by descending order of PR. It is expected that a list arranged by *B/C* may not differ very much from a list arranged by PR except for sections with extreme values of ADT and SN.

Budget Constraint

The total present cost of resurfacing per section (TCPS) can be estimated. Sections with *B/C* greater than a chosen value that yield a TCPS less than or equal to the available budget can be selected as shown in Equation 16.

$$(B/C) \geq (B/C)_{cr}$$
and
$$\sum_{i=1}^{N} \text{TCPS}_i \leq B \quad (16)$$

where N = the total number of sections which satisfy both B/C and budget constraints.

Because a given section may have two different priority ratings, a weighted value for B/C and PR can be calculated so that it is possible to rank them on the basis of the new weighted PR. The weighted values for B/C, PR, and benefits are given in Equations 17, 18, and 19.

Weighted benefit to cost ratio

$$\left(\frac{B}{C}\right)_w = \frac{\left(\frac{B}{C}\right)_a + \left(\frac{B}{C}\right)_b}{2} \tag{17}$$

Weighted priority rating

$$\mathrm{PR}_w = \frac{\mathrm{PR}_a + \mathrm{PR}_b}{2} \tag{18}$$

Weighted benefits

$$\mathrm{BN}_w = \frac{\mathrm{ABN} + \mathrm{BBN}}{2} \tag{19}$$

Selected common sections based on Criteria A and B can be ranked by the new weighted priority rating. The section with the highest priority rating is selected first if its total cost is less than the budget. If there is more money in the budget, selecting sections continues until the total cost of a selected section exceeds the budget; in that case, the search continues for a section whose total cost does not exceed the money left in the budget. In a case in which the budget is greater than the total cumulative costs of all sections in the common list, other additional sections can be selected from those that satisfy Criteria A or B starting with the section with the highest priority rating. As before, the process continues until the total cost of a selected section exceeds the money left in the budget. The process requires optimizing the allocation of budget money so that only the minimum amount of money is left in the budget.

Field Visits

The maintenance engineer will need to visit each selected site. The field review will help to determine whether pavement skid resistance is a major contributing factor to the excessive rate of wet weather accidents at that location. The effects of skid resistance and other important factors such as speed limit and horizontal and vertical alignments should be carefully reviewed during the field assessment, and a judgment should then be made on whether or not improving skid resistance of the pavement would significantly reduce the rate of wet pavement accidents on that section.

The maintenance engineer can then make necessary recommendations on whether a given pavement section should be kept on the resurfacing list or whether other specific measures should be taken to solve the problem. If a section is selected because of lack of skid resistance and high potential of wet weather accidents, the maintenance engineer can make recommendations on whether or not the minor rehabilitation treatment is sufficient or whether other measures may be necessary. Other measures may include major rehabilitation if other defects in addition to the skid resistance problem are found by the field review. After reviewing all pavement sections on the resurfacing list, the maintenance engineer can then make the final recommendations as to which sections should remain on the list and which should be left out or transferred to other lists.

Finally, the maintenance engineer should evaluate all the treated sections and provide data to update the skid and accident files. This process includes comparing wet pavement accident rates before and after resurfacing as well as skid numbers. This will help in the continuing assessment of the overall effectiveness of the decision process.

COMPUTER PROGRAM

A computer program was written to illustrate the approach that allows the identification and review of high risk sections on state highways with inadequate skid resistance or with high potential for wet weather accidents. The logic of the proposed program and an application example are presented in the following two sections.

Program Logic

The logic of the program for Risk Criterion A is presented in Figure 2. The program gives the user the ability to enter selected critical levels as input variables. Otherwise, the program will use the default values. As a result of an "if statement," the program will then select the sections that should be listed for further investigation (sections with $\mathrm{EWA} > \mathrm{EWA}_{cr}$). Let this list be List 1. The program generates two other lists (List 2 and List 3) that are related to List 1. List 2 is a subgroup of List 1 that contains all sections that satisfy a given critical condition of benefit to cost ratio (B/C), whereas List 3 is a subgroup from List 2 that contains all sections from List 2 arranged in descending order by priority ratings (PR). The program selects two-lane rural asphalt concrete sections by default from the SN file. The program can select other sections such as multilane highways after changing the program logic for this step mainly with respect to lane identification and accident locations.

The logic of the program for Risk Criterion B is presented in Figure 3. The Risk Criterion B is defined by an "if statement" that will select a section if actual accident rates are equal or greater than the specified critical (maximum) values. Any site that satisfies these conditions will be selected for further evaluation (List 4). The program then generates two other lists (List 5 and List 6). As with Criterion A, List 5 is a subgroup of List 4 and contains all sections that satisfy critical (B/C) and List 6 contains the same sections of List 5, but arranged in descending order by priority rating.

Next, the program merges the two lists of selected sections (List 3 and List 6). Common sections may be found in the two lists and are presented as List 7. The program makes the given budget available to sections from this list first before considering any other section regardless of the actual priority ratings from List 3 and List 6. When the budget money is allocated to sections of the common list, the program uses a weighted priority rating for each section. This step is needed because a given section from the common list (List 7) may have two different priorities in List 3 and List 6.

The logic of the program for budget constraint and final section selection is presented in Figure 4. The program starts with sections recommended for treatment on basis of SN as well as accident frequencies (Criteria A and B). The user must enter the budget available for the resurfacing program. The total cost of each section in the common list is then added and printed as part of List 7. For each section in the common list, two values of B/C and PR are printed. The first

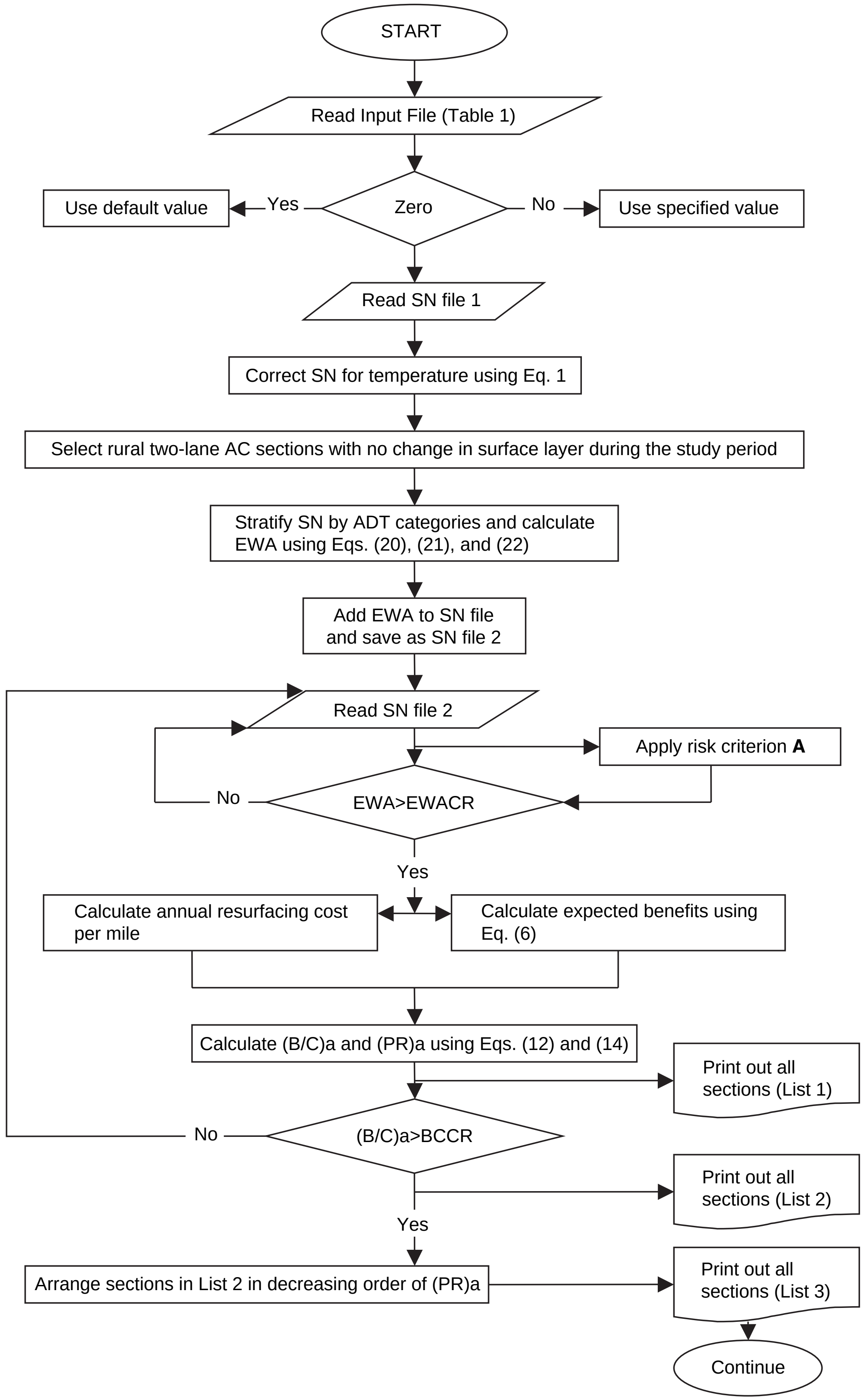

FIGURE 2 Flowchart of program logic for Risk Criterion A.

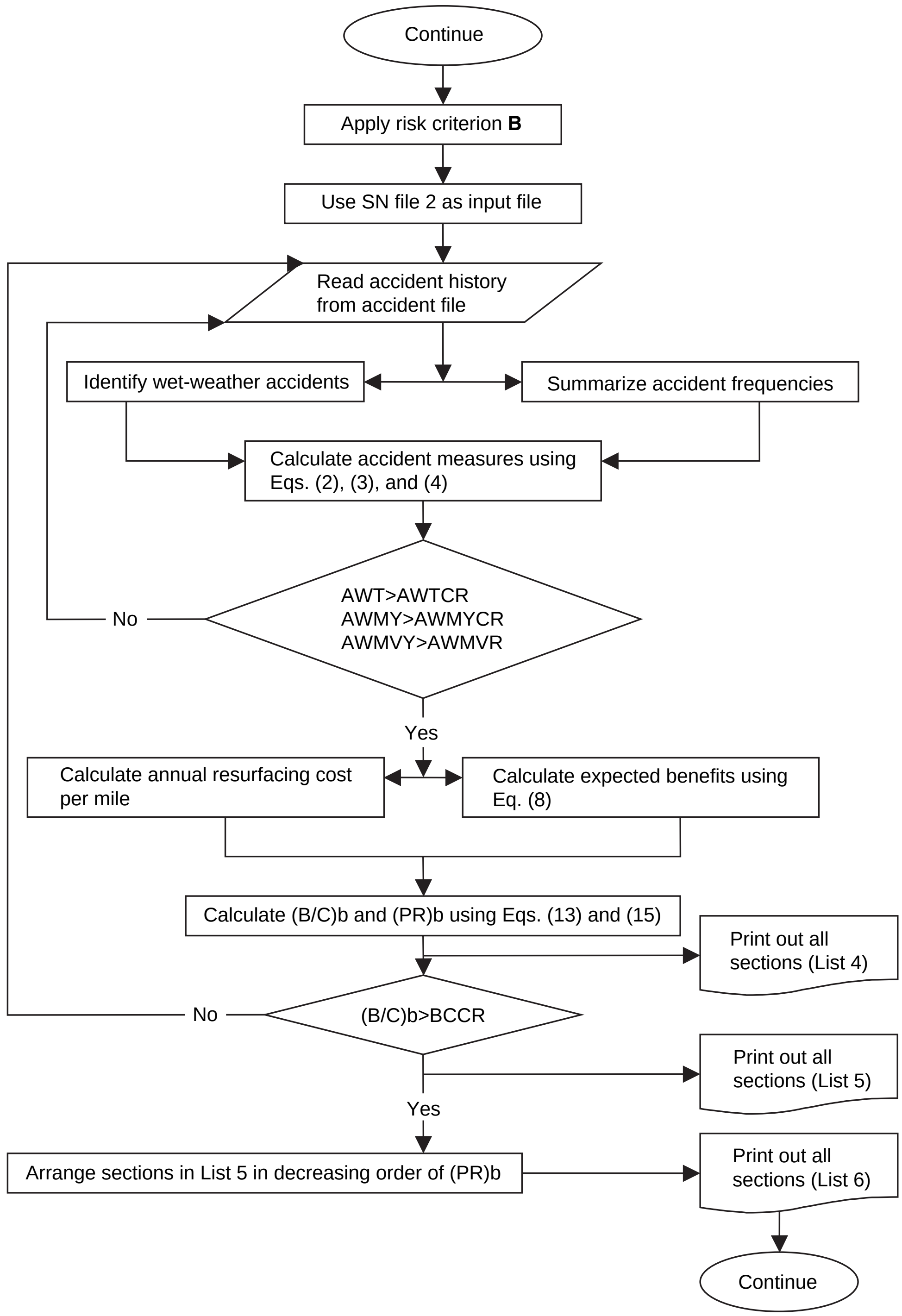

FIGURE 3 Flowchart of program logic for Risk Criterion B.

B/C and PR values correspond to Criterion A, whereas the second pair corresponds to Criterion B. The program then generates List 8, which contains all the sections of List 7 but ranked by the new weighted priority rating.

Next, as shown in Figure 4, the program selects sections for resurfacing from List 8, taking into consideration the budget constraint. The program prints the sections that satisfy the budget constraint as List 9. In a case where the budget is greater than the total cumulative costs of all sections in the common list, the program prints the amount of money left in the budget and prints out a list of sections left after selecting the common sections (List 10). The program continues by selecting additional sections from List 10, starting with the section with the highest priority rating. As before, the process continues until the total cost of a selected section exceeds the money left in the bud-

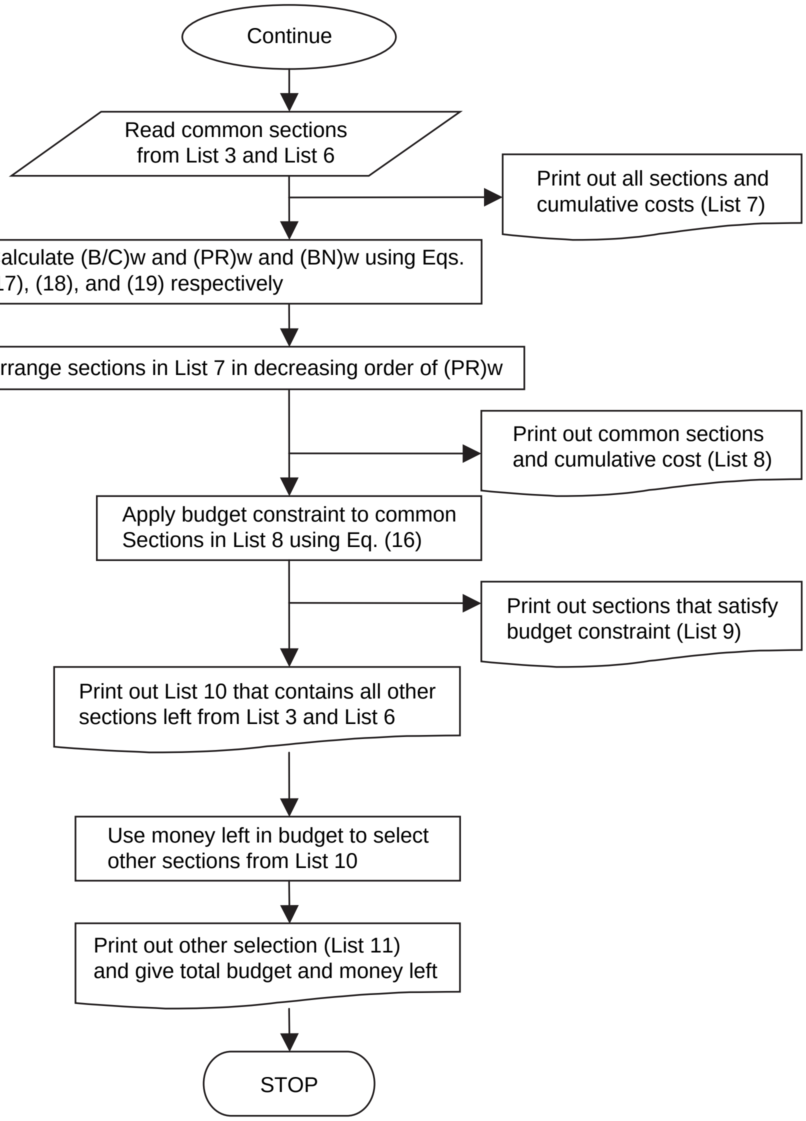

FIGURE 4 Flowchart of program logic for budget constraint.

get. The program then prints the selected sections from other selections, given that the budget constraint is satisfied. This is List 11 and is the last list the program generates. Finally, the program lists the subtotal of other selections and the total cost of all selected sections which should be less than or equal to the budget. The money left in the budget if any is also printed.

Application Example

The logic of the program is explained with the help of a numerical example. The SN file made available from the State of Ohio was loaded, and the Statistical Analysis System (SAS) was used to perform the necessary data management. A SAS program was written to read the SN file so that all rural highway sections have been included where the number of lanes is two and the surface type is asphalt. In this example, data used most of the available state records because the vast majority of the state highways have asphalt surface courses and much of the state system consists of two-lane roads. The SAS program also was written to organize and sort the data by county and route and to create a file that contains the parameters selected. Even though data used are actual data from the State of Ohio, these data are not current and were used only to demonstrate the proposed procedures. Numerical results or parameters used do not necessarily characterize conditions in the State of Ohio or any part of it.

A random sample was taken without replacement from the SN population. The random number function of SAS functions was used to carry out the procedure with the help of IF statements. The list of sections in its final form consists of 501 sections. An input file containing information to identify each section (county, route, beginning log, and ending log) was prepared. In addition, a fixed period of 3 years was specified as part of the input for each section. The input file was loaded, and the output was another file that contained the history of accidents at all selected sections. Wet weather accidents made up approximately 20% of all traffic accidents. The total number of accidents on all sections and over a 3-year period was 36,166 accidents.

This example represents a case when the budget available for the resurfacing program is limited and is less than the cumulative total cost of all sections in the common list. In this case, only a subgroup of sections from the common list is chosen taking into account the priority ratings and the budget constraint. The program is designed to maximize the allocation of budget moneys. In general and before running the program, the user must check the variables presented in the "user input file" similar to that shown in Table 1 and decide what values to be entered for each variable. If a value of zero is entered for any variable, the program will automatically use the default value. Normally the user enters the appropriate values in accordance with the state policies and practices. The budget available for resurfacing is set at $2 million.

The output of running the program for this case study is summarized in 11 lists. Lists 8 and 9 are given in Table 2. The lists are arranged in the same order as the logic of the program discussed earlier. The program starts out with 107 sections, 50 of which selected because they showed evidence of high and unacceptable potential for wet weather accidents (Risk Criterion A) and 57 sections selected because they actually experienced unacceptable level of wet weather accidents (Risk Criterion B).

The common sections that satisfy both Risk Criteria A and B are shown in Table 2 (List 8), where sections are ranked by weighted PR. For illustrative purposes only, the program uses the models given in Equations 20, 21, and 22. Such models predict the number of wet weather accidents for a given corrected skid number (*13*). The selected models have been used only to illustrate how the program works. Other valid predictive models may be specified by the user.

$$\text{EWA} = \frac{10^{3.174 - 0.0461 \times \text{SN}_c}}{100} \qquad (\text{ADT} < 2000) \qquad (20)$$

$$\text{EWA} = \frac{10^{3.706 - 0.0462 \times \text{SN}_c}}{100} \qquad (2000 \leq \text{ADT} < 4000) \qquad (21)$$

$$\text{EWA} = \frac{10^{4.470 - 0.0581 \times \text{SN}_c}}{100} \qquad (\text{ADT} \geq 4000) \qquad (22)$$

An important note on the output is that the total cumulative cost of all common sections (Table 2) is $3,943,686, which exceeds the budget ($2 million). The program selects sections from List 8 in the order presented and adds the cumulative total cost until the budget is exceeded. In this case, it happened when the program considered selecting route 309 in all county. Its total resurfacing cost of ($299,347), when added to the cumulative total cost would have exceeded the $2 million budget. For that reason, the program skips that particular section and continues with what is left in the budget to find another cheaper section that can use the money. In this case, Route 6 of ERI county was found as the best next choice with a maintenance cost of ($177,320). The program shows at the bottom of Table 2 that only $94,859 are available in the budget. One can see that no section in the common list was found appropriate to use the money left. The other choice is to search in the list that contains the sections after selecting the common sections. No section was found that can be resurfaced with a cost less than or equal to $94,859 and so the only list provided for resurfacing remains that given in Table 2 (List 9).

CONCLUSIONS

This study presented an approach that allows the identification and review of high-risk sections on state highways with inadequate skid resistance or with high potential for wet weather accidents. A high-

TABLE 1 User Input File

Variable Name	Name in Program	Description	Default Values
$(\text{EWA})_{cr}$	EWACR	Critical (maximum) level of wet weather accidents per mile per year for risk criterion A	1.0
Start	IFROM	Starting date for accident history	mm/dd/yy
End	IEND	Ending date for accident history	mm/dd/yy
$(\text{Awt})_{cr}$	AWTCR	Critical (maximum) rate of wet weather accidents for risk criterion B	20.0
$(\text{Awmy})_{cr}$	AWMYCR	Critical (maximum) level of wet weather accidents per mile per year for risk criterion B	1.0
$(\text{Awmvy})_{cr}$	AMWVYR	Critical (maximum) level of wet weather accidents per million vehicle miles for risk criterion B	0.5
$(\text{EWA})_{min}$	EWAMIN	Minimum expected number of wet weather accidents per mile per year for risk criterion A	0.1
$(\text{AWMY})_{min}$	AWMYM	Minimum expected number of wet weather accidents per mile per year for risk criterion B	0.1
CPI_{yr}	CPI	Consumer price index in a given year (average)	432
IAHE_{yr}	AHE	Index of hourly earnings in a given year	225
Thickness	THICK	Thickness of overlay (in.) (three values for low, medium, and high traffic sections)	1.0, 1.25, 1.5
Width	WIDTH	Width of lane (ft)	12
Service years	NYYEARS	Expected number of years in service of an overlay for ADT groups	12, 10, 8
Unit cost	UCOST	Unit cost of resurfacing ($/yd^3)	65
Rate	RATE	Interest rate (i)	10%
Budget	BUDGET	Available resurfacing budget ($)	2,000,000
$(\text{B/C})_{cr}$	BCCR	Critical (minimum) value of benefit to cost ratio	4.0
$(\text{PR})_{cr}$	PRCR	Critical (minimum) value of priority rating	4.0

TABLE 2 Common Sections and Budget Constraint (List 8 and 9)

County	Route	BLOG	ELOG	*(B/C)w*	(PR)*w*	(BN)*w*	Total Cost($)
List 8: common sections ranked by weighted priority rating							
Col	062R	486	1,002	49.2	282.5	456,677	196,768
Cle	131R	8	553	11.7	43.4	108,686	207,827
Gal	035R	659	1,314	11.8	40.2	109,627	249,773
Col	014R	1,174	1,688	12.6	29.5	117,404	196,005
But	747R	237	870	8.3	17.6	77,109	241,384
Mar	004R	363	838	11.7	15.7	109,084	181,133
Lor	082R	0	768	6.8	14.9	63,459	292,864
Log	068R	204	629	8.2	12.5	76,391	162,067
All	309R	1,721	2,506	7.7	11.9	71,716	299,347
Eri	006R	2,235	2,700	6.9	11.5	64,409	177,320
But	122R	0	463	6.6	9.7	60,947	176,557
Mah	014R	0	677	10.1	8.5	75,910	215,136
Gre	042R	1,195	1,739	6.6	7.9	61,017	207,445
Gre	235R	6	657	5.4	7.4	50,049	248,248
Col	164R	1,799	2,301	6.3	7.3	47,145	159,524
Med	094R	537	937	5.9	6.6	54,548	152,533
War	028R	52	519	5.1	6.5	47,278	178,083
Hig	050R	571	1,243	5.1	5.6	38,183	213,547
Vin	093R	157	749	4.6	5.0	34,663	188,124
						Cumulative cost ($)	3,943,686
List 9: sections that satisfy the budget constraint							
Col	062R	486	1,002	49.2	282.5	456,677	196,768
Cle	131R	8	553	11.7	43.4	108,686	207,827
Gal	035R	659	1,314	11.8	40.2	109,627	249,773
Col	014R	1,174	1,688	12.6	29.5	117,404	196,005
But	747R	237	870	8.3	17.6	77,109	241,384
Mar	004R	363	838	11.7	15.7	109,084	181,133
Lor	082R	0	768	6.8	14.9	63,459	292,864
Log	068R	204	629	8.2	12.5	76,391	162,067
Eri	006R	2,235	2,700	6.9	11.5	64,409	177,320
						Cumulative cost ($)	1,905,141
						Budget left for other selections ($)	94,859

way section is considered at risk if expected rate of wet weather accidents (predicted as function of SN) of a given highway section is greater than a critical specified value or if actual rate(s) of wet weather accident on a given highway section is greater than critical specified value(s). It is concluded that accident rates cannot be computed without information available from skid number file, such as ADT and section length. A limited budget may not accommodate all sections deemed to be at risk. The proposed approach, therefore, establishes a priority rating system by means of economical analysis (benefit–cost analysis) to permit rational allocation of available funds to selected locations.

The cost in the benefit–cost analysis is the estimated cost of resurfacing or surface improvement. Sections are selected for resurfacing based on calculated priorities and budget constraints. The study approach recommends that the maintenance engineer visit the selected sections and make appropriate recommendations based on the inspection of such sections for other contributing factors such as speed limit and alignment. An important feature of the computer program is that it can minimize the "leftover" money in the budget. The effectiveness of this program can be evaluated by comparing wet weather accident rates before and after resurfacing. It is recommended that skid and accident files be continuously updated.

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REFERENCES

1. Murad, M. M. A Review of Asphalt Pavement Friction Testing, Safety Requirements, and Their Applications in Design and Maintenance in USA. *International Journal of Pavements,* Vol. 3, Number 1–2, 2004, pp. 63–75.
2. Gramling, W. L. *NCHRP Synthesis of Highway Practice 203:* Current Practices in Determining Pavement Condition. TRB, National Research Council, Washington, D.C., 1994.
3. Haas, R., and W. R. Hudson. Defining and Serving Clients for Pavements. In *Transportation Research Record 1524,* TRB, National Research Council, Washington, D.C., 1996, pp. 1–9.
4. Colony, D. C. *Influence of Traffic Surface Age and Environment on Skid Number.* ODOT Job No. 14460(0), University of Toledo, Ohio, January 1992.
5. *NCHRP Synthesis of Highway Practice 291: Evaluation of Pavement Friction Characteristics.* TRB, National Research Council, Washington, D.C., 2000.
6. Anderson D. A., W. E. Meyer, and J. L. Rosenberger. Development of a Procedure for Correcting Skid-Resistance Measurements to a Standard End-of-Season Value. In *Transportation Research Record 1084.* TRB, National Research Council, Washington, D.C., 1986, pp. 40–48.
7. Burchett, J. L., and R. L. Rizenbergs. Seasonal Variations in the Skid Resistance of Pavements in Kentucky. In *Transportation Research Record 788.* TRB, National Research Council, Washington, D.C., 1980, pp. 6–14.
8. Saito, K, and J. J. Henry. Mechanistic Model for Predicting Seasonal Variations in Skid Resistance. In *Transportation Research Record 946.* TRB, National Research Council, Washington, D.C., 1983, pp. 29–38.
9. Flintsch, G. W., Y. Luo, and I. L. Al-Qadi. Analysis of the Effect of Pavement Temperature on Frictional Properties of Flexible Pavement Surfaces. Presented at 84th Annual Meeting of the Transportation Research Board, Transportation Research Board of the National Academies, Washington, D.C., 2005.
10. Ksaibati K., M. Cole, and M. Farrar. Evaluation of Surface Treatment Practices in United States. In *Transportation Research Record 1545,* TRB, National Research Council, Washington, D.C., 1996, pp. 26–34.
11. Cleveland, D. E. Effect of Resurfacing on Highway Safety. In *State of the Art Report 6,* TRB, National Research Council, Washington, D.C., 1987, pp. 78–95.
12. Rollins, J. B., and W. F. McFarlane. Costs of Motor Vehicle Accidents and Injuries. In *Transportation Research Record 1068,* TRB, National Research Council, Washington, D.C., 1986, pp. 1–7.
13. Alghazzawi, M. M. Pavement Management for Wet Weather Accident Reduction. Ph.D. dissertation. University of Toledo, Ohio, 1994.

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