EVALUATION OF PAVEMENT SHOULDERS

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Disclaimer

ABSTRACT

This report describes a study conducted at the University of Wyoming by Dr. Khaled Ksaibati, Associate Professor of Civil Engineering, and Israel Crowe, Graduate student of Civil Engineering. In this study the researchers examined the effect of pavement shoulders on the safety and structural strength of highways in Wyoming. The costs of adding shoulders to various types of highways also was examined. The study consisted of: selecting representative highway sections, collecting accident data on all test sections over a five-year analysis period, obtaining geometric information on the sections, and summarizing all collected data in a computerized database. A statistical analysis using the Poisson distribution was used to analyze the collected data. Accident costs and shoulder construction costs were obtained from the Wyoming Department of Transportation. In addition, a structural analysis was performed using finite element analysis and BISAR. The following main conclusions can be drawn from this study: accidents can be reduced by increasing shoulder widths and shoulders slightly reduce the vertical stresses.

TABLE OF CONTENTS

INTRODUCTION 1
  Background 1
  Problem Statement and Objectives 2
  Report Organization 2

LITERATURE REVIEW 3
  Introduction 3
  Safety Studies 3
    Shoulders and Accident Rates 3
    Geometrics and Safety Considerations 5
  Structural Strength Due to Pavement Shoulders 7
    Stresses in Flexible Pavements 7
    Stresses in Rigid Pavements 8
    Thickness Recommendations for Pavement Shoulders 10
  A Policy on Geometric Design Of Highways and Bridges 10
  Chapter Summary 11

DESIGN OF EXPERIMENT 13
  Experiment Methodology 13
  Selection of Test Sections 13
  Data Collection and Database Preparation 19
    Accident Data 19
    Test Section Data 19
    Database Preparation 20
  Chapter Summary 21

SAFETY ANALYSIS 23
  Statistical Terminology 23
    Regression Analysis 23
    Normal Regression 23
    Coefficient of Determination 24
    Poisson Regression 24
  Analysis of Test Sections 25
    Results from Statistical Analysis 25
    Effect of Shoulder Width on Accident Numbers 28
    Effect of Shoulder Width on Accident Costs 30
  Chapter Summary 32

STRUCTURAL ANALYSIS 33
  Analysis Methods 33
    Finite Element Analysis 33
    Patran 34
    BISAR 34

Model Characteristics 35
    Finite Element Analysis 36
    BISAR 37

Results of Analysis 38
    Finite Element Analysis 38
    BISAR 46
    Comparison of BISAR and Finite Element Analysis 47
Chapter Summary 47

CONCLUSIONS AND RECOMMENDATIONS 49
    Safety Effectiveness of Shoulders 49
    Structural Effectiveness of Shoulders 49
    Effectiveness of Shoulders 50
    Recommendations 50

REFERENCES 51

APPENDIX A: Information on Accident Data 53

APPENDIX B: Statistical Information 68

APPENDIX C: Collected Data from the Structural Analysis 78

LIST OF TABLES

2.1 Primary Advantages and Disadvantages of Design Alternatives 6
2.2 Minimum Width of Traveled Way and Graded Shoulder 11
3.1 List of Test Sections 14
3.2 Number of Accidents in Analysis 20
4.1 Models for Predicting Accident Numbers for a Five-Year Analysis Period 27
4.2 Predicted Accident Numbers for Sections with Variable VKMTs for a Five-Year Period 27
4.3 Interstate Models 28
4.4 Primary Models 28
4.5 Percent Reduction in Accidents Due to the Addition of Shoulders with Variable Widths 29
4.6 Percent Reduction in Accidents Due to the Incremental Increase in Shoulder Width by 0.6 m 29
4.7 Accident Costs in the State of Wyoming 30
4.8 Cost of Accidents for a Five-Year Period 31
4.9 Reduction in Costs for a Five-Year Period 31
5.1 Material Properties 35
5.2 Stresses Under the Load in the Vertical Direction from Finite Element Analysis on Asphalt Sections 40
5.3 Stresses Between Traveled Way and Shoulder in the Vertical Direction from Finite Element Analysis on Asphalt Sections 41
5.4 Stresses Under the Load in the Vertical Direction from Finite Element Analysis on Concrete Sections 42
5.5 Stresses Between Traveled Way and Shoulder in the Vertical Direction from Finite Element Analysis on Concrete Sections 43
5.6 Strains at the Bottom of the Base in the Vertical Direction from Finite Element Analysis on Asphalt Sections 44
5.7 Strains at the Bottom of the Base in the Vertical Direction from Finite Element Analysis on Concrete Sections 45
5.8 BISAR Stresses 46
5.9 Comparison of Results 47

LIST OF FIGURES

5.1 Finite Element Model 36
5.2 BISAR Model 38

CHAPTER 1

INTRODUCTION

Background

Pavement shoulder widths are highly variable in rural roadways. Some rural highway sections are even constructed without any pavement shoulders. Pavement shoulders generally are provided to improve the safety characteristics of roadways. They also help in increasing roadway capacity. One theory states that shoulders may help increase the service life of pavements by reducing stresses due to loadings.

Shoulder width is the distance from the edge of the traveled way to the edge of the roadway. They are used to accommodate stopped vehicles for emergency use and are commonly used by pedestrians and bicyclists. Shoulder widths vary depending on traffic volumes, terrain, and the cost of added width to the roadway section. The materials used to construct shoulders are variable, and include concrete, asphalt, grass, gravel, and bituminous surface treatments. This study examined only paved shoulders, including asphalt and concrete.

The increased width to the roadway that shoulders offer helps to improve the safety of that roadway section. The extra space provides a place in case of emergencies, such as a flat tire. This additional roadway width also helps motorists to avoid potential accidents or reduce their severity. The increased width gives the driver room to maneuver and avoid conflicts. It also helps to accommodate driver errors. Drivers will have a little more time to react and compensate before they go off the road. Improving safety is a major advantage of pavement shoulders.

Some additional advantages of shoulders are: increased sight distance in cut sections, improved highway capacity and added lateral clearance for signs and guardrail. Storm water can be discharged farther from the traveled way. The use of shoulders has many advantages, however, there are some disadvantages. These disadvantages include: additional construction cost and improper use by motorists, such as, using the shoulder as an additional driving lane.

Problem Statement and Objectives

State highway agencies select shoulder width primarily according to traffic volumes. The possible increasing structural strength normally is a secondary factor. Thus, some of the rural roadways do not have any shoulders. They have low traffic volumes and it is more economical not to construct shoulders in these situations, however these are the conditions where advantages of shoulders come into play and show that shoulders probably should be built.

The main objective of this research was to utilize the performance and accident rates in evaluating effectiveness of pavement shoulders in rural areas. The results of this research will help to determine appropriate widths of shoulders to be used under different conditions. This objective was accomplished by collecting extensive data on various roadway sections throughout Wyoming, analyzing the data and drawing conclusions from the analysis.

Report Organization

This research project was performed in two phases. The first phase of the research concentrated on collecting information related to pavement shoulders. It also emphasized collection of necessary data for the project. A literature search was conducted to retrieve information on pavement shoulders. Chapter 2 summarizes findings of the literature review. Chapter 3 outlines the data collection process, which examines the selection of test sections and the type of data that was collected for these test sections.

The second phase of the research was to analyze collected data. A complete statistical analysis of the accident data is presented in Chapter 4. Chapter 4 also examines accident costs relating to pavement shoulder widths. The structural effect of shoulders is discussed in Chapter 5. Finally, Chapter 6 presents a summary of the research. Conclusions and recommendations also are offered in Chapter 6.

CHAPTER 2

LITERATURE REVIEW

Introduction

As part of this study, a comprehensive literature review was performed on pavement shoulders. This chapter summarizes the findings of this review. The literature considered for review were studies related to shoulder widths and accident rates. Literature concerning the structural strength of roadways also were examined. AASHTO design guidelines were included for review.

Safety Studies

A number of studies have been performed to study the relationship between safety and roadway design. Some of these studies examined geometrics of the roadways; and others looked at cross sectional characteristics of the roadways. The following section looks at some of the studies that examined effects of lane and shoulder widths on accident rates. They also examined other benefits of adjusting lane and shoulder widths.

Shoulders and Accident Rates

In 1987, the Federal Highway Administration (FHWA) prepared the report, <u>Safety Effects of Cross-Section Design for Two-Lane Roads</u>, about a study that was intended to determine the effects of lane width, shoulder width, shoulder type, sideslope and roadside condition on accidents for two lane roads in the United States. Expected accident reductions and construction costs were quantified for lane and shoulder widening, shoulder surfacing, sideslope flattening, and roadside improvement projects.

Detailed accident, traffic, and roadway data were collected from 1944 roadway sections in the United States. These sections accounted for 4,951 miles of two-lane roads in seven states: Alabama, Michigan, Montana, North Carolina, Utah, Washington, and West Virginia.

The study concluded that many traffic and roadway features were associated with a reduced rate of single vehicle accidents. These features include: wider lanes, wider shoulders, greater recovery distance, lower roadside hazard rating and flatter terrain. Paved shoulders had lower accident rates than unpaved shoulders.Using the predictive model developed in the study, effects of lane width and shoulder widening on accidents were quantified. A 12 percent reduction in accidents occurred with the first 0.3 m (1 ft) of lane widening. Lane widening of 0.6 m (2 ft) corresponded to a 23 percent reduction in accidents. With 0.9 m (3 ft) of lane widening, a 32 percent reduction was found and 1.2 m (4 ft) of widening resulted in a 40 percent reduction in accidents. These reductions only apply for lane widths between 2.4 m (8 ft) and 3.6 m (12 ft). Adding paved shoulders of 0.6 m (2 ft) resulted in a 16 percent reduction in accidents. 1.2 m (4 ft) of widening corresponded to a 29 percent reduction and 1.8 m (6 ft) of widening resulted in a 40 percent reduction in accidents [1].

The study presented in NCHRP (National Cooperative Highway Research Program) Report 369 was performed to evaluate using shoulders with or without narrow lanes to increase the capacity of urban freeways. Another objective of this project was to develop recommendations and design guidelines for the strategies. The operational and safety performance of various applications of the strategies were concentrated on in this research. Eleven corridors throughout the country were selected for this research. They are located in: Boston, MA; Alexandria, VA; Seattle, WA; Atlanta, GA; Minneapolis, MN; and Los Angeles, CA. The project evaluated 42 altered sites and 10 unaltered sites. Analysis on the operational data was performed for all the corridors. Accident data were analyzed for five corridors.

The NCHRP study found that shoulders and narrow lanes can be used to increase capacity in congested urban corridors. The safety analysis indicated higher accident rates on three of the corridors. Two of the corridors showed a decrease, possibly attributed to a smooth traffic flow. The report suggests that the strategies should only be employed to improve traffic flow in congested corridors. The first modification that is recommended by the study should be to reduce the traveled way to 11 feet. Also, reduction of the left shoulder should be considered before reducing the right shoulder. Table 2.1 summarizes the advantages and disadvantages of altering shoulder widths.

Recommendations of NCHRP Report 369 follow:

- Use of shoulders and narrow lanes to achieve an additional travel lane normally should not be considered as an option to a traditional widening project for adding capacity to a freeway corridor.
- For areas of limited length and having turbulent flow conditions, use of shoulder(s) and narrow lanes should be considered as one alternative for achieving smother flow. Such use typically should be limited to sections of 1 mile or less.
- Where large truck traffic is a significant proportion of peak period (i.e., 5 to 10 percent), use of shoulders and narrow lanes is not recommended.
- For projects involving possible application of shoulders and narrow lanes, a step-by-step approach (site specific) must be used to ensure an adequate evaluation.
- Additional research efforts on traffic flow and safety impacts of the use of shoulders and narrow lanes should be made part of other freeway-oriented research projects [2].

Geometrics and Safety Considerations

The research study presented in Transportation Research Record 960 examined relationships between geometric design elements and accidents on two lane rural roads. Two data sets with traffic volumes greater than 2,000 vehicles per day were used for analysis in this project. The first data set was a national data set, which represented two-lane rural total accident experience from 14 states with 152 sections. These sections account for 800 miles with 3,224 accidents in the year of the study. This data set used the following information to model their effect on total accident occurrence: driveway and intersectional conflict frequency, roadside obstacle characteristics, and geometric design elements. The second data set included information on 137, two-mile sections of Michigan state highway with 1,300

Table 2.1: Primary Advantages and Disadvantages of Design Alternatives [2]

Design Alternative	Advantages	Disadvantages
Use of Left Shoulder	Left shoulder not used as much for emergency stop/or emergency enforcement Least expensive if width is available Trucks often restricted from left lane	Usually requires restriping Sight distance problem with some median treatments
Use of Right Shoulder	Often the easiest to implement	Right shoulder is preferred area for emergency stops and enforcement Sight distance changes at merge and diverge areas of ramps
Use of Both Shoulders	Not recommended Use ONLY in extreme cases	Requires restriping Safety concerns (no refuge) Enforcement is difficult Incident response longer Maintenance more difficult and expensive

off-road accidents. Five hundred and fourteen of these accidents resulted in injuries. This data set was used to examine the effect of off-road accident frequency and severity on total accident occurrence.

The study concludes that for the prediction of accidents, the effects of average daily traffic (ADT) was the most important factor, followed by driveway and intersection density and the geometric elements. An interaction between access point density and geometric characteristics was found to effect accidents as well as an interaction between access point density and volume. This study found that no significant independent effects of cross sectional elements in total accident prediction [3].

Structural Strength Due to Pavement Shoulders

The structural strength of a pavement section can be contributed to several factors within the following cross sectional elements of the roadway system: the number of layers, types of materials used, condition of these materials, and the dimensions of the layers and cross section. The combination of these variables determine the structural strength of the pavements. When heavy traffic loads are applied to pavement surfaces, the pavement will be subjected to variable levels of stresses. The main objective of pavement engineers is to insure that these stresses do not exceed the strength of materials used in different pavement layers. Some pavement designers suggest that the addition of pavement shoulders can reduce edge stresses in pavements and therefore increase pavement service life. The following two sections describe stresses experienced by flexible and rigid pavements.

Stresses in Flexible Pavements

Flexible pavements normally have a relatively thin asphalt wearing course with layers of granular base and subbase used to protect the subgrade from being overstressed. The basic concept of granular base flexible pavements is to provide a base thickness that insures that the vertical compressive subgrade stress or deflection is reduced to some limiting value less than the allowable distress level. This pavement system consists of built up layers having successively higher modulus values in the upper layers. The load spreading capabilities of this system must occur primarily through the thickness of the granular base and subbase layers.

Employing stiffer and stiffer materials in the upper layers result in a noticeable reduction of subgrade stress or deflection. For any given subgrade soil type, this allows a reduction of thickness of a stiffer layer over similar thickness of unbound granular material to satisfy the requirements of an allowable subgrade distress or limiting deflection criteria. This is a direct result of better load spreading capabilities of stiff or rigid layers. However, it is important to note that even though stiffer materials reduce the risk associated with a subgrade mode of distress, such as shear, the presence of this stiff layer brings about an increase in the tensile stress magnitude at the bottom of this layer as well as a marked increase in the horizontal shearing stresses [4].

Asphalt Institute procedures for designing asphalt pavements consider two specific stress-strain conditions. In the first condition, the wheel load is transmitted to the pavement surface through the tire as an approximately uniform vertical pressure. The pavement structure then spreads the load stresses, thus reducing their intensity until, at the surface of the subgrade, the vertical pressure has a maximum intensity. If the vertical pressure on top of the subgrade is higher than the strength of that subgrade, rutting may develop due to repeated loading. The second condition results from the wheel load deflection of the pavement structure, which causes tensile and compressive stresses and strains in the asphalt layer. When the tensile stress exceeds the strength of the asphalt mix, cracks will start developing in the asphalt layer [5].

Stresses in Rigid Pavements

Rigid pavements have a relatively thin slab placed on a subgrade or base course. A major portion of the load carrying capacity is derived from the concrete slab, since its modulus of elasticity is much greater than that of the foundation material.

A variety of causes contribute to stresses in rigid pavements including: wheel loads, cyclic changes in temperature (warping and shrinkage or expansion), changes in moisture, and volumetric changes in the subgrade or base course. These changes tend to deform the slab, causing stresses of widely varying intensity. Additionally, the magnitude of stresses depends upon continuity of subgrade support. In analyzing rigid pavements, the stress inducing factors may be placed into several categories: restrained temperature and moisture deformations, externally applied loads, volume changes of the supporting material, including frost action, and continuity of the subgrade support [4].

The Portland Cement Association (PCA) pavement design procedure, has a section that helps in the effect of pavement shoulders in reducing stresses. Comparing equivalent stresses for single axle loads on a section with and without shoulders, there is a decrease in the stress. For example, with a slab thickness of six inches and the k of subgrade-subbase of 100 pci the stress of the section with no shoulders is 411 psi and for the section with concrete shoulders the stress is 327 psi. Also, by using this design procedure and implementing concrete shoulders can help to decrease the necessary slab thickness [6].

A study performed by the FHWA in 1982 determined that concrete shoulders, if tied to the traveled lane, have an effect on deflections and stresses. The study found that shoulders greater than 1.5 m (5 ft) have a significant effect on deflections and that for widths less than 1.5 m (5 ft) the deflections increase rapidly. Widening the concrete shoulder from 0.9 m to 1.5 m (3 - 5 ft) reduces stress 20 percent for a 20 cm (8 in) thick slab and widening the shoulder from 1.5 m to 3.0 m (5 - 10 ft) causes a decrease of only 5 percent. The effect of shoulder width on tensile stress is about the same regardless of slab thickness. Thus, a concrete shoulder wider than 1.5 m (5 ft) has a reduced effect on stresses from encroaching truck traffic near the longitudinal joint [7].

Thickness Recommendations for Pavement Shoulders

Asphalt Institute recommends that shoulders be designed using the same principles and procedures as for the main travel lanes. This is recommended because shoulders must withstand encroachment of moving vehicles and often must serve as temporary driving lanes during construction or maintenance activities. Also, at times shoulders are used by slow moving vehicles as travel lanes. It also is practical for future traffic usage [5].

AASHTO has no specific design criteria for shoulder thicknesses. However, the AASHTO design guide states that the use of tied shoulders has proven to be beneficial to overall performance of rigid pavements. Paved shoulders adjacent to flexible pavements will provide lateral support for the base and surface courses. AASHTO recommends that local practice, experience and cost analysis should be considered as factors in shoulder design [8].

A Policy on Geometric Design Of Highways and Bridges

The AASHTO manual A Policy on Geometric Design of Highways and Streets (1994) states that a 3.0 m (10 ft) shoulder should be used along high volume highways. This may not be possible for mountainous or low volume roadways, thus a minimum of 0.6 m (2 ft) should be used. However, shoulder widths of 1.8 m (6 ft) to 2.4 m (8 ft) are preferable. High speed and heavily traveled highways and those carrying a large number of trucks should use a shoulder width of 3.0 m (10 ft) to 3.6 m (12 ft). A minimum of 1.2 m (4 ft) should be used where bicyclists are common [9]. Table 2.2 shows AASHTO guidelines for using shoulder widths with respect to traffic volumes.

Table 2.2: Minimum Width of Traveled Way and Graded Shoulder [9]

	Design Traffic Volumes			
Design Speed (km/h)	ADT Less Than 400	ADT 400 - 1500	ADT 1500 - 2000	ADT over 2000
	Width of Traveled Way (m)[c]			
30	5.4	6.0[a]	6.6	7.2
40	5.4	6.0[a]	6.6	7.2
50	5.4	6.0[a]	6.6	7.2
60	5.4	6.0[a]	6.6	7.2
70	6.0	6.6	6.6	7.2
80	6.0	6.6	6.6	7.2
90	6.6	6.6	7.2	7.2
100	6.6	6.6	7.2	7.2
	Width of Graded Shoulder - Each Side (m)[c]			
All Speeds	0.6	1.5[a,b]	1.8	2.4

a. Mountainous Terrain - ADT 400 - 600 5.4 m width and 0.6 m shoulders.

b. May be adjusted to achieve a minimum roadway width of 9 m for design speed of 60 km/h or less.

c. Where the width of traveled way is shown to be 7.2 m, the width of the traveled way may remain at 6.6 m on reconstructed highways where alinement and safety results are satisfactory.

Chapter Summary

This chapter summarizes the various studies related to pavement shoulder widths and accident rates. These studies showed that shoulder widths do affect accident rates. Increasing the shoulder width helps to decrease the number of accidents. A discussion of the stresses present in pavement sections also were presented. In addition, AASHTO design guidelines for shoulder widths and recommendations for pavement shoulder thickness were presented.

CHAPTER 3

DESIGN OF EXPERIMENT

Experiment Methodology

The major objectives of this study were to evaluate the effect of various shoulder widths on the safety and structural strength of roadways in Wyoming. To achieve this objective, several roadway sections were included in the experiment. Accident and geometric data were collected on all test sections. The data collection procedures are presented in this chapter. The data were summarized in a computerized database. A statistical data analysis was performed on the database. This statistical analysis used Normal regression and Poisson regression to predict accident numbers based on shoulder width. The SAS program was used to conduct all regression analysis.

Structural strength of roadways was examined with finite element analysis and BISAR. These analysis methods determined the stresses directly under a load application at the bottom of the surface layer and at the top of the subgrade. The finite element analysis was performed by using a software package called Patran. Both concrete and asphalt pavements were analyzed with finite element method. BISAR only was used to determine stresses in asphalt pavements. BISAR was developed to solve for stresses in asphalt pavements. The results from these two procedures were then compared. Conclusions were drawn pertaining to the effect of shoulders on accident numbers and on the structural strength of pavements.

Selection of Test Sections

To determine the effect of pavement shoulders on safety, test sections were selected from all over Wyoming to represent various climatic conditions and traffic characteristics. Interstate, Primary, and Secondary highway sections were obtained from each of the five highway districts in Wyoming. In each district, approximately five concrete and five asphalt pavement sections were selected for each of the highway functional classifications. These sections had various shoulder widths. This selection criteria resulted in a total of 153 pavement sections for inclusion in this study. A list of the test sections is shown in Table 3.1. The test sections account for 1,488 kilometers (924 mi) of highway in Wyoming. Of this, 409 km (254 mi) were interstate highways, 401 km (249 mi) were primary highways and 678 km (421 mi) were secondary highways. The shoulder widths for these test sections vary from 0 to 3.0 m (10 ft).

Table 3.1: List of Test Sections

SYS[a]	RT[b]	BMP[c]	EMP[d]	DI[e]	SECTION NAME	AADT	ESAL
I	25	0.00	8.40	1	COLORADO NORTH	5290	945
I	25	13.60	17.00	1	VANDEHEI-TORRINGTON	2900	637
I	25	25.86	30.75	1	WHITAKER SOUTH	2055	493
I	80	186.60	199.00	1	CHEROKEE SECTION	3911	2136
I	80	216.20	221.20	1	SINCLAIR WEST	4241	2011
I	80	233.70	240.00	1	WALCOTT JCT EAST	3870	1923
I	80	285.00	289.90	1	QUEALY DOME SECTION	3785	1970
I	80	319.10	322.50	1	TELEPHONE CANYON	4050	1303
I	80	348.50	358.40	1	OTTO ROAD EAST	3965	1311
I	80	358.40	360.10	1	CHEYENNE WEST	3920	1343
P	21	22.81	33.15	1	RAWLINS-MUDDY GAP JCT.	945	307
P	22	8.42	13.07	1	JCT FAI-80 - SARATOGA	555	70
P	22	13.07	20.60	1	SARATOGA NORTH	715	70
P	23	272.19	278.98	1	MED BOW-ALBANY CO	315	60
P	23	278.98	286.49	1	ALBANY CO LINE EAST	410	60
P	23	327.35	327.39	1	LARAMIE	2350	100
P	23	421.64	424.50	1	TIE SIDING-COLO ST LINE	1690	665
P	23	424.50	425.42	1	TIE SIDING-COLO ST LINE	1690	665
SYS[a]	RT[b]	BMP[c]	EMP[d]	DI[e]	SECTION NAME	AADT	ESAL
P	25	8.31	8.47	1	CHEYENNE	7650	260
P	25	16.94	17.23	1	CHEYENNE	625	140
P	25	17.23	18.67	1	CHEYENNE-GOSHEN CO	740	130
P	25	18.67	19.82	1	CHEYENNE-GOSHEN CO	790	130
P	25	19.82	23.20	1	CHEYENNE-GOSHEN CO	790	130
P	25	23.20	24.18	1	CHEYENNE-GOSHEN CO	790	130
P	25	24.18	27.06	1	CHEYENNE-GOSHEN CO	790	130
P	25	27.06	31.42	1	CHEYENNE-GOSHEN CO	790	130
P	26	1.26	1.38	1	LARAMIE	4735	150
P	26	2.60	15.94	1	LARAMIE-WOODS LANDING	785	80

P	26	16.02	27.06	1	LARAMIE-WOODS LANDING	490	70
P	26	32.93	42.04	1	WOODS LANDING-COLORADO	342	50
P	54	211.87	211.99	1	RAWLINS	2315	320
P	56	359.55	359.73	1	CHEYENNE; I-80 BUSINESS	2420	245
S	102	0.00	10.94	1	CENTENNIAL-ALBANY	148	15
S	103	11.81	16.94	1	LARAMIE-CENTENNIAL	456	32
S	103	16.94	21.69	1	LARAMIE-CENTENNIAL	449	15
S	103	21.69	22.13	1	LARAMIE-CENTENNIAL	370	28
S	103	22.13	27.75	1	LARAMIE-CENTENNIAL	365	26
S	103	27.75	33.72	1	CENTENNIAL-SARATOGA	255	14
S	104	0.00	0.02	1	WYO 130-HERRICK LANE	85	15
S	104	0.02	1.70	1	WYO 130-HERRICK LANE	85	15
S	104	1.70	2.46	1	WYO 130-NORTH WEST	85	15
S	104	2.46	2.78	1	WYO 130-NORTH WEST	85	15
S	104	2.78	3.01	1	WYO 130-NORTH WEST	85	15
S	104	3.01	12.18	1	WYO 130-HERRICK LANE	85	15
S	105	0.00	1.25	1	ROCK RIVER-MCFADDEN	109	25
S	105	1.25	9.53	1	ROCK RIVER-MCFADDEN	74	16
S	105	9.53	17.19	1	MCFADDEN-ARLINGTON	78	19
S	107	10.38	20.39	1	HAPPY JACK ROAD	412	27
S	107	20.39	26.45	1	HAPPY JACK ROAD	287	25
S	107	26.45	32.45	1	HAPPY JACK ROAD	195	23
S	401	46.97	49.61	1	SAVERY-ENCAMPMENT	60	8
S	401	51.10	55.95	1	SAVERY-ENCAMPMENT	255	18
S	410	241.66	252.59	1	WALCOTT JCT-MED BOW	413	72
S	410	252.59	263.67	1	WALCOTT JCT-MED BOW	213	50
S	410	263.67	266.90	1	WALCOTT JCT-MED BOW	215	50
S	1104	0.88	17.14	1	PINE BLUFFS-ALBIN	175	22
SYS[a]	RT[b]	BMP[c]	EMP[d]	DI[e]	SECTION NAME	AADT	ESAL
S	1105	9.32	18.54	1	JCT US 85-ALBIN	99	15
I	25	47.84	51.60	2	CHUGWATER SOUTH	2005	493
I	25	75.31	81.50	2	WHEATLAND MARGINAL	2024	483
I	25	109.11	120.82	2	GLENDO NORTH	2115	540
I	25	134.90	141.42	2	DOUGLAS MARGINAL	2160	603
I	25	141.42	150.00	2	DOUGLAS NORTH	2610	675
I	25	175.10	185.40	2	CASPER SOUTH	2965	644
I	25	185.40	190.00	2	CASPER MARGINAL	6533	755
I	25	219.00	228.00	2	NATRONA CO LINE SOUTH	1065	285
I	25	263.70	271.14	2	BUFFALO SOUTH	1005	263
P	21	44.77	51.06	2	MUDDY GAP-NA CO LINE	655	230
P	21	57.01	58.89	2	NA CO LINE-CASPER	695	230

P	21	117.15	117.21	2	CASPER	4860	485
P	24	46.03	55.98	2	NA CO LINE-JCT P-21	300	40
P	25	72.30	74.49	2	GOSHEN CO-HAWK SPRINGS	865	150
P	25	93.12	93.63	2	HAWK SPR-TORRINGTON	3810	350
P	25	150.22	160.52	2	LUSK-MULE CR	795	200
P	27	15.51	18.50	2	GUERNSEY-FT. LARAMIE	920	214
P	34	1.10	3.87	2	CASPER-NATRONA	5436	331
P	34	39.23	41.86	2	PWD RIV-HELL'S 1/2 ACRE	885	228
P	42	100.00	102.05	2	MIDWEST-JOHNSON CO	1065	210
P	57	79.00	79.42	2	WHEATLAND	2215	115
P	58	135.47	135.83	2	DOUGLAS	1185	205
S	406	4.28	4.64	2	LAMONT-BAIROIL	235	88
S	502	8.28	9.26	2	DOUGLAS-ORPHA	161	28
S	502	9.26	14.38	2	ORPHA-ROSS	135	25
S	505	166.22	172.44	2	GLENROCK-CASPER	607	85
S	807	0.00	7.73	2	TORRINGTON-HUNTLEY	365	55
S	807	7.73	10.99	2	HUNTLEY-NEBR ST LINE	262	49
S	807	10.99	14.07	2	TABLE MT RD-NEB ST LINE	180	35
S	811	0.00	7.03	2	YODER JCT-HUNTLEY	140	30
S	1000	100.00	107.53	2	KAYCEE-BARNUM	80	13
S	1002	15.88	35.64	2	KAYCEE-LINCH	91	27
S	1400	517.30	523.28	2	HARTVILLE-MANVILLE	81	11
S	1604	0.09	3.37	2	WHEATLAND EAST	302	40
S	1604	3.37	11.91	2	WHEATLAND EAST	66	16
S	1610	0.00	0.47	2	WHEATLAND-DWYER JCT	1035	38
S	1610	0.47	1.94	2	WHEATLAND-DWYER JCT	775	35
S	1610	1.94	2.47	2	WHEATLAND-DWYER JCT	625	33

SYS[a]	RT[b]	BMP[c]	EMP[d]	DI[e]	SECTION NAME	AADT	ESAL
I	80	0.00	2.90	3	UTAH ST LINE	4730	2363
I	80	6.90	12.30	3	EVANSTON EAST	4585	2237
I	80	22.70	27.50	3	BIGELOW BENCH	4305	2125
I	80	44.00	49.00	3	LYMAN EAST	3956	2029
I	80	83.00	86.00	3	GREEN RIVER WEST	5850	2752
I	80	92.20	101.70	3	GREEN RIVER EAST	7121	2668
I	80	120.30	130.00	3	POINT OF ROCKS WEST	4860	2473
I	80	143.00	148.50	3	PATRICK DRAW SECTION	3910	2105
I	80	153.80	161.00	3	TABLE ROCK EAST	3900	2105
I	80	153.80	161.00	3	TABLE ROCK EAST	3900	2105
I	80	171.70	186.60	3	SWEETWATER CO LINE WEST	3925	2105
P	10	85.59	87.16	3	AFTON	1864	175
P	10	154.25	155.12	3	JACKSON STREETS	4206	302

P	11	36.58	38.20	3	KEMMERER-LABARGE	2130	160
P	11	85.92	93.04	3	SUBLETTE CO LINE	430	100
P	12	48.79	52.09	3	SAGE JCT-KEMMERER	845	495
P	12	52.42	52.63	3	KEMMERER	814	488
P	13	70.94	88.59	3	SB CO LINE-PINEDALE	640	60
P	17	504.19	511.40	3	FLMNG GRG INT-UTAH LINE	230	40
P	52	89.75	91.63	3	GREEN RIVER	3530	230
P	53	105.86	106.48	3	ROCK SPRINGS	2310	215
S	1207	0.13	0.88	3	US 89-FREEDOM	440	38
S	1800	0.50	4.56	3	BIG PINEY-WEST	493	55
S	1903	20.00	30.15	3	ROCK SPRINGS-HIAWATHA	138	28
S	1906	0.00	4.78	3	GREEN RIVER-FONTENELLE	812	254
S	1906	4.78	8.08	3	GREEN RIVER-FONTENELLE	795	250
S	2000	6.58	13.71	3	WILSON-IDAHO ST LINE	1112	49
I	25	279.40	285.00	4	BUFFALO SOUTH	1005	263
I	25	293.81	299.30	4	BUFFALO MARGINAL	1015	263
I	90	19.96	21.50	4	SHERIDAN NORTH	2379	454
I	90	85.50	93.20	4	POWDER RIVER EAST	1735	250
I	90	106.70	112.50	4	WILD HORSE CR SECTION	1740	255
I	90	124.30	129.60	4	GILLETTE MARGINAL	2680	357
I	90	145.20	152.20	4	MOORCROFT WEST	2015	435
I	90	155.10	160.30	4	MOORCROFT EAST	1625	310
I	90	185.70	195.00	4	SUNDANCE MARGINAL	1742	310
I	90	202.00	207.14	4	STATE LINE WEST	1770	318
P	25	209.56	211.95	4	WESTON CO-NEWCASTLE	395	110
P	35	62.05	71.12	4	BURGESS JCT-DAYTON	400	45
SYS[a]	RT[b]	BMP[c]	EMP[d]	DI[e]	SECTION NAME	AADT	ESAL
P	35	89.38	89.87	4	RANCHESTER	1225	85
P	36	91.96	92.12	4	BUFFALO	3420	145
P	43	56.51	62.19	4	CAMPBELL CO-WRIGHT	365	95
P	43	72.42	83.73	4	CAMPBELL CO-WRIGHT	953	238
P	43	118.83	119.56	4	GILLETTE-MONTANA ST	315	60
P	43	122.64	123.84	4	GILLETTE-MONTANA ST	310	60
P	43	146.11	152.93	4	GILLETTE-MONTANA ST	165	38
P	48	4.64	7.10	4	S DAKOTA-MONTANA ST	525	239
P	49	0.39	1.08	4	NEWCASTLE	2330	70
P	60	22.97	23.48	4	SHERIDAN	8240	110
P	62	125.47	126.25	4	GILLETTE	6610	270
S	300	31.90	38.88	4	SAVAGETON	314	59
S	300	38.88	45.25	4	SAVAGETON	235	30
S	300	45.25	52.67	4	SAVAGETON	235	30

S	302	89.26	99.33	4	CLEARMONT-GILLETTE	233	51
S	600	16.46	28.21	4	SUNDANCE-UPTON	216	28
S	604	7.62	13.20	4	HULETT-ALZADA	89	13
S	604	13.20	21.69	4	HULETT-ALZADA	60	10
S	604	21.69	29.50	4	HULETT-ALZADA	60	10
S	607	167.18	174.63	4	MOORCROFT-SUNDANCE	331	45
S	1003	100.00	104.01	4	BUFFALO-SHERIDAN	192	28
S	1006	289.15	295.05	4	KAYCEE-BUFFALO	115	13
S	1006	297.55	299.30	4	KAYCEE-BUFFALO	340	18
S	1704	1.22	11.52	4	SHERIDAN	198	20
S	2300	32.00	44.91	4	CLARETON-RENO JCT	170	33
S	2300	44.91	50.66	4	CLARETON-RENO JCT	170	33
S	2302	0.68	13.45	4	UPTON-HAY CREEK	65	18
S	2302	13.45	19.98	4	HAY CREEK-CLARETON	65	18
S	2302	19.98	25.06	4	HAY CREEK-CLARETON	65	18
S	2302	25.06	32.46	4	HAT CREEK-CLARETON	65	18
P	20	68.18	72.87	5	JEFFERY CITY-LANDER	305	70
P	30	40.71	46.88	5	MORAN JCT-DUBOIS	690	63
P	31	10.00	20.00	5	YELLOWSTONE-CODY	810	60
P	31	45.06	45.89	5	YELLOWSTONE-CODY	1035	80
P	31	51.78	52.96	5	CODY	5880	290
P	31	72.71	75.72	5	CODY-BIGHORN CO LINE	650	70
P	33	57.66	62.98	5	MEETEETSE-CODY	730	120
P	34	116.14	116.44	5	SHOSHONI-THERMOPOLIS	1025	322
P	34	236.26	237.42	5	LOVELL	2292	251
SYS[a]	RT[b]	BMP[c]	EMP[d]	DI[e]	SECTION NAME	AADT	ESAL
P	37	0.00	0.25	5	GREYBULL-SHERIDAN CO	1370	70
S	200	112.06	116.90	5	BASIN-BURLINGTON	245	25
S	202	12.16	127.33	5	FOSTER GULCH RD	210	35
S	708	22.73	24.15	5	SAND DRAW-SWEETWATER	185	38
S	1505	7.66	12.17	5	WILLWOOD-POWELL	527	59
S	2203	0.55	7.27	5	TENSLEEP-BIG TRAILS	125	15

a. SYS = Highway System
  I = Interstate
  P = Primary
  S = Secondary
b. RT = Route Number
c. BMP = Beginning Milepost
d. EMP = Ending Milepost
e. DI = District

Data Collection and Database Preparation

Extensive data were collected on all test sections from the Highway Safety Branch of the Wyoming Department of Transportation (WYDOT) and from the WYDOT Pavement Management System. Information also was gathered from the Wyoming's Comprehensive Report on Traffic Crashes published by WYDOT. The collected data were then summarized into a computerized database for analysis.

Accident Data

Accident data collected from the Highway Safety Branch included the time and location of each accident as well as vehicle and driver information. The data also contained information on surface and light conditions, and road alignment. Accident data were collected for a five-year period between 1991 and 1995. Data pertaining to accidents included: route number, year of accident, rural or urban route, county, highway system (interstate, primary or secondary), milepost, highway element involved in accident, highway district, divided highway, side of highway, accident date, day of week, time of accident, number of vehicles involved, number of pedestrians, number injured, number killed, first harmful event, location of first harmful event, number of lanes, type of road surface, light conditions, conditions of the road, weather conditions, road alignment, junction relationship, adverse road conditions, collision type, functional classification, drinking involved, traffic control, repair cost, posted speed, estimated speed, vehicle type, visual obstruction, damage severity, human contributing factor, activity prior to crash, direction of travel, driver's age and sex. All of the possible data fields pertaining to each item listed above are included in Appendix A. Examples of the collected data can be seen in Appendix A.

Test Section Data

Information related to the materials and dimensions of test sections also was collected from the WYDOT Pavement Management System. The data included shoulder width, lane width, thickness of the various layers, material type for the shoulder and traveled way. WYDOT's Pavement Management System also contained the Average Annual Daily Traffic (AADT) and the Equivalent Single Axle Loads (ESAL) for each section. These AADTs and the ESALs are presented in Table 3.1 with their corresponding test section.

Database Preparation

After gathering the required data on all test sections, data was organized into a format that could be used in the analysis. A comprehensive statistical analysis was performed using the SAS statistical software package. Various statistical methods were considered. It was decided that the generalized linear model using the Poisson distribution would best represent the data for analysis.

The data was organized to include number of accidents that occurred on each test section, length of the test section, and AADT for each section. Also, for each section, information was included on light conditions, surface conditions, alignment of the roadway, and whether accidents were fatal or non-fatal. Finally, vehicle kilometers traveled (VKMT) were calculated and included in the database. VKMTs were calculated using the following equation: VKMT = length (km) * AADT * 365(days) * 5(years). The number of accidents for each functional classification and year can be seen in Table 3.2. It is clear from this table that the total number of accidents over the five-year analysis period for the test sections was 8,785.

Table 3.2: Number of Accidents in Analysis

Year	1991	1992	1993	1994	1995	Total
Interstate	646	1122	784	718	683	3953
Primary	711	777	1020	846	871	4225
Secondary	120	90	119	122	156	607
Total						8785

Chapter Summary

This chapter described the research project organization and test sections selection process. The data to be used in the analysis was presented. In addition, the process of preparing the database for analysis was described.

CHAPTER 4

SAFETY ANALYSIS

Statistical Terminology

After collecting accident and related data on all test sections, a comprehensive analysis was performed on the data. Two regression techniques were used to conduct the analysis: Normal regression and Poisson regression. This chapter describes the regression methods and other statistical terms used. In addition, results of the analysis on the accident data are summarized in this chapter.

Regression Analysis

Regression analysis is a statistical method that uses the relationship between two or more quantitative variables so that one variable can be predicted from the other or others. Regression analysis is widely used in business, the social and behavioral sciences, and the biological sciences in addition to transportation studies. Regression analysis results in a regression model to predict an outcome based on the predictor variable or variables. When more than one predictor variable is used, it is referred to as multiple regression. This study uses multiple regression techniques [10].

Normal Regression

Normal regression is a linear regression model. The general linear regression model follows [10]:

$$Y_i = {}_0 + {}_1X_{i1} + {}_2X_{i2} + \qquad + {}_{p-1}X_{i,p-1} + {}_i \tag{4.1}$$

where: ${}_{0,}\ {}_1,\ldots,{}_{p-1}$ are parameters,

$X_{i1},\ldots, X_{i,p-1}$ are known constants,

${}_i$ are independent normally distributed, with mean 0 and variance ^{2}, and

$i = 1,\ldots, n$.

In matrix terms, the general linear regression model (4.1) is [10]:

$$\mathbf{Y} = \mathbf{X} \quad + \tag{4.2}$$

where: **Y** is a vector of responses,

is a vector of parameters,

X is a matrix of constants, and

is a vector of independent normal random variables.

The random vector **Y** has expectation [10]:

$$\mathbf{E}\ (\mathbf{Y}) = \mathbf{X} \tag{4.3}$$

In this study, two linear models were examined. The first model (4.4) looks at the expectation of the number of accidents that will occur for the analysis period. The second model (4.5) examines the expectation of the rate of accidents.

$$E\ (\ Y_i\ ) = X_i \quad + VKMT_{i\ v} \tag{4.4}$$

$$E\ (\ RY_i\ ) = X_i \tag{4.5}$$

Coefficient of Determination

The coefficient of determination, usually denoted as R^2, is interpreted as the proportionate reduction of total variation associated with use of the predictor variable X. Therefore, the larger the R^2 is, the more the total variation of Y is reduced by introducing the predictor variable X. The R^2 value can vary between zero and one. Thus, the closer the R^2 value is to one, the stronger the relationship, and an R^2 close to zero shows that the relationship is weak [10].

Poisson Regression

Poisson regression is a nonlinear regression model where the response outcomes are discrete. It is a log-linear model. Poisson regression often is used when the outcome is a count, such as the number of accidents [10]. It has one parameter equal to the mean, which must be non-negative, as compared to the parameter of the Normal distribution, which is unrestricted. The ideas of a regression model remain the same as for the Normal model, except that now the parameters measure effects on the scale of log frequencies [11]. This study concentrated on estimating the number of accidents that occur with various shoulder widths and thus, Poisson regression was used. The following is the log-linear Poisson model used in the analysis [12]:

$$\log\{n_i\} = \log\{N_i\} + x_i \; . \qquad (4.6)$$

where: n_i is the expected number of events,

N_i is the offset,

x_i is the variable matrix, and

is the vector of coefficients.

For this analysis, the events are accidents, the offset is vehicle kilometers traveled (VKMT) and the variables include: alignment, light, and surface conditions. The coefficients are determined by analysis. In this report, log is base e. To use the Poisson regression, an assumption was made that, all other factors being equal, with twice the VKMT there would be twice the number of accidents.

Analysis of Test Sections

Analyses were performed using Normal and Poisson regressions as described in the above sections. This was done using the SAS software package [12]. An example of the SAS input can be seen in Appendix B. Appendix B also contains the output for the statistical analysis conducted on SAS. This section presents the results of this analysis.

Results from Statistical Analysis

The statistical analysis, using Normal regression, did not yield adequate models for the prediction of accident numbers or accident rates. The coefficient of determination for the models were very low, which means that the relation between the accident numbers or rates and the specific conditions considered was weak. Some of these R^2 values were equal to: 0.000171, 0.0633, 0.000051 and

0.149. Furthermore, with count data, model assumptions for Normal regression are less appropriate than are assumptions for Poisson regression. Therefore, Poisson regression was examined, and it was found to give better models.

The statistical analysis, using Poisson regression, yielded prediction models for the conditions analyzed. The following model was developed to predict accidents by considering shoulder width only and regardless of functional classification, surface conditions, light conditions or roadway alignment:

$$\log(n) = \log(\mathrm{VKMT}) - 12.046 - 0.358 * \mathrm{ShWidth}. \tag{4.7}$$

where: n = number of accidents for a five year period,

VKMT = vehicle kilometers traveled and

ShWidth = shoulder width in meters.

Similar models were developed to predict accident numbers based on surface conditions, light conditions and alignment. These conditions and the models are summarized in Table 4.1. The models are applicable to roadways of any functional classification. The equations can be used to predict the number of accidents that would occur with various shoulder widths. The general model, equation (4.7), was examined by plugging information from typical test sections with the lowest, average and highest VKMT. The results from these calculations are shown in Table 4.2. These predicted accident numbers are for the five-year analysis period. For example, on a highway with a VKMT of 21,574,000 and 0.6 m shoulders, it would be expected to have approximately 102 accidents over a five-year period.

Table 4.1: Models for Predicting Accident Numbers for a Five-Year Analysis Period

Conditions		Equation
All Conditions		log(n)=log(VKMT) - 12.046 - 0.358*ShWidth
Surface Conditions	Dry	log(n)=log(VKMT) - 12.357 - 0.483*ShWidth
	Poor	log(n)=log(VKMT) - 13.320 - 0.162*ShWidth
Light Conditions	Daylight	log(n)=log(VKMT) - 12.391 - 0.400*ShWidth
	Dark	log(n)=log(VKMT) - 13.428 - 0.269*ShWidth
	Dawn or Dusk	log(n)=log(VKMT) - 15.208 - 0.313*ShWidth
Alignment	Straight	log(n)=log(VKMT) - 12.204 - 0.363*ShWidth
	Curved	log(n)=log(VKMT) - 13.970 - 0.330*ShWidth

Table 4.2: Predicted Accident Numbers for Sections with Variable VKMTs for a Five-Year Period

	Shoulder Width (m)[a]					
VKMT	0	0.6	1.2	1.8	2.4	3.0
lowest value: 248,600	1.46	1.18	0.95	0.77	0.62	0.50
average value: 21,574,000	126.54	102.10	82.38	66.47	53.63	43.27
highest value: 198,770,600	1165.88	940.70	759.02	612.43	494.14	398.71

a. 0.3 m = 1.0 ft

In addition, using Poisson regression, the number of lanes and fatalities were considered but they resulted in poor models. Also, the Poisson regression was performed based on the following functional classifications: interstate, primary, and secondary roadways. Surface conditions, light conditions and roadway alignment were included in the analysis. Table 4.3 presents the models for the the interstate sections, Table 4.4 includes the models for the primary sections. Similar appropriate models could not be obtained on secondary roadways.

Table 4.3: Interstate Models

Conditions		Equation
Shoulders Only		log(n)=log(VKMT) - 12.859 - 0.171*ShWidth
Road Conditions	Dry	log(n)=log(VKMT) - 13.632 - 0.212*ShWidth
	Poor	log(n)=log(VKMT) - 13.529 - 0.138*ShWidth
Light Conditions	Daylight	log(n)=log(VKMT) - 13.140 - 0.269*ShWidth
	Dark	log(n)=log(VKMT) - 14.482 - 0.023*ShWidth
	Dawn or Dusk	log(n)=log(VKMT) - 16.400 - 0.0003*ShWidth
Alignment	Straight	log(n)=log(VKMT) - 13.403 - 0.072*ShWidth
	Curved	log(n)=log(VKMT) - 13.775 - 0.409*ShWidth

Table 4.4: Primary Models

Conditions		Equation
Shoulders Only		log(n)=log(VKMT) - 11.613 - 0.155*ShWidth
Road Conditions	Dry	log(n)=log(VKMT) - 11.956 - 0.169*ShWidth
	Poor	log(n)=log(VKMT) - 12.932 - 0.121*ShWidth
Light Conditions	Daylight	log(n)=log(VKMT) - 12.002 - 0.119*ShWidth
	Dark	log(n)=log(VKMT) - 12.950 - 0.249*ShWidth
	Dawn or Dusk	log(n)=log(VKMT) - 15.029 - 0.225*ShWidth
Alignment	Straight	log(n)=log(VKMT) - 11.734 - 0.124*ShWidth
	Curved	log(n)=log(VKMT) - 13.847 - 0.558*ShWidth

Effect of Shoulder Width on Accident Numbers

After models were developed for predicting accident numbers, an analysis was performed to estimate the percent reduction in accidents due to variable increases in shoulder widths. Table 4.5 shows the percent reduction in accidents when compared to the number of accidents that would occur at locations with no shoulders. From this table, it can be seen that when considering all conditions in the analysis, if a 1.8 m (6 ft) shoulder was in place instead of a 0 m shoulder, there would be a 47.5 percent reduction in accidents. It also is clear from Table 4.5, that shoulders are more effective under dry conditions than in poor conditions. In other words, when the pavement is slippery, wider shoulders will not be as effective as when the pavement is dry. Also, this table indicates that shoulders are more effective during daylight and on straight sections.

Another analysis was performed on the database to determine the percent reduction in accidents due to incremental increase in shoulder width by 0.6 meters (2 ft). Table 4.6 shows that adding 0.6 m (2 ft) of shoulder to a location with no shoulders has the largest effect on the percent reduction in accidents. The percent reduction in the number of accidents steadily decreases after this point. This clearly indicates that the first 0.6 m (2 ft) of shoulders is the most effective in reducing accidents.

Table 4.5: Percent Reduction in Accidents Due to the Addition of Shoulders with Variable Widths

		Shoulder Width (m)[a]					
Conditions		0	0.6	1.2	1.8	2.4	3.0
All Conditions		0.0	19.3	34.9	47.5	57.6	65.8
Surface Conditions	Dry	0.0	25.2	44.0	58.1	68.7	76.5
	Poor	0.0	9.3	17.7	25.3	32.3	38.6
Light Conditions	Daylight	0.0	21.3	38.1	51.3	61.7	69.9
	Dark	0.0	14.9	27.6	38.4	47.6	55.4
	Dawn or Dusk	0.0	17.1	31.3	43.1	52.9	60.9
Alignment	Straight	0.0	19.6	35.3	48.0	58.2	66.3
	Curved	0.0	17.9	32.7	44.8	54.7	62.8

a. 0.3 m = 1.0 ft

Table 4.6: Percent Reduction in Accidents Due to the Incremental Increase in Shoulder Width by 0.6 m

		Shoulder Width (m)[a]					
Conditions		0	0.6	1.2	1.8	2.4	3.0
All Conditions		0.0	19.3	15.6	12.6	10.1	8.2
Surface Conditions	Dry	0.0	25.2	18.8	14.1	10.5	7.9
	Poor	0.0	9.3	8.4	7.6	6.9	6.3
Light Conditions	Daylight	0.0	21.3	16.8	13.2	10.4	8.2
	Dark	0.0	14.9	12.7	10.8	9.2	7.8
	Dawn or Dusk	0.0	17.1	14.2	11.8	9.8	8.1
Alignment	Straight	0.0	19.6	15.7	12.7	10.2	8.2
	Curved	0.0	17.9	14.7	12.1	9.9	8.1

a. 0.3 m = 1.0 ft

Effect of Shoulder Width on Accident Costs

The next step in this study examined cost-effectiveness of increasing shoulder widths. Accident costs were estimated using Wyoming's Comprehensive Report on Traffic Accidents [13 - 17]. Statewide, the total number of accidents and total cost were determined over the analysis period. The average cost per accident then was calculated. The accident numbers and costs are summarized in Table 4.7. The average cost per accident for the five-year study period was $21,777.35. Using this estimate and the predicted number of accidents, it was possible to determine cost of the accidents corresponding to various shoulder widths. Once again, the highest, lowest, and average VKMTs were used in the calculations. The costs of accidents with respect to shoulder widths and VKMTs are summarized in Table 4.8. It is clear from this table that building high volume highways with no shoulders will result in extremely high accident costs. However, building a low volume road with no shoulders can be tolerated since accident costs are relatively low. Table 4.9 shows the reduction in accident costs due to the addition of shoulders with variable widths.

Table 4.7: Accident Costs in the State of Wyoming

Year	Cost	Accidents	VKMT	Average Cost
1991	$172,462,100	12,677	9,658,390,000	$13,604
1992	$198,192,500	13,081	9,980,390,000	$15,151
1993	$347,135,500	14,443	10,899,700,000	$24,035
1994	$371,248,800	14,227	10,772,510,000	$26,095
1995	$432,775,000	14,425	NA	$30,002
Total				$108,887
Average Cost				$21,777

Table 4.8: Cost of Accidents for a Five Year Period

	Shoulder Width (m)[a]		
VKMT	0	0.6	1.2
248,600 lowest value	$31,753	$25,620	$20,672
198,770,600 highest value	$25,389,684	$20,486,025	$16,529,438
21,574,000 average value	$2,755,725	$2,223,495	$1,794,059

	Shoulder Width (m)[a]		
VKMT	1.8	2.4	3.0
248,600 lowest value	$16,679	$13,458	$10,859
198,770,600 highest value	$13,337,011	$10,761,155	$8,682,790
21,574,000 average value	$1,447,562	$1,167,985	$942,406

a. 0.3 m = 1.0 ft

Table 4.9: Reduction in Costs for a Five Year Period

	Shoulder Width (m)[a]		
VKMT	0	0.6	1.2
248,600 lowest value	$0.00	$6,133	$11,081
198,770,600 highest value	$0.00	$4,903,659	$8,860,245
21,574,000 average value	$0.00	$532,229	$961,666

	Shoulder Width (m)[a]		
VKMT	1.8	2.4	3.0
248,600 lowest value	$15,073	$18,295	$20,894
198,770,600 highest value	$12,052,673	$14,628,528	$16,706,893
21,574,000 average value	$1,308,163	$1,587,739	$1,813,319

a. 0.3 m = 1.0 ft

Chapter Summary

In this chapter, the methods used to analyze accident data and the results of this analysis were presented. Poisson regression was performed. Then the results of this regression were used to predict accident numbers for various shoulder widths. It is clear from this analysis that wider pavement shoulders will result in lower accident numbers. This accident reduction depends on traffic level and the length of the section.

CHAPTER 5

STRUCTURAL ANALYSIS

Analysis Methods

The finite element analysis and the BISAR computer program were used in the structural analysis of pavement shoulders. The model characteristics, procedures used in these methods, and results are described in this chapter.

Finite Element Analysis

Finite element analysis is used in all types of applications to calculate a field quantity. This field quantity could be displacement or stress for a stress analysis, temperature or heat flux in a thermal analysis or the stream function or the velocity potential in a fluid flow analysis. Finite element analysis is a way of getting a numerical solution to a specific problem. The solution to a finite element analysis is approximate unless the problem is so simple that a convenient exact formula already is available.

Finite element analysis consists of dividing a structure into several elements, describing the behavior of each element in a simple way, then reconnecting elements at “nodes” as if nodes were pins or drops of glue that hold elements together. This process results in a set of simultaneous algebraic equations. In stress analysis the equations are equilibrium equations of nodes. There may be several hundred or several thousand equations, which makes computer analysis mandatory.

A more complex description of the finite element method regards it as piecewise polynomial interpolation. That is, over an element, a field quantity such as displacement is interpolated from values of the field quantity at nodes. By connecting elements together, the field becomes interpolated over the entire structure in a piecewise fashion, by as many polynomial expressions as there are elements. The “best” values of the field quantity at nodes are those that minimize some function such as total energy. The minimization process generates a set of simultaneous algebraic equations for values of the field quantity at nodes. Matrix symbolism for this set of equations is **KD = R**, where **D** is a vector of unknowns (values of the field quantity at nodes), **R** is a vector of known loads and **K** is a matrix of known constants. In stress analysis, **K** is known as a “stiffness matrix.”

The finite element method is a versatile tool for structural analysis. The structure analyzed can be of any shape, type of supports, and loading configuration [18].

Patran

Patran is a software package developed by PDA Engineering that was used to perform the finite element analysis in this study. It allows the user to solve many types of structural problems using finite element analysis. The following is the input that Patran required for this analysis: the geometrics of the problem, loading conditions, and boundary conditions. Geometrics included the shape and dimensions of the structure and the number of elements to be used in the structure.

BISAR

BISAR is an acronym for Bituminous Structures Analysis in Roads. It was developed by the Shell Oil Company. BISAR is a program to find stresses, strains, and displacements in asphalt pavement structures. It assumes that the pavement structure is infinite in the x and y directions. The z direction is the depth and is dependent on the input. The bottom layer in the z direction is assumed to be infinite in depth. The pavement structures are a N-Layer System in BISAR. Examples of the input and output for this program are included in Appendix C.

BISAR solves various asphalt pavement problems. To solve these problems, certain information about the problem must be specified in the input coding. The required input for BISAR includes number of layers in the structural system, modulus of elasticity, and Poisson’s ratio for each of those layers, thickness of each layer, number of loads being applied to the system, horizontal and vertical components of these loads, position of the loads, radius of the loads, number of points where the displacement, stress and strain are to be determined, and the location of the points. Furthermore, all the units for the input must be the same, so the units of the output are known. The output from BISAR does not specify the units being used, neither does the input [19].

Model Characteristics

Characteristics of the models used for the two analysis methods are quite similar. These characteristics include thickness of the layers, types of materials, and properties for the various materials. BISAR only uses the information pertaining to asphalt pavement structures. This section examines these characteristics for each analysis procedure.

A three-layer system was used in the analysis. The materials incorporated in the surface layer were asphalt or concrete. Base materials included granular base course, asphalt treated base (ATB), or cement treated base (CTB). Subgrade is the existing in place soil. Table 5.1 summarizes the modulus of elasticity (E) and Poisson's ratio (n) for the materials analyzed in this study.

Table 5.1: Material Properties

Material	E(kPa)[a]	
Concrete	24,131,650	0.15
Asphalt	2,757,900	0.35
CTB	4,136,850	0.25
ATB	1,378,950	0.37
Granular Base	172,370	0.40
Subgrade	103,420	0.43

a. 1.0 psi = 6.89 kPa

Maximum and minimum layer thicknesses were used in this analysis. Minimum concrete thickness used was 152.4 mm (6 inches) while the maximum was 304.8 mm (12 inches). Minimum asphalt thickness was 76.2 mm (3 inches) and the maximum was 304.8 mm (12 inches). The base layer thickness used in the analysis was the average base layer thickness of all test sections, which was 152.4 mm (6 inches).

Finite Element Analysis

The finite element model used in this study represented a typical driving lane and a shoulder. This was done for simplicity and ease of analysis. The pavement structure consists of a 3.6 m (12 ft) traveled way and a variable shoulder width. The material properties described in the previous section were used to create various models for analysis. An example of one of the finite element models is shown in Figure 5.1. The nodes that previously were described are represented by points where the lines intersect in Figure 5.1. Plane strain analysis was used for this model. The materials were assumed to be isotropic and linearly elastic. Plane strain is a situation in which $_{z}$ = 0, because physical constraints prevent the strain from occurring in that direction. Furthermore, plane sections that are perpendicular to the longitudinal axis remain plane and at the same distance apart. An isotropic material is one in which the material properties are the same regardless of direction. A material is elastic if the strains caused by the application of a given load disappear when the load is removed [20]. It is linearly elastic if the strains increase or decrease linearly. Rollers were used as the boundary condition along the bottom of the model and on the left side of the model.

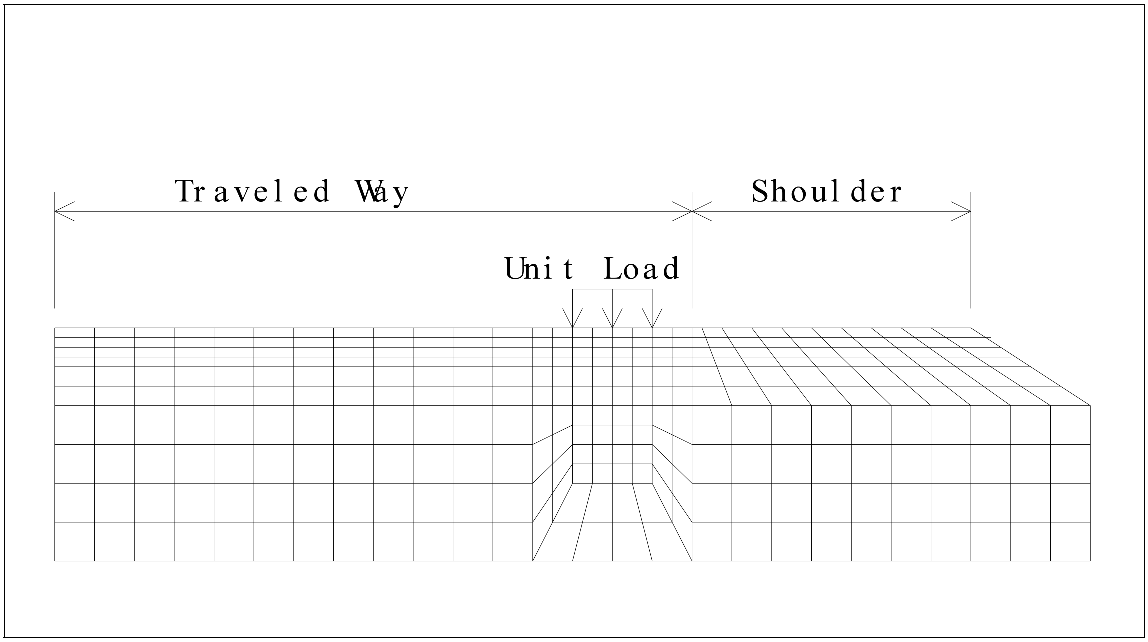

Figure 5.1: Finite Element Model

A unit load was applied to the model at 0.3 m (1 ft) away from the edge of the traveled way. This load was applied as one foot wide to approximately represent the width of a truck tire. This method yielded stresses and strains for the entire pavement structure. For the purpose of this analysis the stresses were found directly under the load, at the edge between the traveled way and the shoulder and at the edge of the shoulder. More specifically, stresses located at the bottom of the surface layer, middle of the surface layer, bottom of the surface layer, bottom of the base, and at the top of the subgrade were collected. This collected data can be seen in Appendix C for all of the models that were analyzed.

BISAR

In the BISAR analysis, the basic model characteristics described above were used only for the asphalt pavement structures. BISAR only can be used to analyze asphalt pavement systems. The load used in this analysis was 40 kN(9000 lbs.), to represent one wheel of the standard 80 kN (18 kip) axle. The tire pressure was assumed to be 689.5 kPa (100 psi). With a circular contact area. The load and tire pressure yield a tire patch radius of 135.9 mm (5.35 in.) by using the equation F = P/A where: F is a force, P is a pressure, and A is the area. In this case, F = 40 kN (9000 lbs.), P = 689.5 kPa (100 psi) and A equals the area of a circle ($A = r^2$). A representation of the conditions for the BISAR analysis can be seen in Figure 5.2. The stresses that were found by this analysis were the ones located directly below the load; at the bottom of the surface and at the top of the subgrade.

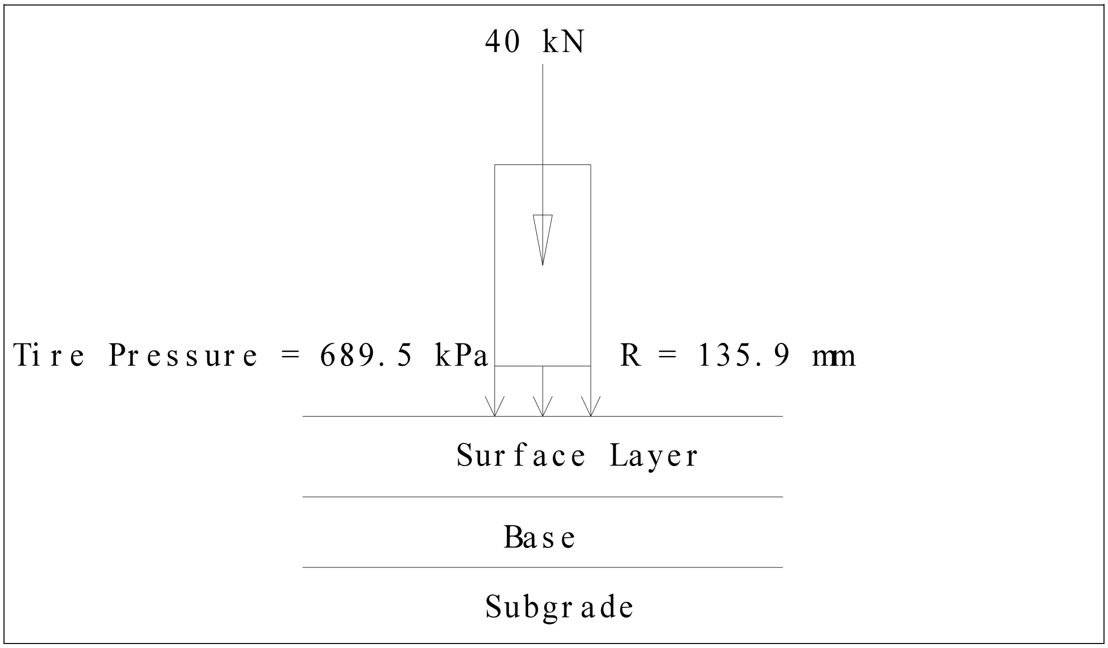

Figure 5.2: BISAR Model

Results of Analysis

The two structural analysis methods yielded stresses and strains for the various locations of interest. The locations include stresses at the bottom of the base layer and the top of the subgrade. The results of the two analysis methods are summarized in the following sections.

Finite Element Analysis

The finite element analysis was conducted by using Patran. The stresses were determined by obtaining the stress at a node on the model that was of interest. At locations where there was a transition from one material to another (material interface) the stresses for the specific layer could not be obtained by specifying the node. This is because the finite element method averages stresses from around the node. Thus the stresses would be the same at the bottom of one material and at the top of the other. Stresses normally change at material interfaces. To get these stresses, strains were determined at these nodes. The strain remains the same across the material interface, no matter the change in materials. Then the following equation was used to obtain the stresses from the strains obtained. The equation is the plane stress-strain relation of a linearly elastic and isotropic material.

$$\begin{bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{bmatrix} = \frac{E}{(1+\nu)(1-2\nu)} \times \begin{bmatrix} (1-\nu) & \nu & 0 \\ \nu & (1-\nu) & 0 \\ 0 & 0 & (\frac{1-2\nu}{2}) \end{bmatrix} \times \begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{bmatrix} \qquad (5.1)$$

where: σ_x = x stress,

σ_y = y stress,

τ_{xy} = xy shear,

E = modulus of elasticity,

ν = Poisson's ratio,

ε_x = x strain,

ε_y = y strain, and

γ_{xy} = xy strain.

The stresses at material interfaces were calculated with equation 5.1. Other stresses were obtained by examining the node of interest. The stresses obtained from the finite element analysis are summarized in Tables 5.2 through 5.5. Tables 5.2 and 5.3 contain stresses for the asphalt sections and Tables 5.4 and 5.5 include stresses for the concrete sections. Strains obtained from the finite element analysis are summarized in Tables 5.6 and 5.7 for asphalt and concrete sections, respectively.

Table 5.2: Stresses Under the Load in the Vertical Direction from Finite Analysis on Asphalt Sections

Materials		Thickness (mm)[a]		Shoulder Width (m)[b]	Stresses (kPa)[c]	
Surface	Base	Surface	Base		Top of Subgrade	Percent Change
Asphalt	Untreated	76.2	152.4	0	-188.1	- - -
Asphalt	Untreated	76.2	152.4	3.0	-218.5	16.2
Asphalt	ATB	76.2	152.4	0	-74.6	- - -
Asphalt	ATB	76.2	152.4	3.0	-71.8	-3.8
Asphalt	CTB	76.2	152.4	0	-47.0	- - -
Asphalt	CTB	76.2	152.4	3.0	-44.7	-4.9
Asphalt	Untreated	304.8	152.4	0	-82.8	- - -
Asphalt	Untreated	304.8	152.4	3.0	-80.3	-3.0
Asphalt	ATB	304.8	152.4	0	-40.2	- - -
Asphalt	ATB	304.8	152.4	3.0	-39.0	-3.0
Asphalt	CTB	304.8	152.4	0	-27.6	- - -
Asphalt	CTB	304.8	152.4	3.0	-26.4	-4.3

a. 1.0 inch = 25.4 mm
b. 1.0 ft = 0.3 m
c. 1.0 psi = 6.89 kPa

Table 5.3: Stresses Between Traveled Way and Shoulder in the Vertical Direction from Finite Element Analysis on Asphalt Sections

Materials		Thickness (mm)[a]		Shoulder Width (m)[b]	Stresses (kPa)[c]	
Surface	Base	Surface	Base		Bottom of Base	Percent Change
Asphalt	Untreated	76.2	152.4	0	-112.0	- - -
Asphalt	Untreated	76.2	152.4	3.0	-99.5	-11.2
Asphalt	ATB	76.2	152.4	0	-513.2	- - -
Asphalt	ATB	76.2	152.4	3.0	-467.1	-9.0
Asphalt	CTB	76.2	152.4	0	-1051.4	- - -
Asphalt	CTB	76.2	152.4	3.0	-956.6	-9.0
Asphalt	Untreated	304.8	152.4	0	-97.0	- - -
Asphalt	Untreated	304.8	152.4	3.0	-91.4	-5.8
Asphalt	ATB	304.8	152.4	0	-383.5	- - -
Asphalt	ATB	304.8	152.4	3.0	-362.0	-5.6
Asphalt	CTB	304.8	152.4	0	-741.1	- - -
Asphalt	CTB	304.8	152.4	3.0	-702.8	-5.2

a. 1.0 inch = 25.4 mm
b. 1.0 ft = 0.3 m
c. 1.0 psi = 6.89 kPa

Table 5.4: Stresses Under the Load in the Vertical Direction from Finite Element Analysis on Concrete Sections

Materials		Thickness (mm)[a]		Shoulder Width (m)[b]	Stresses (kPa)[c]	
Surface	Base	Surface	Base		Top of Subgrade	Percent Change
Concrete	Untreated	152.4	152.4	0	-88.3	- - -
Concrete	Untreated	152.4	152.4	3.0	-83.2	-5.8
Concrete	CTB	152.4	152.4	0	-32.0	- - -
Concrete	CTB	152.4	152.4	3.0	-27.8	-13.1
Concrete	Untreated	304.8	152.4	0	-53.4	- - -
Concrete	Untreated	304.8	152.4	3.0	-49.3	-7.7
Concrete	CTB	304.8	152.4	0	-23.4	- - -
Concrete	CTB	304.8	152.4	3.0	-20.7	-11.5

a. 1.0 inch = 25.4 mm
b. 1.0 ft = 0.3 m
c. 1.0 psi = 6.89 kPa

Table 5.5: Stresses Between Traveled Way and Shoulder in the Vertical Direction from Vertical Direction from Finite Element Analysis on Concrete Sections

Materials		Thickness (mm)[a]		Shoulder Width (m)[b]	Stresses (kPa)[c]	
Surface	Base	Surface	Base		Bottom of Base	Percent Change
Concrete	Untreated	152.4	152.4	0	-3488.6	- - -
Concrete	Untreated	152.4	152.4	3.0	-3292.1	-5.6
Concrete	CTB	152.4	152.4	0	-831.6	- - -
Concrete	CTB	152.4	152.4	3.0	-745.5	-10.4
Concrete	Untreated	304.8	152.4	0	-71.1	- - -
Concrete	Untreated	304.8	152.4	3.0	-61.6	-13.4
Concrete	CTB	304.8	152.4	0	-577.4	- - -
Concrete	CTB	304.8	152.4	3.0	-530.0	-8.2

a. 1.0 inch = 25.4 mm
b. 1.0 ft = 0.3 m
c. 1.0 psi = 6.89 kPa

Table 5.6: Strains at the Bottom of the Base in the Vertical Direction from Finite Element Analysis on Asphalt Sections

Materials		Thickness (mm)[a]		Shoulder Width (m)[b]	Strains			
Surface	Base	Surface	Base		Under the Load	Percent Change	Between Trvld Wy & Shldr	Percent Change
Asphalt	Untreated	76.2	152.4	0	-1.725 e-7	- - -	-5.397 e-8	- - -
Asphalt	Untreated	76.2	152.4	3.0	-1.69 e-8	-90.2	-4.04 e-8	-25.1
Asphalt	ATB	76.2	152.4	0	-8.386 e-8	- - -	-3.817 e-8	- - -
Asphalt	ATB	76.2	152.4	3.0	-8.232 e-8	-1.8	-3.26 e-8	-14.6
Asphalt	CTB	76.2	152.4	0	-5.137 e-8	- - -	-2.962 e-8	- - -
Asphalt	CTB	76.2	152.4	3.0	-5.025 e-8	-2.2	-2.645 e-8	-10.7
Asphalt	Untreated	304.8	152.4	0	-6.868 e-8	- - -	-5.316 e-8	- - -
Asphalt	Untreated	304.8	152.4	3.0	-6.53 e-8	-4.9	-4.69 e-8	-11.8
Asphalt	ATB	304.8	152.4	0	-4.27 e-8	- - -	-3.151 e-8	- - -
Asphalt	ATB	304.8	152.4	3.0	-4.151 e-8	-2.8	-2.90 e-8	-8.0
Asphalt	CTB	304.8	152.4	0	-2.811 e-8	- - -	-2.154 e-8	- - -
Asphalt	CTB	304.8	152.4	3.0	-2.766 e-8	-1.6	-2.045 e-8	-5.1

a. 1.0 inch = 25.4 mm
b. 1.0 ft = 0.3 m

Table 5.7: Strains at the Bottom of the Base in the Vertical Direction from Finite Element Analysis on Concrete Sections

Materials		Thickness (mm)[a]		Shoulder Width (m)[b]	Strains			
Surface	Base	Surface	Base		Under the Load	Percent Change	Between Trvld Wy & Shldr	Percent Change
Concrete	Untreated	152.4	152.4	0	-6.311 e-8	- - -	-5.35 e-8	- - -
Concrete	Untreated	152.4	152.4	3.0	-5.85 e-8	-7.3	-4.34 e-8	-18.9
Concrete	CTB	152.4	152.4	0	-2.943 e-8	- - -	-2.34 e-8	- - -
Concrete	CTB	152.4	152.4	3.0	-2.89 e-8	-1.8	-2.15 e-8	-8.1
Concrete	Untreated	304.8	152.4	0	-3.253 e-8	- - -	-3.192 e-8	- - -
Concrete	Untreated	304.8	152.4	3.0	-3.037 e-8	-6.6	-2.696 e-8	-15.5
Concrete	CTB	304.8	152.4	0	-1.768 e-8	- - -	-1.593 e-8	- - -
Concrete	CTB	304.8	152.4	3.0	-1.741 e-8	-1.5	-1.503 e-8	-5.6

a. 1.0 inch = 25.4 mm
b. 1.0 ft = 0.3 m

Looking at Table 5.2 for stresses under the load on asphalt sections, it is observed that when shoulder width is increased from 0 m to 3.0 m (10 ft), the stresses decrease slightly. This is true for stresses at the interface between the traveled way and the shoulder on asphalt sections, as prsented in Table 5.3. Examining Table 5.4 for stresses under the load for concrete sections a similar trend can be observed. Table 5.5 indicates the same trend for stresses at the edge between the traveled way and shoulder for concrete sections. Tables 5.6 and 5.7 display the strains that occur at the bottom of the base in the vertical direction for asphalt and concrete sections respectively. These tables indicate that as the shoulder width increses the strains decrease slightly.

BISAR

Input files were created for various conditions, and stresses were calculated using BISAR. The BISAR output was printed and stresses were obtained from this printed output. The stresses from the BISAR analysis are summarized in Table 5.8. All of the printed output from BISAR is included in Appendix C.

Table 5.8: BISAR Stresses

Base	Thickness (mm)[a]		Stresses (kPa)[b]
Type	Surface	Base	Top of Subgrade
Untreated	76.2	152.4	-136.4
ATB	76.2	152.4	-81.4
CTB	76.2	152.4	-48.9
Untreated	304.8	152.4	-23.0
ATB	304.8	152.4	-19.7
CTB	304.8	152.4	-14.9

a. 1.0 inch = 25.4 mm
b. 1.0 psi = 6.89 kPa

Comparison of BISAR and Finite Element Analysis

To conduct a comparison of the two methods, the results had to be converted to the same units. Therefore, stresses from the finite element analysis were converted from pounds per square feet (psf) to pounds per square inch (psi). Also, since the load applied in the finite element method was a unit load and the load applied using BISAR was 9,000 pounds (40 kN), the stresses from the finite element analysis were then multiplied by 9,000. The results of the conversion and the comparison can be seen in Table 5.9. From Table 5.9, it is observed that the two methods yielded different results. However, both methods showed similar trends, such as when the base material becomes stiffer the stresses decreased.

Table 5.9: Comparison of Results

Base	Thickness (mm)[a]		Stresses (kPa)[b] Top of Subgrade		Percent
Type	Surface	Base	BISAR	Finite Element	Difference
Untreated	76.2	152.4	-136.4	-188.1	27.5
ATB	76.2	152.4	-81.4	-71.8	13.4
CTB	76.2	152.4	-48.9	-44.7	9.4
Untreated	304.8	152.4	-23.0	-80.3	71.4
ATB	304.8	152.4	-19.7	-39.0	49.5
CTB	304.8	152.4	-14.9	-26.4	43.6

a. 1.0 inch = 25.4 mm
b. 1.0 psi = 6.89 kPa

Chapter Summary

This chapter presented the methods of structural analysis used in this research study. Finite element analysis was performed and the BISAR program was run. The results of this analysis provided stresses and strains at the desired locations with variable shoulder widths.

The stresses and strains indicated that shoulder width had a minimal effect on stresses and strains at the top of the subgrade and the bottom of the base layer. The stresses and strains were only slightly reduced when no shoulder is compared to a 3.0 m (10 ft) shoulder. The comparison between BISAR and the finite element method showed that the results were different from each other.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

The main objectives of this study were to examine the effect of pavement shoulders on the safety and structural strength of highways. This was performed by collecting data on representative highway sections from throughout Wyoming for a five-year period. A statistical and structural analysis were performed on the data. This chapter summarizes conclusions drawn from the analyses. Recommendations also are included in this chapter.

Safety Effectiveness of Shoulders

This study was performed to determine the effectiveness of pavement shoulders on the safety of highways in Wyoming. It was determined that significant reductions in accidents can be expected when shoulder widths were increased or if shoulders were added to a roadway. Adding 0.6 m (2 ft) of shoulder width to a section with no shoulders has the most effect in reducing accident numbers. For each increment of 0.6 m (2 ft) of increased width thereafter, accident numbers will decrease, but not as significantly. These findings are consistent with similar studies performed at the national level.

Structural Effectiveness of Shoulders

This study also was performed to determine the effect of pavement shoulder width on stresses in the base and subgrade layers. Stresses under the load were examined to determine if there is a reduction in stresses with the added width of shoulders. This analysis indicated that shoulder width would result in a slight reduction of vertical stresses.

Effectiveness of Shoulders

Effectiveness of adding pavement shoulders also was examined. Adding shoulders or increasing shoulder widths on roadways with relatively high traffic volumes reduced accident costs significantly. However, on roadways with very low traffic volumes it was determined that increasing the shoulder width would result in insignificant reduction in accident numbers.

Recommendations

The findings of this research have led to the following recommendations:

- Pavement shoulders should be implemented on roadways with high volumes. These shoulders will help in significantly reducing the number of accidents.
- Wide shoulders are not effective on low volume roadways. However, the first 0.6 m (2 ft) of shoulder widening should be considered since it is quite effective in reducing accident numbers.

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