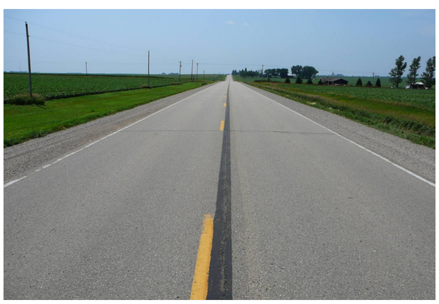
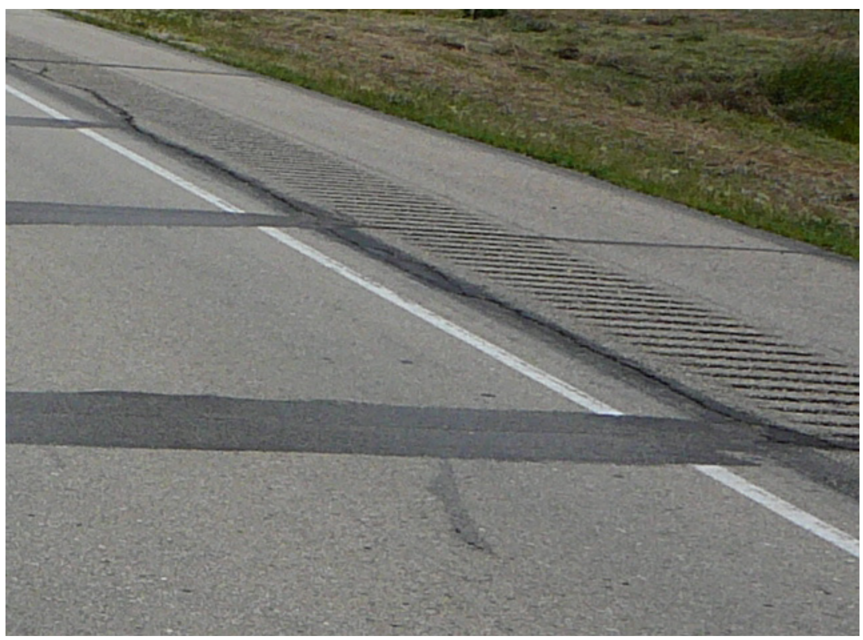
# Safety Benefits of Paved Shoulders

Center for Transportation Research and Education

**Final Report**
**November 2009**





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**Sponsored by**
Iowa Department of Transportation
(InTrans Project 05-239)

The preparation of this (report, document, etc.) was financed in part through funds provided by the Iowa Department of Transportation through its "Agreement for the Management of Research Conducted by Iowa State University for the Iowa Department of Transportation," and its amendments.

**Technical Report Documentation Page**

| 1. Report No. | 2. Government Accession No. | 3. Recipient's Catalog No. | |
|---|---|---|---|
| InTrans Project 05-239 | | | |
| **4. Title and Subtitle**<br>Safety Benefits of Paved Shoulders | | **5. Report Date**<br>November 2009 | |
| | | **6. Performing Organization Code** | |
| **7. Author(s)**<br>Shauna L. Hallmark, Thomas J. McDonald, Ye Tian, David J. Andersen | | **8. Performing Organization Report No.** | |
| **9. Performing Organization Name and Address**<br>Center for Transportation Research and Education<br>Iowa State University<br>2711 South Loop Drive, Suite 4700<br>Ames, IA 50010-8664 | | **10. Work Unit No. (TRAIS)** | |
| | | **11. Contract or Grant No.** | |
| **12. Sponsoring Organization Name and Address**<br>Iowa Department of Transportation<br>800 Lincoln Way<br>Ames, IA 50010 | | **13. Type of Report and Period Covered**<br>Final Report | |
| | | **14. Sponsoring Agency Code** | |
| **15. Supplementary Notes**<br>Visit www.ctre.iastate.edu for color PDF files of this and other research reports. | | | |

**16. Abstract**


Single vehicle run-off-road (ROR) crashes are the largest type of fatal passenger vehicle crash in the United States (NCHRP 500 2003). In Iowa, ROR crashes accounted for 36% of rural crashes and 9% of total crashes in 2006. Run-off-road crashes accounted for more than 61.8% of rural fatal crashes and 32.6% of total fatal crashes in Iowa in 2006.

Paved shoulders are a potential countermeasure for ROR crashes. Several studies are available which have generally indicated that paved shoulders are effective in reducing crashes. However, the number of studies that quantify the benefits are limited.

The research described in this report evaluates the effectiveness of paved shoulders. Model results indicated that covariate for speed limit was not significant at the 0.05 confidence level and was removed from the model. All other variables which resulted in the final model were significant at the 0.05 confidence level. The final model indicated that season of the year was significant in indicating expected number of total monthly crashes with a higher number of crashes occurring in the winter and fall than for spring and summer. The model also indicated that presence of rumble strips, paved shoulder width, unpaved shoulder width, and presence of a divided median were correlated with a decrease in crashes. The model also indicated that roadway sections with paved shoulders had fewer crashes in the after period as compared to both the before period and control sections.

The actual impact of paved shoulders depends on several other covariates as indicated in the final model such as installation year and width of paved shoulders. However, comparing the expected number of total crashes before and after installation of paved shoulders for several scenarios indicated around a 4.6% reduction in the expected number of monthly crashes in the after period.


| 17. Key Words | | 18. Distribution Statement | |
|---|---|---|---|
| paved shoulders—run-off-road crashes | | No restrictions. | |
| **19. Security Classification (of this report)** | **20. Security Classification (of this page)** | **21. No. of Pages** | **22. Price** |
| Unclassified. | Unclassified. | 61 | NA |

**Form DOT F 1700.7 (8-72)** **Reproduction of completed page authorized**

# SAFETY BENEFITS OF PAVED SHOULDERS

**Final Report**
**November 2009**


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The Midwest Transportation Consortium
provided funding for a graduate research assistant assigned to this project.

Preparation of this report was financed in part
through funds provided by the Iowa Department of Transportation
through its research management agreement with the
Institute for Transportation,
InTrans Project 05-239.



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## TABLE OF CONTENTS

## LIST OF FIGURES



## LIST OF TABLES

## ACKNOWLEDGMENTS

The research team would like to thank the Iowa Department of Transportation (Iowa DOT) for funding this research. We would especially like to thank Dr. Michael Pawlovitch of the Iowa DOT for extracting monthly crashes and volume for the analysis. We would also like to thank the Iowa DOT districts that responded to the maintenance survey and law enforcement personnel who responded to the law enforcement survey. Additionally, we would like to thank several students who were not included as co-authors in this report who helped collect data.

## EXECUTIVE SUMMARY

Single vehicle run-off-road (ROR) crashes are the most common type of fatal passenger vehicle crash in the United States (NCHRP 500 2003). In Iowa, ROR crashes accounted for 36% of all rural crashes, more than 61.8% of rural fatal crashes, 9% of total crashes, and 32.6% of total fatal crashes in 2006.

Paved shoulders are a potential countermeasure for ROR crashes. Several studies are available that have generally indicated that paved shoulders are effective in reducing crashes. However, the number of studies that quantify the benefits is limited.

In 2004, Iowa adopted a paved shoulder policy for higher volume roads, but a wide range of paved shoulder types has been utilized for many years in the state. Because the benefits of paved shoulders have not been quantified, the Iowa Department of Transportation (Iowa DOT) requested a study to analyze the safety performance of various paved shoulder designs on a wide spectrum of traffic and roadway types.

The research described in this report was designed to evaluate the effectiveness of paved shoulders. As part of the research, two surveys were conducted that assessed the opinions of field maintenance personnel and law enforcement personnel regarding the effectiveness of paved shoulders. Most maintenance personnel felt that paved shoulders lead to reduced maintenance costs, and most law enforcement personnel felt that paved shoulders reduce ROR crashes and improve safety for officers who have to pull over for traffic stops.

This research also included a crash analysis for non-Interstate roadways where paved shoulders have been installed in Iowa. The team made site visits and collected roadway data for 256 roadway sections in Iowa. The majority included locations where paved shoulders had been installed, but a number of control sections were collected as well. Each test segment was reviewed, and the construction year in which paved shoulders were implemented was determined. In some cases, the roadway segment could not be located in a geographic information management systems (GIMS) database, and in other cases the construction year could not be determined. These cases were removed from further analysis. This resulted in a total of 220 sites analyzed, including 77 control sections and 143 test sections. Sections included both two- and four-lane roadways. Four-lane roadways were both divided and undivided.

A generalized linear model (GLM) using a Poisson distribution with a log link function was used to investigate the relationship between crash reduction and paved shoulder implementation. The response variable was monthly crash frequency. Traffic volume and segment length were modeled as offsets. An attempt was made to model only ROR and cross-centerline crashes, but because we were using individual months as the observation period, this attempt resulted in a large number of observations with no crashes, which made it difficult to fit an adequate model.

Model results indicated that the covariate for speed limit was not significant at the 0.05 confidence level and was removed from the model. All other variables that resulted in the final model were significant at the 0.05 confidence level. The final model indicated that the season of the year was significant for predicting the expected number of total monthly crashes, with a higher number of crashes occurring in the winter and fall than in the spring and summer. The model also indicated that the presence of rumble strips, paved shoulder width, unpaved shoulder width, and the presence of a divided median correlated with a decrease in crashes. The model also indicated that roadway sections with paved shoulders had fewer crashes in the after period than in both the before period and control sections.

The actual impact of paved shoulders depends on several other covariates, as indicated in the final model, such as installation year and width of paved shoulders. However, comparing the expected number of total crashes before and after paved shoulder installation for one scenario indicated around a 3% crash reduction in the after period, after accounting for differences in control sections.

The report is organized in the following way:

- Chapter 1 summarizes a literature review of the effectiveness of paved shoulders and rumble strips.
- Chapter 2 describes the project scope and summarizes Iowa DOT paved shoulder practices.
- Chapter 3 provides the results of a survey of field maintenance personnel and law enforcement personnel regarding their experience with paved shoulders.
- Chapter 4 describes data collection.
- Chapter 5 describes the analysis of the data.

# 1. INTRODUCTION

Single vehicle run-off-road (ROR) crashes are the single most common type of fatal passenger vehicle crash in the United States (NCHRP 500 2003). A ROR crash is defined as a crash in which one or more vehicles has at least one of the vehicle's first three sequences of events coded as ROR-right, ROR-left, or ROR-straight. Many ROR crashes are rural crashes, which are defined as crashes that occur one or more miles outside of an incorporated area. In Iowa, rural crashes accounted for 13,255 out of 54,785 crashes in 2006 (24.2%). An extraction of rural ROR crashes that occurred in 2006 from the Iowa Department of Transportation (DOT) crash database indicated that ROR crashes accounted for 35.5% of rural crashes and 8.6% of total crashes. Moreover, ROR crashes accounted for more than 61.8% of rural fatal crashes and 32.6% of total fatal crashes in Iowa in 2006.

Paved shoulders are a potential countermeasure for ROR crashes. Shoulder rumble strips are also potentially effective in reducing ROR crashes.

## 1.1 Paved Shoulders

It is generally accepted that shoulders play an important role in highway design. They provide additional recovery space for errant vehicles and lateral support for the pavement structure.

Regarding lateral support, Benekohal (1990) stated that, as a rule of thumb, loads applied within 6 in. of the concrete slab edge will produce significant stresses at the slab edge. Benekohal also concluded that, on roads widened beyond the conventional 12 ft, painted lane lines have a greater influence on truck wheel placement than the slab edge. The author also found that providing an additional 18 to 22 in. of pavement beyond the lane line can prevent tractor-semitrailers from passing within 6 in. of the slab edge.

### *1.1.1 Safety Benefits*

Heimbach (1974) found that rural two-lane highways with paved shoulders had a significantly lower crash rate than highways with unstabilized shoulders. The National Cooperative Highway Research Program (NCHRP) Report 197, published in 1978, also found that paved shoulders exhibit safety benefits. The report concluded that roads with paved shoulders have lower crash rates than roads with unpaved shoulders of the same width. It also concluded that shoulder widths and whether shoulders were paved or unpaved had a greater effect on crash rates than lane widths. A linear model was developed to predict crash rates for roadways with varying lane and paved shoulder widths. The model was generally able to represent predicted relationships, but there were some inconsistencies. In general, crash rates decreased as shoulder widths increased. This rule applies for sections of roadway with 3° or less of horizontal curvature. However, the opposite result was true for roadways with an average daily traffic (ADT) of less than 1,000 vehicles per day (VPD) or greater than 5,000 VPD (NCHRP 197 1974).

Zegeer (1981) conducted a comparative analysis study of state primary, state secondary, and rural two-lane roads in Kentucky. The sections were selected so that they did not include any major intersections. A database of 15,944 miles of road was compiled from computer tape, and eight classifications of roads based on ADT were used. Due to about 70% of the total sample having no shoulder, shoulders were defined as paved or densely graded. Grass and soil were not considered shoulders because they are not suitable for driving. Zegeer found that ROR, head-on, and opposite direction sideswipe crash rates decreased as shoulder width increased from 0 to 9 ft, but the crash rates increased slightly for shoulders of 10 to 12 ft. Crash severity, however, did not decrease with wider shoulders. For roadways with lane widths greater than 10 ft, Zegeer determined that it was economically beneficial to widen the shoulders if there are at least five ROR and/or opposite direction crashes in one year. For roads without shoulders, the optimal shoulder width to install was estimated to be 5 ft (Zegeer 1981).

Not all studies have concluded that paved shoulders offer a significant benefit, however. Abboud (2001) evaluated 2 ft and 4 ft paved shoulders on two-lane highways in Alabama and analyzed them against county statistics for the expected number of crashes on the treated segments. Crash records were not kept on specific routes with similar characteristics, and therefore total county crashes in the before and after period were used as a control. Crash frequency by type and crash severity were analyzed, but no statistically significant differences were found at the 0.05 alpha confidence level (Abboud 2001).

Similarly, a study conducted by Souleyrette (2001) did not demonstrate significant crash reduction benefits. Souleyrette's study focused specifically on rural two-lane and rural four-lane divided non-Interstate freeways in the state of Iowa. Only targeted crashes were considered for this study; intersection crashes, median crashes, and roadway crashes were excluded because they were assumed to be non-shoulder related. Limited data availability due to conservative shoulder construction practices in Iowa prevented statistical significance from being obtained with any of the results. Trends of reduced crash rates were noted but could not be verified with confidence. The report was able to determine, however, that a reduction of up to $366 per mile per year can be realized by paving shoulders on two-lane roads.

### *1.1.2 Bicycle Accommodation*

Bicyclist safety and comfort is another benefit of paved shoulders. In 1997, Harkey found that paved shoulders and bicycle lanes act essentially the same in terms of operations. By studying the separation distance between motorists and bicyclists on varying shoulder widths, Harkey also found that bicycle lane widths (paved shoulder widths) as narrow as three ft can allow safe interactions between motorists and bicyclists. Encroachments by motorists into adjacent lanes when passing bicyclists were also studied, but there were few observed encroachments and the encroachments were not attributable to shoulder width. Harkey's findings, however, only apply to roadways similar to the ones in the study. These include roadways with vehicle speeds at or below 50 mph, lane widths of at least 11 ft, and minimal horizontal and vertical sight restrictions. Roadways with significant curvature or significant large truck traffic may require wider bicycle lanes (Harkey 1997).

The Federal Highway Administration (FHWA) has developed the bicycle compatibility index (BCI), a level of service concept for bicyclists. According to the BCI Implementation Manual, the presence or absence of a bicycle lane or paved shoulder has the greatest effect of any variable on the comfort level of bicyclists. On the one hand, a bicycle lane or a paved shoulder of at least 0.9 m (approximately 3 ft) can increase the level of service for that segment by an entire letter grade on an “A” through ”F” scale. On the other hand, higher volumes and higher speeds result in a slight decrease in level of service. The decrease, however, is much smaller than the increase resulting from a 3 ft paved shoulder (Bicycle Compatibility Index 1999).

#### *1.1.3 Operational Benefits*

The operational benefits of paved shoulders were not the focus of the present study, but they are worth mentioning as an additional benefit of paving shoulders. Turner et al. (1982) have reported findings about roadway operations based on a study conducted on two-lane roadways without shoulders, two-lane roadways with full (at least 6 ft) paved shoulders, and four-lane undivided roadways without paved shoulders. The study focused on three key elements of operations: vehicle speed, platooning, and shoulder use.

On two-lane roads without paved shoulders, vehicle speeds dropped dramatically as volume increased. A similar trend was observed on two-lane roads with shoulders, except the trend diminished at around 150 vehicles per hour. Beyond this point, vehicle speeds did not decrease with an increase in volume. The difference in trends became significant at about 200 vehicles per hour. At volumes above 200 vehicles per hour, the average vehicle speed was about 10% higher on two-lane highways with paved shoulders than on those without (Turner 1982).

The amount of vehicle platooning experienced on a roadway increased with increased volumes, but appeared to level out at approximately 200 vehicles per hour on two-lane roads with paved shoulders. Vehicle platooning on two-lane roads without shoulders appeared to continue to increase exponentially beyond the 200 vehicles per hour mark. This observation led to the interpolated conclusion that, at volumes above 200 vehicles per hour, two-lane roads with paved shoulders would experience a smaller percentage of vehicles driving in platoons than would two-lane roads without paved shoulders (Turner 1982).

### 1.2 Rumble Strips

Paved shoulders allow additional recovery room for errant vehicles, but they do not alert distracted drivers who are no longer driving in their intended lane. Rumble strips provide an audible and tactile alert to drivers who have become distracted and drift away from their travel lane. In evaluating the impact of rumble strips, some research reports have attempted to differentiate between ROR crashes and drift-off-road (DOR) crashes. The difference between the two types is that a ROR crash may result from a driver swerving to avoid some other danger in the roadway. In this case, rumble strips would be ineffective. A DOR crash occurs when a driver has fallen asleep or has become distracted in some other manner, such as by looking at a map. In this case, rumble strips can alert the driver of the impending danger, and the driver can take the appropriate action. In a study conducted by Morena (2003), DOR crashes account for 40% to

71% of all ROR crashes on rural roads in Michigan, with ADT values ranging from 5,000 to 11,000 VPD.

### *1.2.1 Safety Benefits of Shoulder Rumble Strips*

Installing shoulder rumble strips on the Interstate system has proven to be effective in reducing ROR crashes, but these results may not directly translate to rural two-lane roads. Neuman (2003) speculates that rumble strips may be less effective on a two-lane road because there a vehicle has a much smaller recovery area once it has been alerted. However, he also suggests that rumble strips may be more effective on two-lane rural roads than on Interstate roads because two-lane roads have a smaller recovery area and a less forgiving roadside. Thus, allowing the driver time to recover before leaving the road entirely could have a much more significant safety impact on two-lane roads than on an Interstate. The alignment of two-lane highways is also generally less forgiving than that of the Interstate, creating a greater need for a warning device to keep drivers on the roadway. Because no studies are currently available pertaining specifically to the safety benefits of rumble strips on two-lane rural roads, Neuman estimated that a 20% to 30% reduction in ROR crashes after the installation of shoulder rumble strips is realistic based on rural freeway experience.

The New York State Department of Transportation (NYSDOT) began installing continuous shoulder rumble strips on many of its roads in 1993. The NYSDOT began this process by including continuous shoulder rumble strips with its regular construction and as site-specific projects on existing roadways. The New York State Thruway Authority (NYSTA), which owns and operates private toll roads, also installed continuous shoulder rumble strips between 1992 and 1996. The advantage of the NYSTA data is uniformity, because the data are recorded by a dedicated troop of the state police force and there are a limited number of miles from which to collect data. Both New York agencies had a limited amount of before and after data, so statistical significance was not tested, but both agencies found a crash reduction of 65% to 70%. It should be noted, however, that some observations were made during years that included construction of a "[non] significant percentage" of continuous shoulder rumble strips (Perrillo 1998).

Rumble strips were similarly installed on 80% of the Pennsylvania Turnpike between 1989 and 1994. Early results after the first five installation projects were completed found a 70% reduction in DOR crashes. After speculation of regression to the mean and other factors affecting the results, a follow-up study was conducted. The study included all reportable accidents from 1990 to 1995 and found a slightly more modest result of a 60% reduction in DOR crashes (Hickey 1997). These results, however, were not tested for statistical significance.

In another approach, Hanley et al. (2000) evaluated four accident reduction factors currently used by the California Department of Transportation (CALTRANS), including rumble strip installation, defined as any construction for which a laterally positioned rumble strip had been installed. In most cases, the study indicated that some shoulder widening occurred as well. The researchers found statistically significant accident reduction factors for rumble strip installations.

Garder and Davies evaluated the effectiveness of continuous shoulder rumble strips on reducing crashes on rural Interstates in Maine. The authors found that the presence of these installations reduced crashes overall by 27%, sleep-related ROR crashes by about 58%, and dry road ROR crashes by about 43%. They also found that fatal crashes were reduced more than other crashes.

Smith and Ivan (2005) evaluated the amount of crash reduction due to milled-in shoulder rumble strips on limited-access highways. The authors used a three-year before installation and three-year after installation period on sections of 20 freeways, including some sections without rumble strips. They found that shoulder rumble strips overall reduced single-vehicle, fixed-object crashes by 33%. The results also indicated that crashes were reduced by as much as 48.5% within interchange areas and as little as 12.8% on sections where the speed limit was less than 65 mph. The authors also found that crashes increased in areas where rumble strips were not installed.

### *1.2.2 Safety Benefits of Edge line Rumble Strips*

Edge line rumble strips (ERSs) are rumble strips that are milled-in at the painted edge line, as shown in Figure 1.1. They are different from regular shoulder rumble strips because typical shoulder rumble strips are installed several inches outside of the edge line. However, ERSs still require the presence of a shoulder because they are two to three times wider than the lane line itself. There are several potential benefits of ERSs. They can increase painted edgeline visibility and longevity, provide additional recovery room for errant vehicles, and provide more room for bicyclists on the shoulder.


**Figure 1.1. Edge line rumble strip**

Edge line rumble strips provide increased visibility and longevity of the painted edge line based on three factors. First, the painted edge line is more visible at night and in the rain because the paint is on a vertical surface off of which headlights reflect, as shown in Figure 1.2. Second, the painted edge line comes into less contact with tires, because there will be less encroachment onto the edge line and drivers are discouraged from positioning their tires on the edge line for extended periods of time due to the noise and vibrations generated by the rumble strips. Finally, there is less surface area contact with the tires because the edgeline is partially milled into the roadway, preventing full, direct contact with tires (Miles 2005).


**Figure 1.2. Nighttime view of edgeline rumble strip** (image source: http://www.tfhrc.gov/pubrds/06jul/images/morena14.jpg)

Texas conducted a preliminary study to determine the extent of the benefits received by ERSs. The study was conducted on a two-lane road in Texas with an 11 ft travel lane in each direction separated by a 4 ft wide center segment marked with centerline pavement markings. Before and after data were collected along this five-mile segment of road between September 10 and September 22, 2004 and November 5 and November 17, 2004, respectively (Miles 2005).

A study by Miles (2005) used rumble strips that were 12 in. wide, 4 in. on marked edge line and 8 in. on shoulder pavement. Pneumatic road tubes were used to collect volume, speed, and lateral position data. Video footage was also collected in order to classify the shoulder encroachment maneuvers and determine if the ERSs caused any erratic maneuvers by drivers. A total of 2,985 shoulder encroachments were observed during the 13 days of before and 13 days of after installation footage. No erratic maneuvers were observed in the video data. Statistical t-tests were performed on the data to determine significance at the 95% confidence level for any changes in driver behavior (Miles 2005).

The data revealed an overall reduction in shoulder encroachments of 46.7%. When broken down by encroachment type, the "other" case experienced the greatest proportional decrease in shoulder encroachments. The "other" case included "inadvertent contact with the edge line because of natural lane shifting, driver inattention or fatigue, swaying motions of trailers, or large load width." Encroachments classified as "other" are categorized as one of four types, ranging from "right tires hit," for when only the right tires contact the rumble strips, to "around," for when both sets of tires completely cross over the rumble strips (Miles 2005).

While the number of encroachments decreased, lateral position of vehicles increased in distance beyond the edge line. This was not statistically significant, however, and standard deviations were large. The general increase in encroachment distance was attributed to the fact that the treatment was most effective in limiting "other" encroachments that involve only the vehicles' right tires contacting the rumble strips. Certain maneuvers, such as straddling maneuvers by vehicles with three or more axles, actually increased. This is likely because it is difficult to keep wide loads and swaying trailers in the travel lane, so a conscious decision may have been made by these drivers to straddle the ERSs. "Passing" drivers in two-axle vehicles were also more likely to pull completely onto the shoulder when allowing faster vehicles to pass in order to avoid the annoyance of their left tire driving along the ERSs (Miles 2005). These observations may create more wear and tear on shoulders not designed for vehicle traffic and may add to bicyclist discomfort, but these are not necessarily viewed as less safe for drivers using the facility.

In another study, Corkle et al. (2001) summarized eight research studies on edge line rumble strips and found that ROR crashes were reduced by 20% to 72%.

### *1.2.3 Bicycle Accommodation with Shoulder Rumble Strips*

Bicyclists have the right to ride in the right-hand lane on Iowa highways, excluding the Interstate highway system and where explicitly prohibited; therefore, highways should be designed to accommodate them (2007 Iowa Code §321.324). In addition to their legal right to access the right-most travel lane from the shoulder, bicyclists may need to access the travel lanes in order to avoid debris on the shoulder. A bicyclist may also need to access the travel lane when approaching a right-turn lane to avoid any potential collisions with a turning vehicle. Rumble strips present a problem in this regard because they are designed to vibrate cars and alert inattentive drivers. This is a safety feature for motor vehicles, but it is a dangerous obstacle for bicyclists (Moeur 2000).

In Arizona, most of the bicycles operated on the streets and highways do not have any suspension or shock absorbers. The only shock absorption these bicycles have is in their tires, saddles, hand grips, and the riders themselves. This means the vertical displacement created by the rumble strips will have a more severe effect on bicycles than on cars, trucks, or motorcycles. A gap pattern in rumble strips was developed in order to reach a compromise between motorist and bicyclist safety (Moeur 2000).

In their guide for development of bicycle facilities, the American Association of State Highway and Transportation Officials (AASHTO) recommends a minimum design speed of 20 mph in general, whether rumble strips are present or not, and 30 mph where down grades exceeding 4% or strong winds are present (AASHTO 1999). In testing gap lengths in rumble strips, bicyclists attempted to navigate the gaps in a gap pattern with an average of 25 mph, but speeds ranged up to 31 mph. All skill levels of bicyclists were able to navigate both a 10 and 12 ft gap, but the bicyclists felt that the 10 ft gap would be "too tight" for "real world" applications (Moeur 2000).

A 12 ft gap pattern allows for a vehicle to leave the roadway with up to a 4.7° departure angle and still have the full right tire hit a 12 in. wide rumble strip. Moeur (2000) found a study stating that the typical departure angle for a ROR crash is 3°, but other research contradicts this finding. A 1986 study found only 17% of rural arterial ROR crash impacts occur at 5° or less (Mak 1986). While the impact angle may be different than the departure angle, it is reasonable to assume that they would be approximately similar. It may also be appropriate to assume vehicles leaving the roadway at higher angles are doing so to avoid another vehicle or because of ice or edge drop-off, not necessarily because of fatigue or distraction.

Establishing a regular pattern for the rumble strip gaps will allow bicyclists to easily find a gap when necessary. For the 12 ft gap pattern, a 40 ft and 60 ft cycle were considered acceptable. The 40 ft cycle would consist of 28 ft of rumble strips followed by a 12 ft gap, and so on. The 60 ft cycle would likewise consist of 48 ft of rumble strips followed by a 12 ft gap, and so on. The 40 ft cycle allows for 70% coverage of rumble strips and the 60 ft pattern provides 80% coverage. Both patterns provide a sufficient frequency of gaps for bicyclists to depart the shoulder in advance of hazards and intersections (Moeur 2000).

# 2. DESCRIPTION OF PROJECT

## 2.1 Project Scope

The value of paved shoulders has been acknowledged for many years by transportation agencies and road users alike. Improved safety and convenience as well as reduced routine maintenance costs are all common benefits attributed to paved shoulders. In 2004, Iowa adopted a paved shoulder policy for higher volume roads, but a broad diversity of paved shoulder types has been utilized for many years in the state. Since the benefits of paved shoulders have not been quantified, the Iowa DOT requested a study to analyze the safety performance of various paved shoulder designs on a wide spectrum of traffic and roadway types.

Although several types and designs of paved shoulders have been constructed by contract and installed by agency maintenance staff for many years, an extensive analytical analysis of safety benefits has not been undertaken. Many design and maintenance decisions regarding paved shoulders must rely on subjective data and intuitive judgment. As a result, there is a need to quantify the safety impacts of paved shoulders so that agencies can make better decisions on the costs and benefits of improvements.

In order to address this need, this research evaluated the effectiveness of paved shoulders in reducing the number of crashes. This study evaluated all non-Interstate roadway types in Iowa where paved shoulders have been installed. The study collected data over a large number of segments where paved shoulders have been installed and along control sections. A crash analysis was conducted as described in Sections 3 and 4. A survey was also conducted to assess the opinion of field maintenance personnel and law enforcement personnel as to their experience with paved shoulders.

## 2.2 Iowa Department of Transportation Current Practices

The Iowa DOT Design Manual suggests that 4 ft paved shoulders be included in all National Highway System (NHS) projects. Non-NHS projects should also include paved shoulders if the current year ADT is 3,000 or more. The manual's suggestions are as follows:

> For non-NHS highways with a current year ADT of less than 3,000, a combination of other factors such as those listed below needs to be considered to determine if paved shoulders are appropriate:
>
> - Design year ADT: even if current year ADT doesn't warrant paved shoulders, design year ADT may be high enough that the designer should consider paved shoulders.
> - Run-off-the-road crash rate: paved shoulders should be considered for segments of roadway that exhibit a high run-off-the-road crash rate.
> - Horizontal and vertical alignment: paved shoulders should be considered for segments of roadway with a high number of horizontal curves—paved shoulders can reduce problems associated with off-tracking. Segments of road with steep

grades should also receive consideration for paved shoulders, as storm runoff can cause erosion of shoulder rock on steep grades.

- High truck volumes: segments of roadway that carry high truck volumes may be candidates for paved shoulders.
- Maintenance issues: paved shoulders should also be considered for segments of roadway that experience continuing problems with edge rut.
- Shoulder width continuity: continuity of paved shoulder width is desirable along segments of a corridor.
- Rumble strips: rumble strips are normally not placed on paved shoulders less than 4 ft wide.
- Multiple widening units: consider how many times the pavement has been or may be widened. Multiple narrow widening units are undesirable—they can create an uneven surface and lead to additional maintenance. Paved shoulders may be more appropriate.
- Cost differential: the cost for 4 ft paved shoulders is only slightly more than for pavement widening. The safety benefits of paved shoulders may outweigh the extra cost.
- Bicycle accommodation: if bicycle accommodation is warranted, minimum 4 ft shoulders are recommended. (Design Manual)

Wider shoulders may be appropriate if paved shoulders are warranted for bicycle accommodation. The Office of Systems Planning should be consulted for guidance in this decision. For example, if a state highway is within a statewide trail corridor, 6 ft paved shoulders may be recommended (Design Manual).

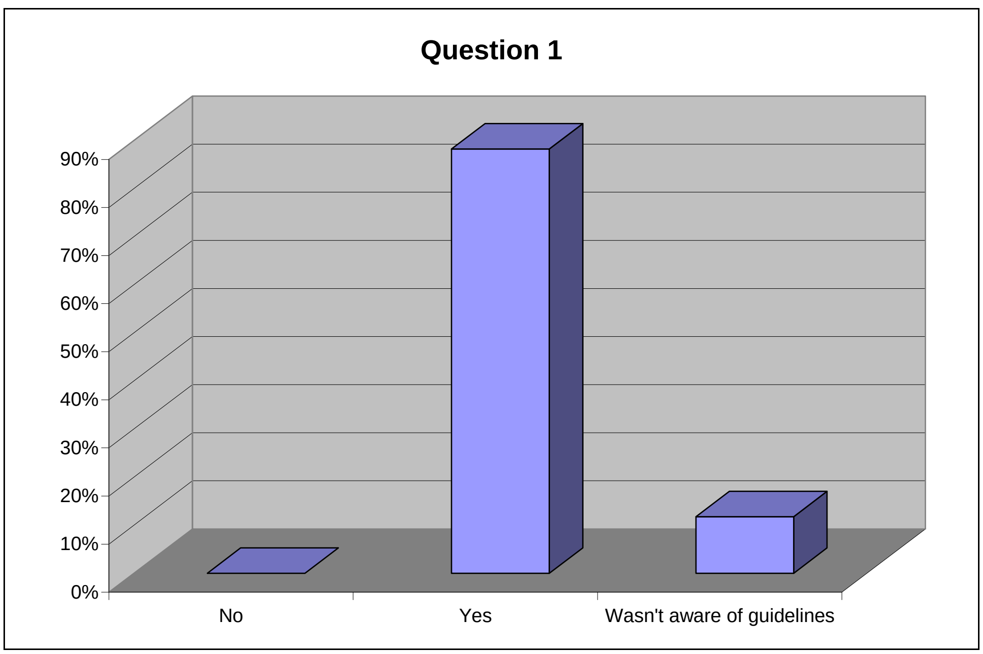
## 3. SURVEY OF EXPERT OPINION FIELD MAINTENANCE AND LAW ENFORCEMENT

A survey was conducted to assess the opinion of field maintenance personnel and law enforcement personnel and to obtain expert opinion about the effectiveness of paved shoulders. Another survey was sent to law enforcement personnel to assess their subjective opinions about how effective paved shoulders are in reducing crashes. The results of both surveys are provided in the following sections.

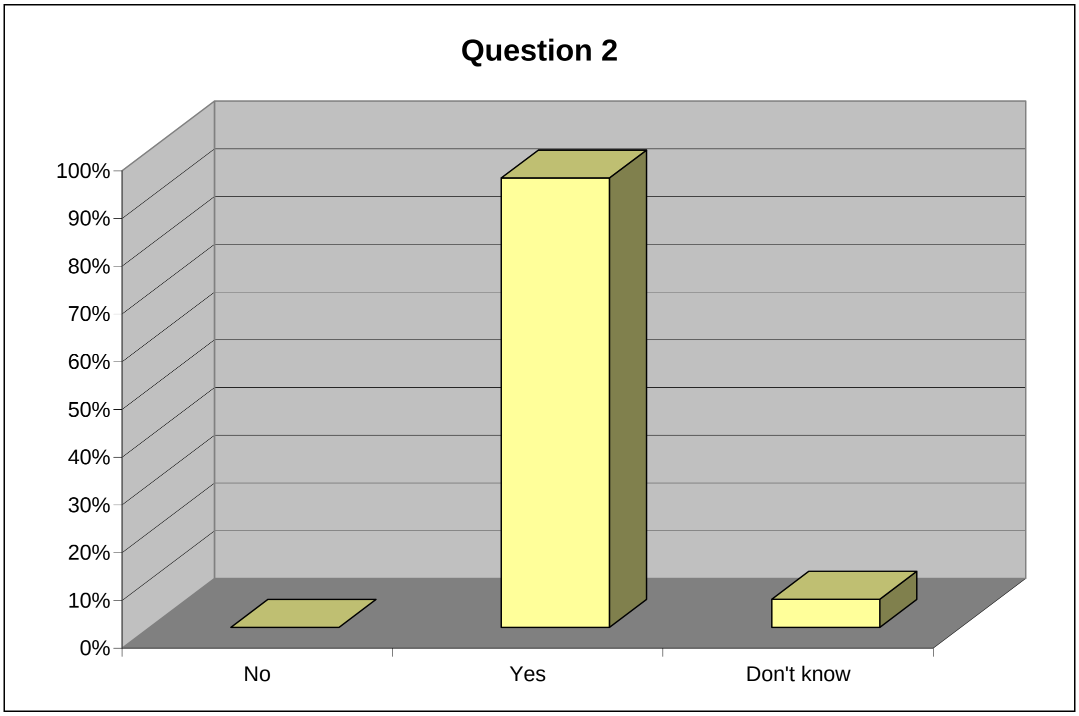
### 3.1 Survey of Field Maintenance Personnel

A survey about the effectiveness of paved shoulders related to maintenance was sent to all six Iowa DOT districts. It was beyond the scope of this project to evaluate the improvement in pavement performance due to the adding of paved shoulders. However, the survey provides a subjective measure of how paved shoulders might improve maintenance based on the expert opinions of maintenance personnel. Seventeen people from the six districts responded to the following questions. Responses to the questions are also shown.

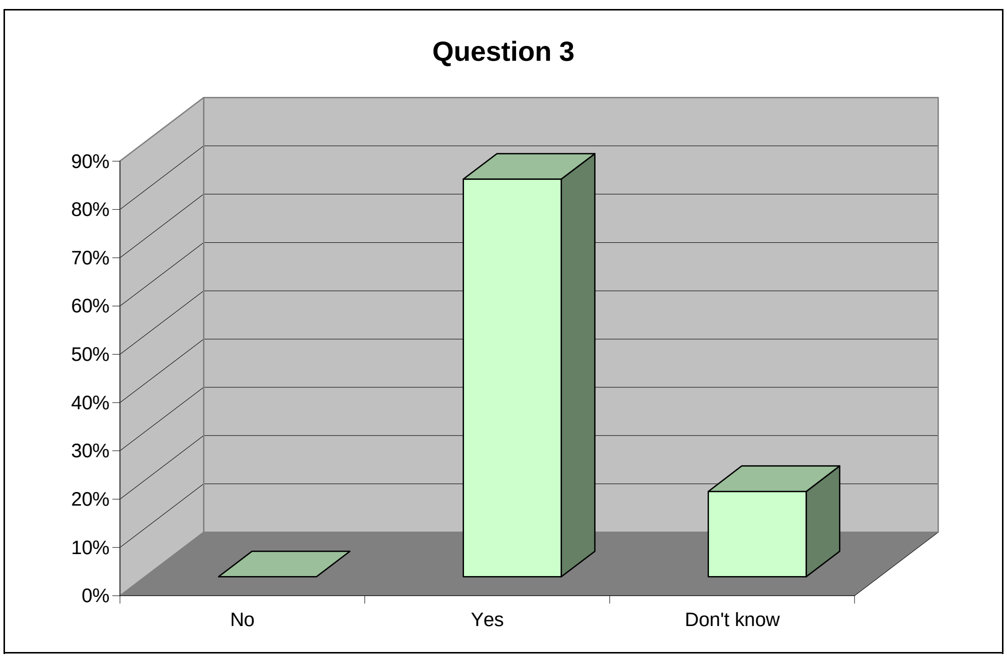
(1) Approximately three years ago, the Iowa DOT adopted paved shoulder guidelines for new and rehabilitated roads in Iowa. Do you approve of these guidelines?



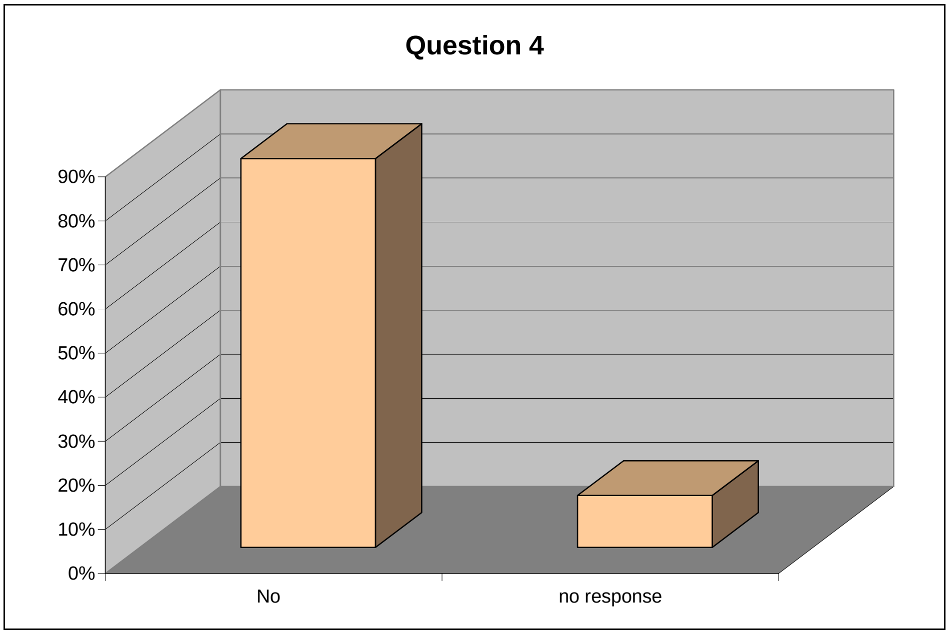

(2) Do you think paved shoulders reduce the hours required to maintain shoulders and perform edge rut repair, allowing more time to be spent on other priority activities?



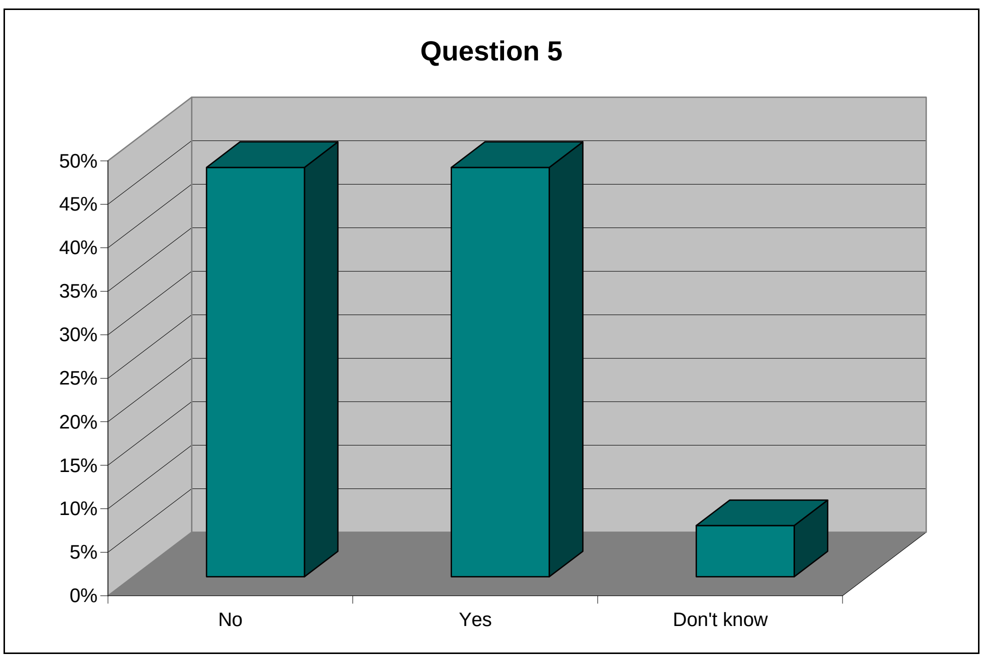

(3) Do you think paved shoulders reduce the cost of shoulder maintenance?



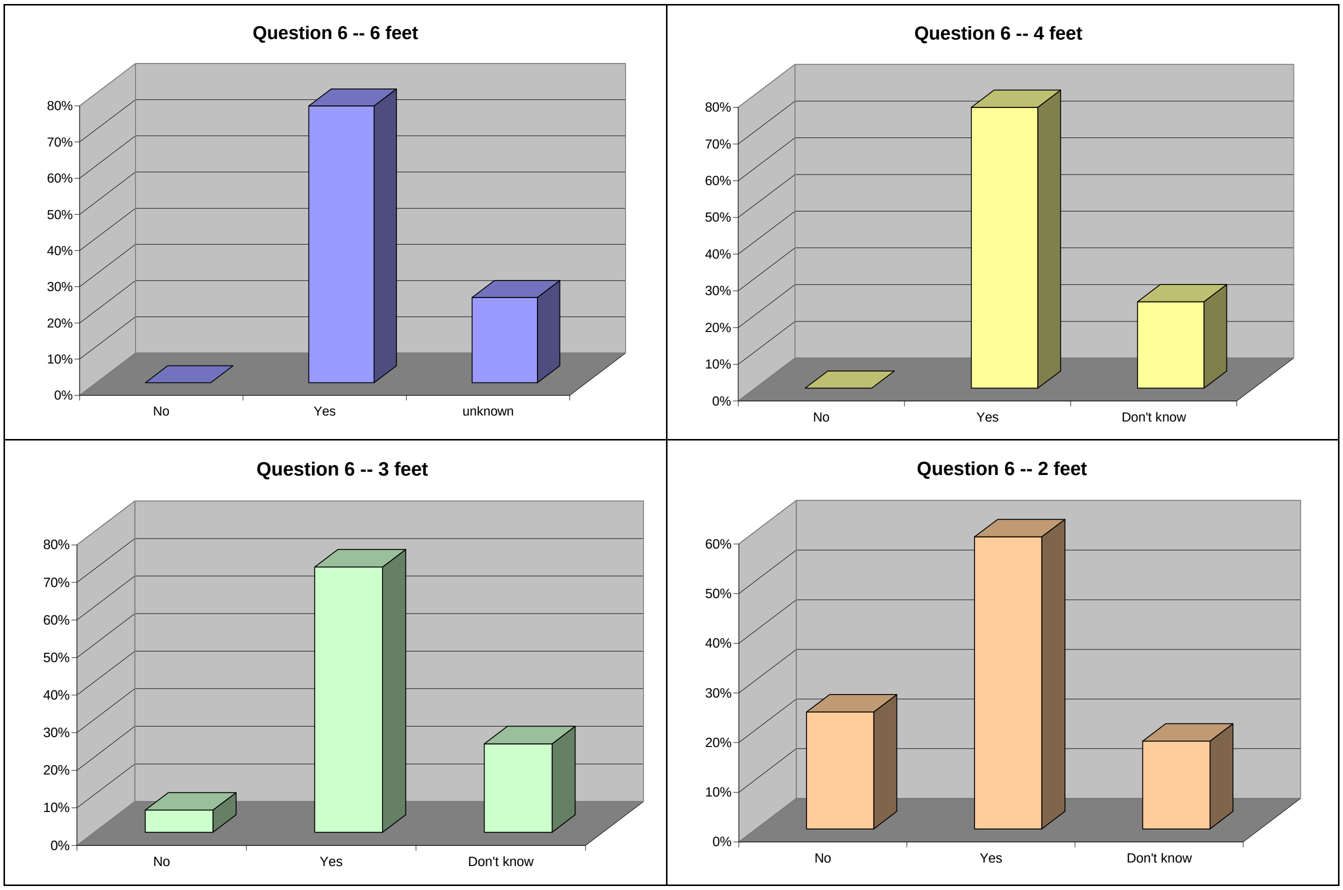

(4) If you answered yes to #3, do you have any documentation or records of reduced costs?



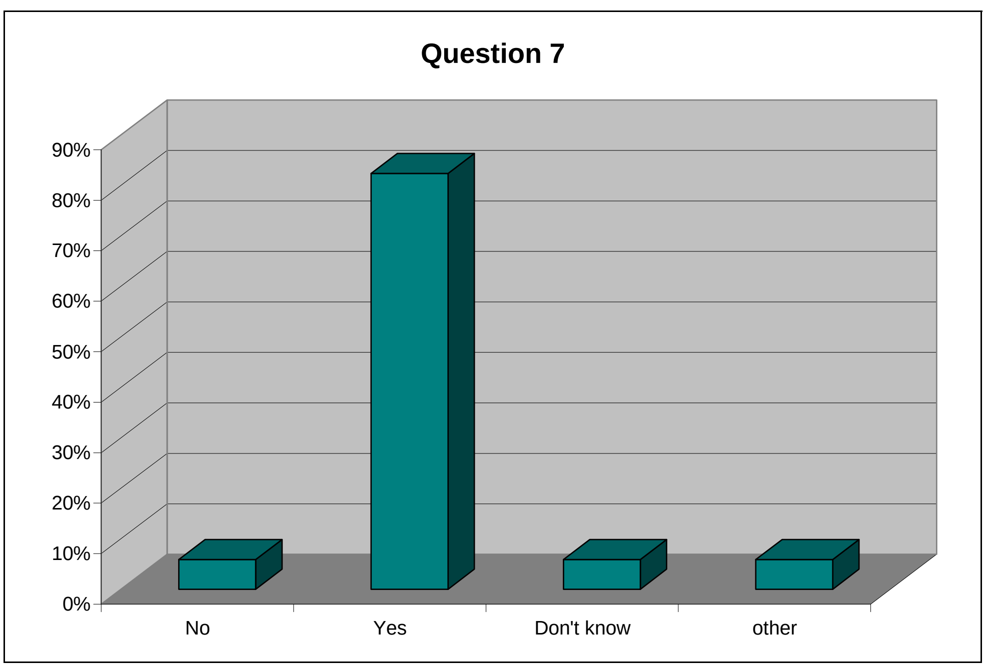

(5) Have you received any response from the public about paved shoulders?



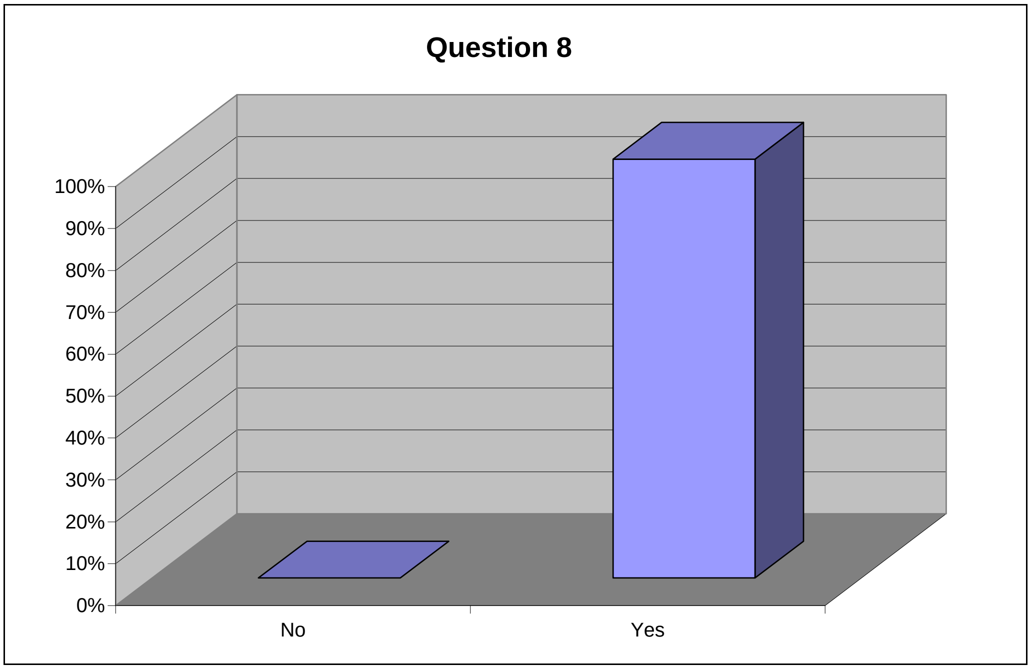

(6) Several widths of paved shoulders are used in Iowa. Is there a difference in reduced maintenance for these various widths?



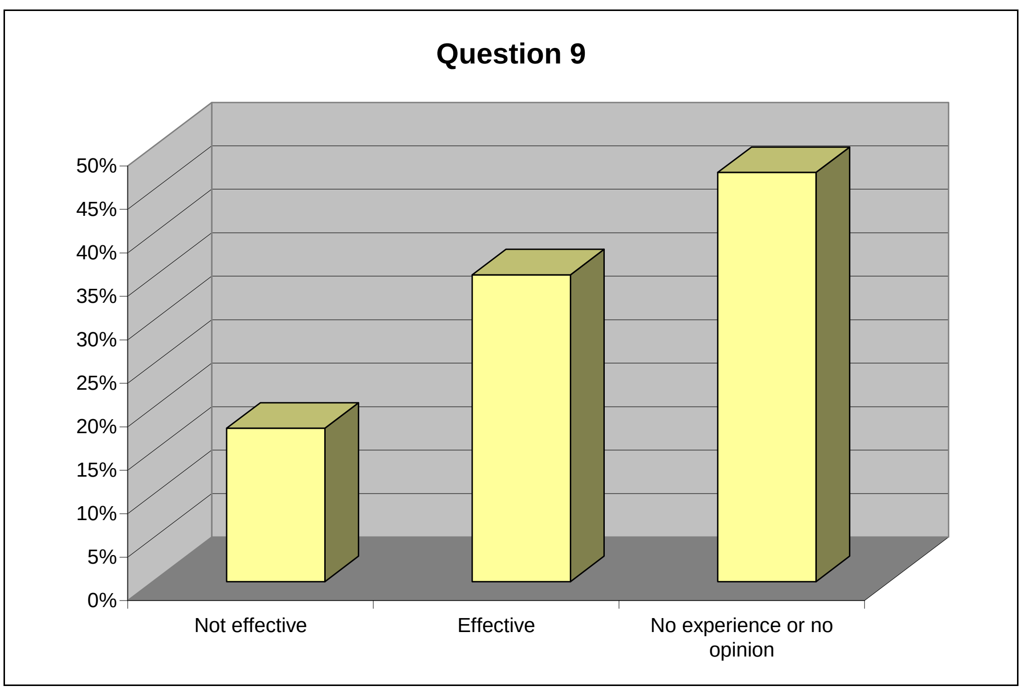

(7) Do you think rumble strips add to the effectiveness of paved shoulders?



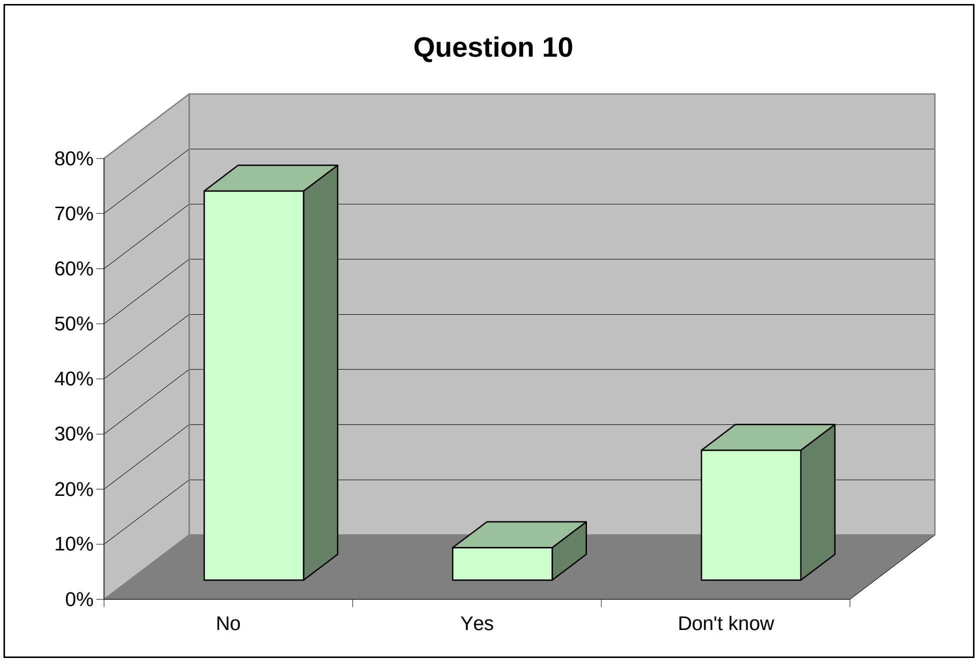
(8) Do you think edge rut paving placed by DOT maintenance is effective in reducing edge rutting and needed maintenance?




(9) Some districts have moved the painted edge line in about 1 ft instead of placing narrow paved shoulders. What do you think of this practice in terms of reduced edge rut maintenance?



(10) Have you or your crews experienced any close calls where paved shoulders proved beneficial in avoiding an accident?



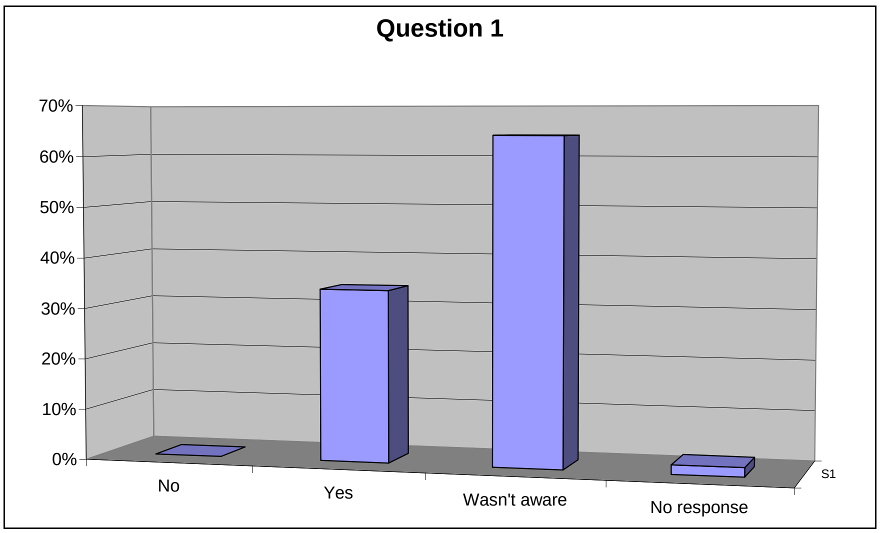

Comments received include the following:

- "We tried several years ago to prove the benefit of paving shoulders full or partial width on discrete roadways. Basically management was not receptive to this, but in all fairness it is also difficult to assess the benefit to us (maintenance forces)."
- "District *"X"* has three supervisors with lane miles where the edge lines were moved in and all three state that this improved the edge rutting problem and [was] an effective way to reduce costs."
- "People believe the shoulder is the rock portion, and so unless [it is] full width they move right until they are off the pavement. This can cause additional maintenance for repair and fixing of the outside shoulder edge."
- "The wider roads with the inset edge line and rumble strips make for nice driving and appear to be a possible remedy to a lot of our immediate edge rut issues. I would sure like the opportunity to try these on some of my routes."
- "Paved shoulders should be a minimum of three feet. The paved shoulders reduce the time we have to blade in edge ruts. Also, paved shoulders are a safety factor in reducing the edge ruts, and with rumble strips it helps motorists in driving."
- "The cost associated with edge rut maintenance is difficult to determine because: (1) stone (material) cost is charged out when receipted for, i.e., we do not record the amount of material actually used, and (2) we should be able to determine labor and equipment."
- "Bituminous shoulders seem to have higher costs associated with them than do PCC shoulders, but that is certainly because of the thickness and mix design originally used."

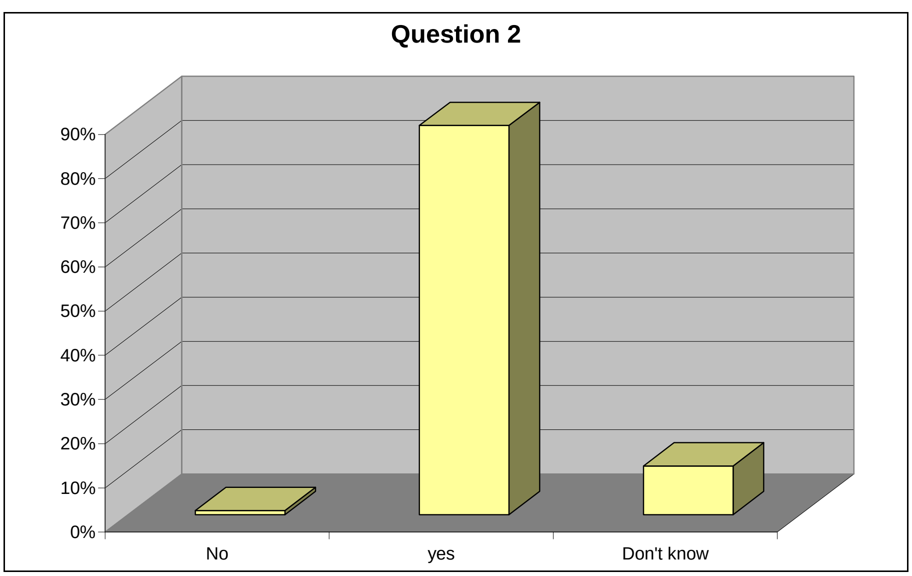
### 3.2 Survey of Law Enforcement

Law enforcement personnel have first-hand experience visiting crash scenes. It was felt that they may have expert opinions about whether the use of paved shoulders has resulted in fewer or less severe crashes. A survey was sent to a number of law enforcement personnel to seek their opinions using the questions provided below. A total of 109 officers responded. Results for each question are summarized following each question.

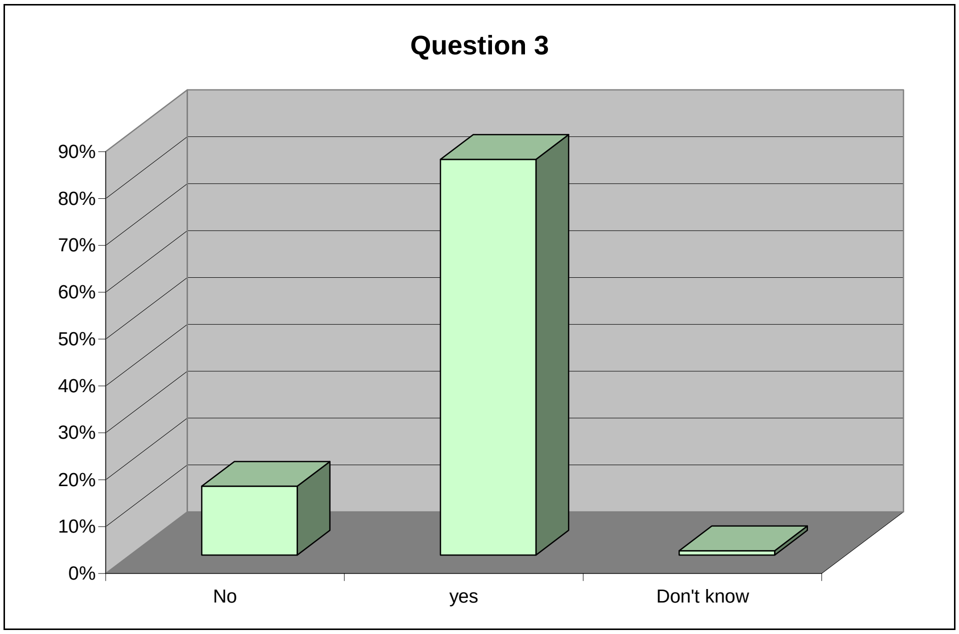
(1) Approximately three years ago, the Iowa DOT adopted paved shoulder guidelines for new and rehabilitated roads in Iowa. Do you approve of these guidelines?



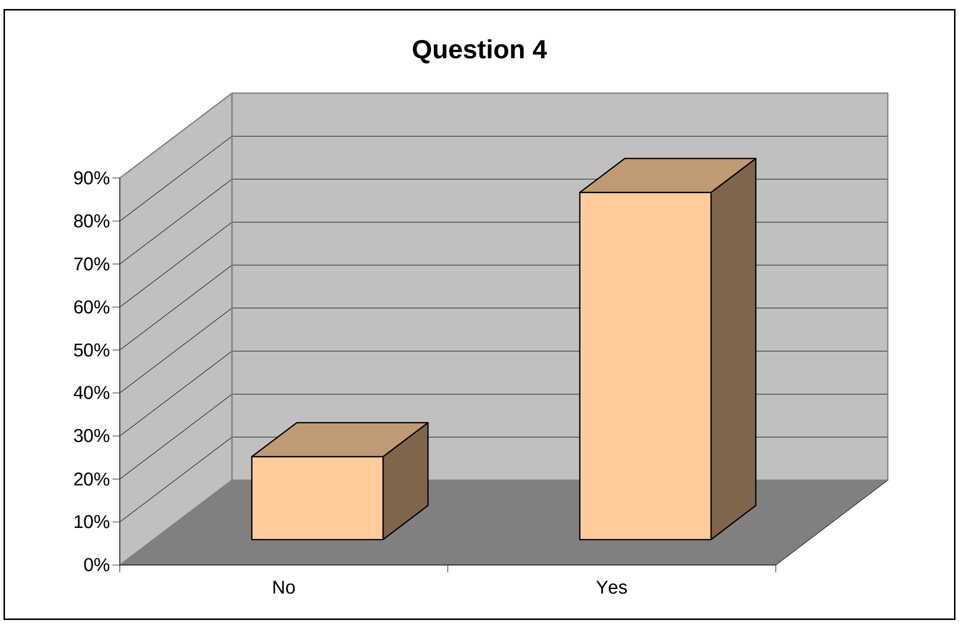

(2) Do you think paved shoulders reduce the incidence of run-off-road crashes and improve safety on Iowa's highways?



(3) Have you investigated crashes where edge drop off possibly contributed to the loss of control of the vehicle?




(4) Does the presence of paved shoulders have any effect on law enforcement?



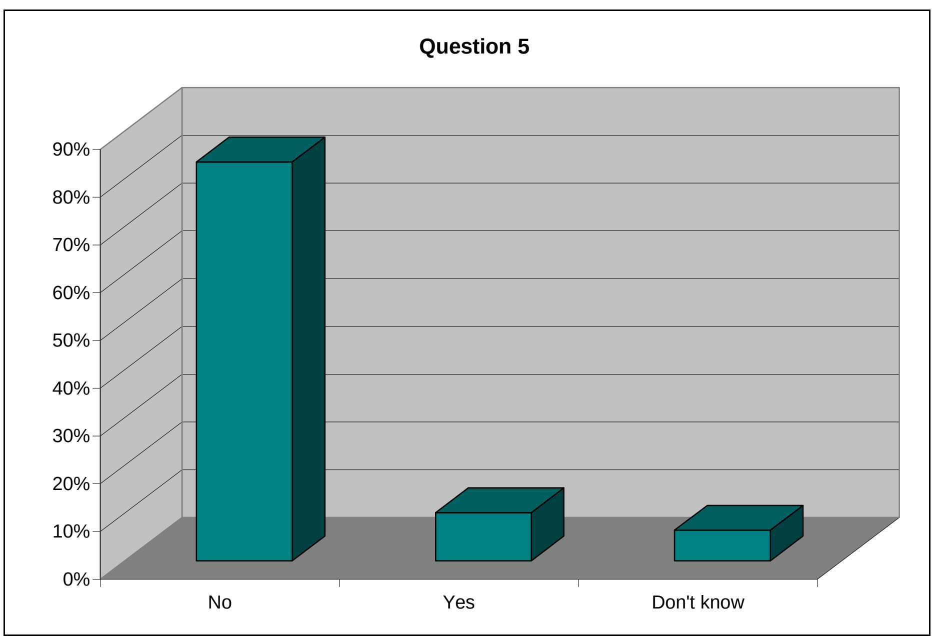

The following are specific responses as to why the respondents to Question 4 felt the paved shoulders had an effect:

- “Provides good location for violator stops”
- “Easier to do traffic stops in bad weather”
- “Safety for everyone”

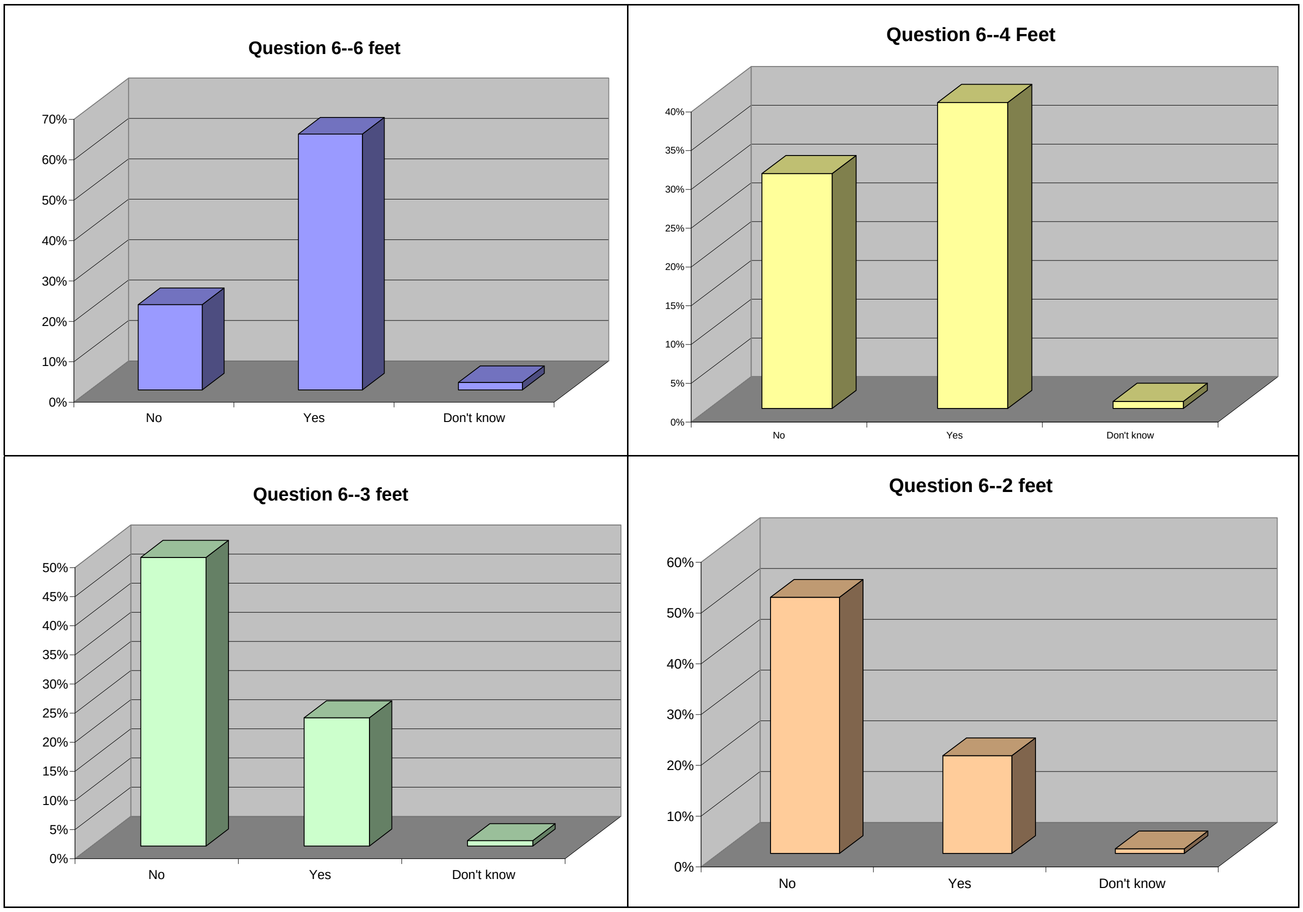
- “May invite passing on the right/shoulder”
- “Allows motorists to pull over on a paved surface when an emergency vehicle running code comes up behind them. Also provides a more stable platform for conducting traffic stops”
- “Should save on accidents of question #3”
- “Officer safety during stops or assisting motorists”
- “If the shoulders are gravel and wet, driving onto them could cause the patrol car and violator may get stuck. With paved shoulders there is a less likely chance of getting stuck.”
- “They are more safe to patrol and there is a better surface to perform standard field sobriety testing (OWI tests) on.”
- “Creates a better environment for officer safety”
- “We use them for turning and abandoned vehicles.”
- “Give more room and better footing when doing approach to traffic stops”
- “Makes turning around safer and allows violators to exit and/or re-enter traffic easier.”
- “I believe it is safer pulling cars over on paved shoulders and is much safer while conducting OWI investigations.”
- “Cleaner cars, safer OWI sobriety tests”
- “Giving people a place to pull off roadway if vehicle breaks down is a good idea.”
- “Safer for traffic stops and would think possibly help prevent accidents”
- “Provides for more safety during traffic stops”
- “Safer turn-around to pursue violators. Safer area for traffic stops and stalled motorists”
- “Not aware of any paved shoulders in Tama County”
- “Safety with vehicles stopped”
- “Reduce overcorrecting accidents”
- “Allows easier turn-around maneuvers to stop violators”
- “Helps with controlled braking when trying to get on shoulder quickly”
- “Paved shoulders present more available roadway to make safe vehicle stops, leaving the traveled portion open to the motoring public.”
- “Safer for traffic stops”
- “Easier to do roadside sobriety tests”
- “Provided the shoulders are wide enough, it allows us to sit at roadside and run radar and maintain traffic.”
- “It provides a safer place for motorists to pull over out of the way of emergency vehicles.”
- “A good surface to conduct OWI SFST’s/vehicle weight”
- “We have one section in town where, because of the fog line, persons think there's an additional traffic lane.”
- “Easier turnarounds, safer environment”
- “Makes traffic stops and motorist assists easier and safer”
- “Safer environment to pull cars over and for disabled vehicles”
- “Safety of officers during traffic stops”

- "Makes it easier to jack-up a car for flat tires, helps in making turnaround to chase violators, stranded motorist, list could go on with more room."
- "Wider turn around, better footing, etc."
- "Less accidents"
- "Makes for easier pull overs on stops"
- "Presumably fewer drop off/loss of controls"
- "Better shoulders make it easier to turn around."
- "Extra measure of traffic safety for public as ourselves"
- "Less crashes—wider shoulders are safer for traffic enforcement."
- "Provides a safe pull off point for traffic stops or 10-50 investigations"
- "Safer and easier to work traffic enforcement"
- "Allows drivers to make mistakes by going off the road. Soft shoulders wouldn't be as forgiving."
- "Safer place to pull vehicles over—possibly reduce accidents"
- "Continuous turning around on shoulder and the safety of standing on and working on a hard shoulder"
- "Safe place to pull over vehicles"
- "Hopefully decreases accidents—safer environment for traffic stops"
- "Safer roadways—less accidents"
- "When there are problems it is easier to have more shoulder room, it also makes it safer in the winter."
- "Safer environment to work from"

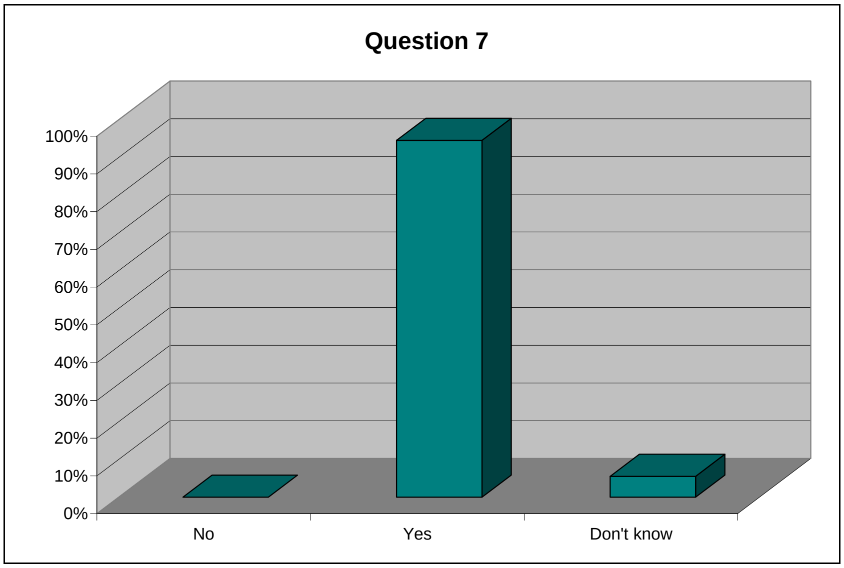
(5) Have you received any response from the public about paved shoulders?



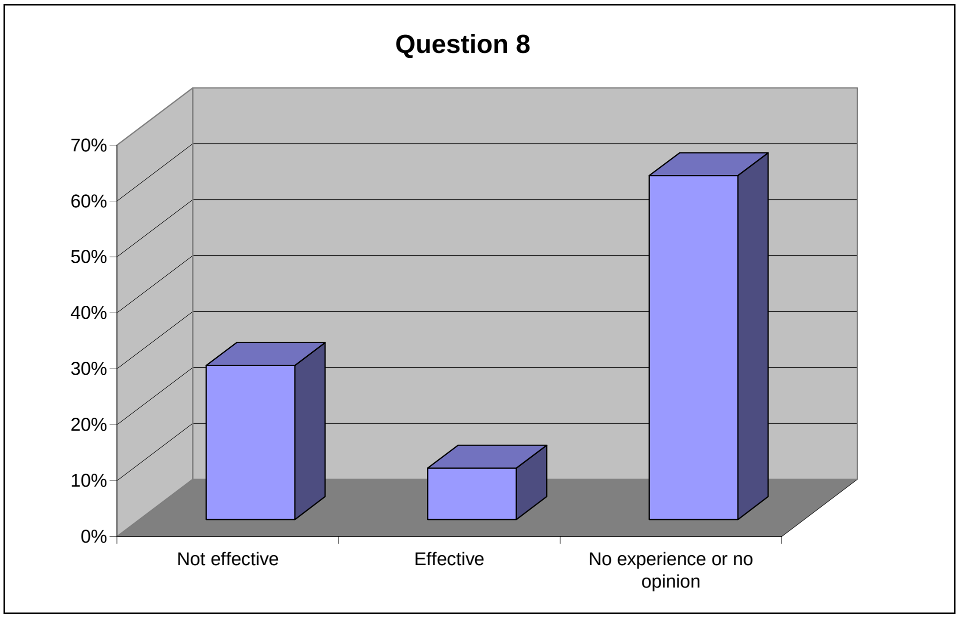
(6) Several widths of paved shoulders are used in Iowa. Is there a difference for law enforcement activities from these various widths?



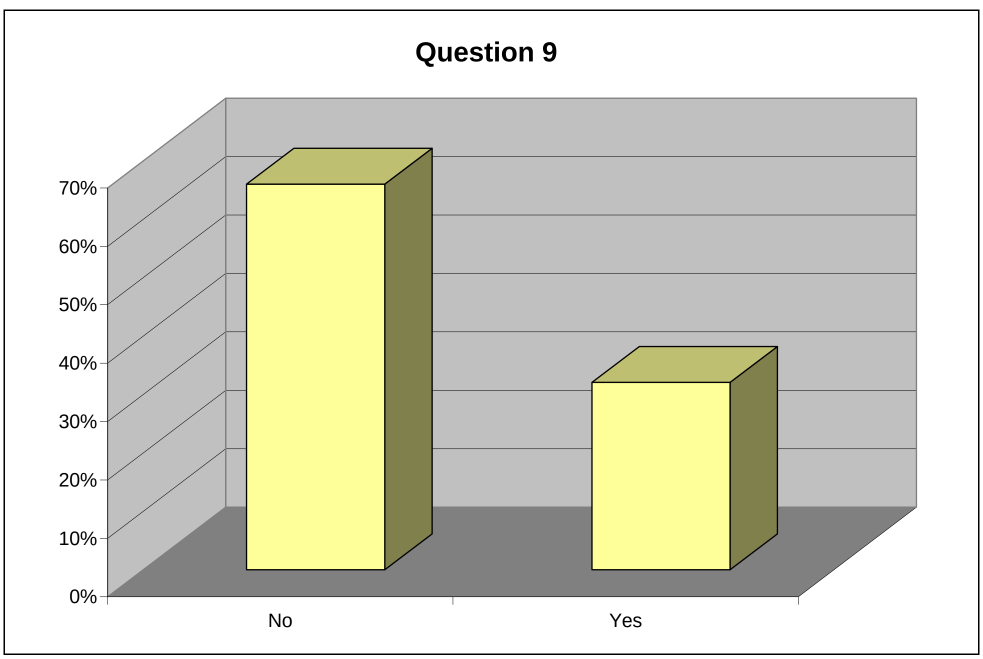

(7) Do you think rumble strips add to the effectiveness of paved shoulders?



(8) In some Iowa DOT districts, painted edge lines have been moved in about 1 ft instead of placing narrow paved shoulders. What do you think of this practice in terms of reducing run-off-road crashes?




(9) Have you experienced any close calls where paved shoulders proved beneficial in avoiding a crash or personal injury?



# 4. DATA COLLECTION

The main objective of this project was to conduct a before and after crash analysis for locations where paved shoulders have been included in maintenance or resurfacing, restoration, and rehabilitation (3R) projects. A total of 277 segments of road data were collected as described in the following sections. Data were collected in 82 counties. Data were collected for segments that had paved shoulders and for a smaller group of similar roadways that did not have paved shoulders, which were used as control sections for the statistical analysis.

## 4.1 Identification of Potential Locations

Engineers from each district in Iowa were contacted in an effort to identify sections of paved shoulders within the State of Iowa. The information received from the engineers was combined with a list of recent 3R projects from fiscal year 2000 through fiscal year 2006 that was obtained from the Iowa DOT. Sections listed as widening projects or those listed as receiving a paved shoulder in the description were selected as potential sites.

In addition to the information received from the Iowa DOT, any locations that the team or the Iowa DOT project monitor were aware of or any locations encountered during site visits were also included. A paved shoulder was defined as a shoulder that had at least 1 ft of paved material beyond the painted edge line. This definition was to distinguish a location with intentional paving from a location where the edge line inadvertently varied as it was laid.

## 4.2 Data Collection

Once the list of potential locations was compiled, each site was visited and roadway data were collected. Data were usually collected in at least two locations to ensure uniformity of the section. Typically, data were collected at a spot one or two miles after the paved shoulder section began and then was collected approximately every two to four miles thereafter. Frequency of data collection depended on the confidence of the data collector in the uniformity of that section.

Beginning and ending points of roadway sections were determined by profile and construction year uniformity. Clearly, a segment began and ended when a paved shoulder started or stopped. In addition to this criterion, however, differences were looked for along the roadway to ensure construction year uniformity. If a segment changed pavement type, then the segment ended not only because of the difference in pavement, but because the sections were most likely constructed in different years. Obvious changes in pavement color or construction techniques, such as rumble strip type or presence, were also cause for a segment to end for construction year uniformity. Finally, speed limit changes and segment length were reason to end a section. Once a section reached about 12 miles in length, it was ended to maintain some uniformity in the section lengths being studied. Additionally, after data were collected, several sections were split into smaller sections if annual average daily traffic (AADT) varied significantly along the section.

The following information was recorded at each location where data were collected using a data collection form:

- Speed limit
- Orientation (i.e., N/S)
- Pavement type
- Shoulder type
- Shoulder pavement type
- Unpaved shoulder type
- Rumble strip type
- Rumble strip location
- Total paved width
- Paved shoulder width
- Unpaved shoulder width
- Presence of paved driveway entrances or widening on curves
- Anything unusual about roadway

Date, county, and a detailed literal description of the segment of roadway were noted at each location. The location of each "sample" of data within a segment was also noted. The roadway segment, including locations of each individual data collection location, was also marked on a detailed map of Iowa at the time of data collection. This was done to ensure the correct location was found later when identifying locations in GIMS files. Finally, a picture was taken at each data collection location for reference if there was any question about what was collected. A description of how each characteristic was collected is provided in the following sections.

*4.2.1 Speed Limit*

When speed limits were not posted, a speed limit of 55 mph was assumed (2007 Iowa Code §321.285) (Iowa 2006–2007).

*4.2.2 Orientation*

North/south and east/west orientations were collected on a spot by spot basis. If a roadway segment was oriented predominantly north/south but a sample was collected on an east/west portion, then the portion was collected as east/west with a note that the overall segment is north/south. For segments that were aligned diagonally, the general orientation of that highway as a whole was looked at or judgment was used to determine which orientation to mark.

*4.2.3 Pavement Type and Shoulder Pavement Type*

Asphalt and concrete pavement types were collected for this project. No bituminous seal coat or other types of pavements were collected.

*4.2.4 Unpaved Shoulder Type*

The unpaved portion of the shoulder was considered to be gravel, earth, or mixed. Gravel shoulders, shown in Figure 4.1 were those that still clearly had some gravel cover. Earth shoulders, shown in Figure 4.2, were either dirt shoulders or grass shoulders. Finally, mixed shoulders (Figure 4.3) were shoulders with some gravel cover but also some grass growing through or a significant amount of dirt showing. The mixed category was only used when neither of the other categories seemed to apply.

**Figure 4.1. Typical gravel unpaved shoulder type**

**Figure 4.2. Typical earth unpaved shoulder type**

**Figure 4.3. Typical mixed unpaved shoulder type**

*4.2.5 Shoulder Type*

A roadway segment was marked as having a fully paved shoulder if the paved shoulder width was approximately 6 ft or greater, as shown in Figure 4.4. Any road with between 1 and 6 ft of paved shoulder was considered as having a partially paved shoulder. An example of a partially paved shoulder is shown in Figure 4.5. Any amount of pavement less than 1 ft beyond the painted edge line was considered unpaved, shown in Figure 4.6.

**Figure 4.4. Two-lane highway with fully paved shoulders**

**Figure 4.5. Two-lane highway with partially paved shoulders**

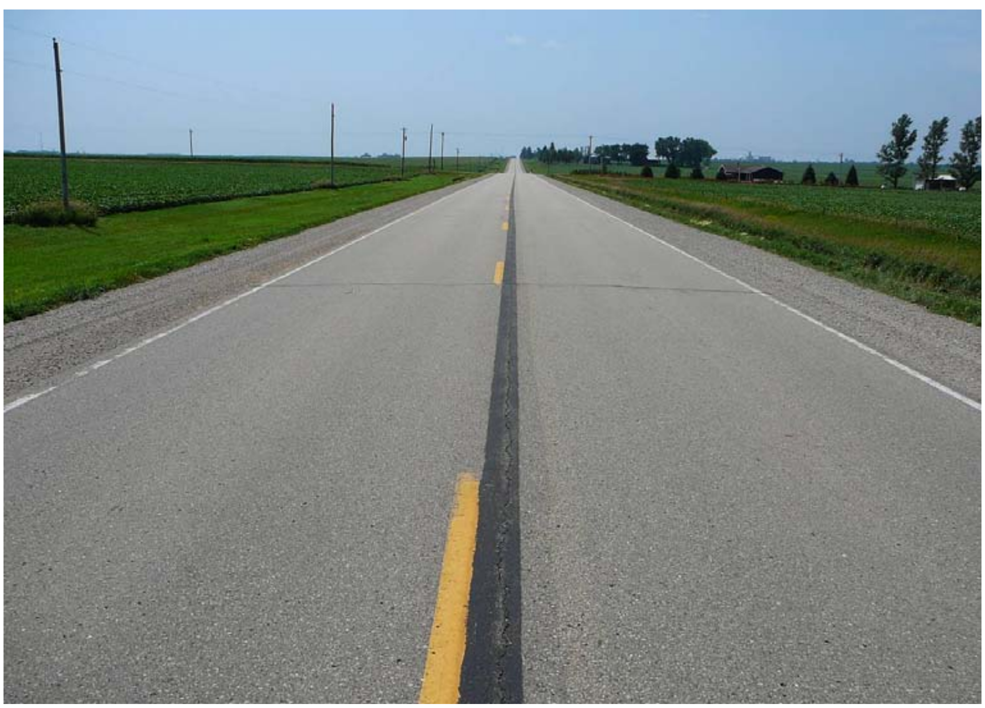


**Figure 4.6. Two-lane highway with unpaved shoulders**

*4.2.6 Rumble Strip Type*

When present, rumble strips were categorized as rolled, milled, or formed. Rolled rumble strips are found on asphalt roadways, and formed rumble strips are their concrete roadway counterpart. Rolled rumble strips are not as common, however, as they are generally considered less effective than milled rumble strips in asphalt. Images of rolled, milled, and formed rumble strips are provided in Figures 4.7 to 4.9.

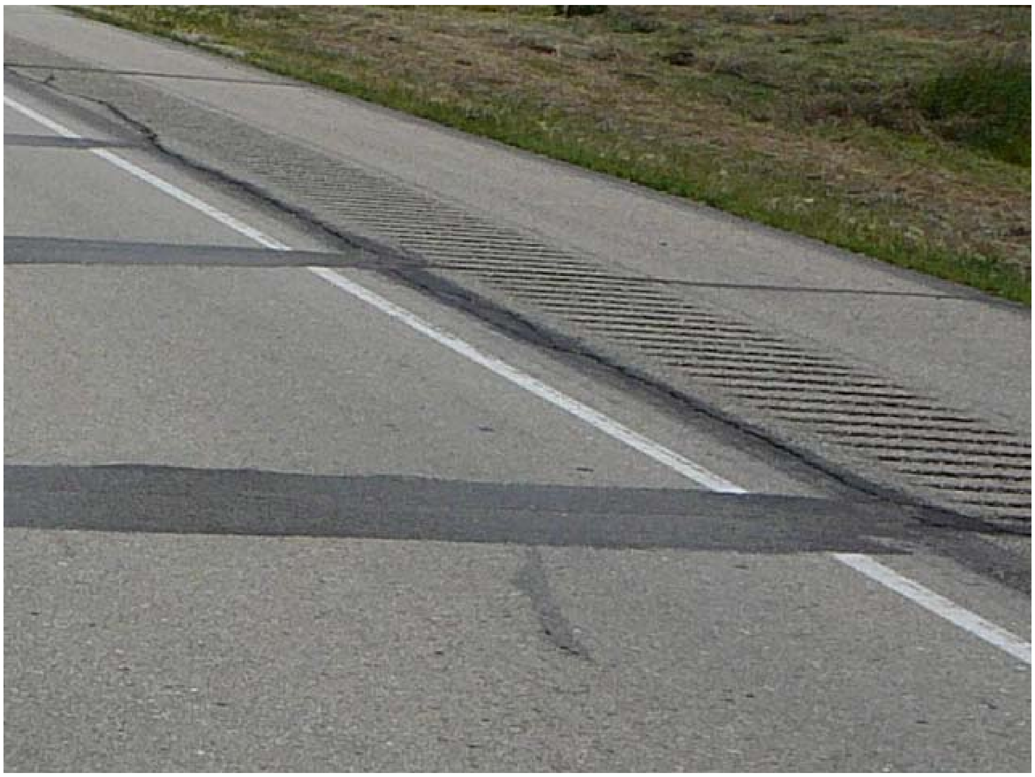


**Figure 4.7. Rolled rumble strips**

**Figure 4.8. Milled rumble strips**

**Figure 4.9. Formed rumble strips**

*4.2.7 Rumble Strip Location*

Rumble strips were recorded at the edge of the paved lane, at the edge of the paved shoulder, or at some distance from the edge of the paved shoulder. Edge line rumble strips were recorded at the edge of the paved lane.

*4.2.8 Total Paved Width*

Total paved width was measured from the edge of the pavement to the edge of the pavement, regardless of the presence of paved shoulders. Paved shoulder width was also measured, and lane width was determined by subtracting paved shoulder width from total width and dividing by two. A measuring wheel or tape measure was used to make the measurements.

*4.2.9 Paved Shoulder Width*

The paved shoulder width was measured from the edge of the pavement to the outside edge of the painted edge line. In the absence of a painted edge line, measurement was made from the outside edge of the pavement to the transition of the shoulder pavement type to the mainline pavement type. However, the absence of a painted edge line was rarely, if ever, an issue. This measurement was made with a tape measure.

*4.2.10 Unpaved Shoulder Width*

The distance from the break in grade to the edge of the pavement was considered the unpaved shoulder width. This measurement was also made with a tape measure. It is often difficult to determine where the break in grade occurs, as it may have rounded off over the years due to erosion. When this was the case, judgment was used to look up and down the highway to determine the best possible point to declare as the break in grade. This was potentially the source of the variation in unpaved shoulder width experienced on some roadway segments.

*4.2.11 Presence of Driveway Entrances or Widening on Curves*

It was noted as a yes or no if any paved driveway entrances were present along the segment of roadway. It was also noted as a yes or no if any curves along the section of road experienced any widening. Some roadways have an additional 1 or 2 ft of paved shoulder on the inside and/or outside edge of curves. This is done to help keep cars on the pavement and to prevent edge rutting that commonly occurs on curves.

*4.2.12 Anything Unusual about Roadway*

Any other types of random widenings or noteworthy unusual characteristics of the roadway were described under this category. The most common entries here were the presence of single or multiple bridges and the presence and location of left- and/or right-turn lanes. Other things noted include, but are not limited to, the following: interchanges, guard rails if they were present for a significant length of time, unusually steep or shallow grades beyond the shoulder, whether the highway was access controlled, school zones, whether housing was present along part of the road, temporary pavement changes, temporary shoulder width changes, unusual signs that would affect driving habits, and anything else that could affect how people drive or the amount of shoulder-related crashes that occur.

### 4.3 Determination of Construction Year

Data for each section were entered into an Excel spreadsheet. The corresponding road segments were selected in the Iowa DOT GIMS database. GIMS segments corresponding to each collected section were coded with a unique ID ("Paved ID") using ArcView. Each section was double-checked against a map to ensure that they were located in the correct location in GIMS, and the database was updated as needed.

#### *4.3.1 Fiscal Year of Construction*

After the data were refined and accurately reflected their original collection location, the fiscal year in which paved shoulders were added during construction was determined. This step was essential for before and after analysis. It was not possible to locate specific calendar dates of construction; however, the fiscal year of construction was noted. Most construction in Iowa takes place during the summer months. This allows for sufficient time on either side of the probable construction time frame to ensure the construction period did not start before or continue past the officially listed fiscal year in which the road was constructed.

The fiscal years of construction were obtained from two main sources: the 3R files obtained from the Iowa DOT and the *2004 Test Sections by Milepost* book, also obtained from the Highway Division of the Iowa DOT. The 3R files consist of Microsoft Excel workbooks that contain six worksheets of data, one worksheet per district in Iowa. The worksheets list projects associated with that file, organized by county and by route number, that were constructed during the year, as well as projects that were scheduled for future years. The lists contain literal descriptions of project limits, project costs, whether or not the project was let that year, and a description of the work done. These files were the first choice for determining fiscal year of construction, but when segments were not found in these files, the *2004 Test Sections by Milepost* book was checked.

The *2004 Test Sections by Milepost* book contains a list of every project constructed on a state route since the routes' initial construction. The book is sorted by county, and projects are listed from milepost to milepost, with a map of each county showing the mileposts mentioned in the project listings. Next to the milepost boundaries are the directions of the roads for four-lane divided highways, the year of construction, the project number, and information about the pavement used for the project. This source was very effective for determining construction years on older projects, as well as any other project on a state route that was overlooked or not included in the 3R files.

Finally, the third source of information was county engineers. If a paved shoulder was collected on a non-state route, then county engineers were contacted via email. The county engineers were quick to respond with the information requested.

### *4.3.2 Length*

The length of each segment was obtained from the segments selected in the GIS database. The GIS lengths are stored in meters and converted to miles.

## 4.4 Data Preparation

A total of 256 treatment and control segments were collected. Data for each location were entered into a database and spatially located using the Iowa DOT's GIMS database.

Several locations were dropped from the analysis because they could not be located in the GIMS database or because the year paved shoulders were added could not be determined. Several locations had paved shoulders that were installed before the study period began in 1984. These sites were removed from the analysis because there was no before and after period. This resulted in a total of 220 sites analyzed, including 77 control sections and 143 test sections.

The location of sections collected is shown graphically in Figure 4.10. This map includes both paved shoulder sections and control sections.

A month was the time interval modeled. This unit allows the effect of time of year to be included, because it is expected that some seasonal pattern may be evident in lane departure crashes. Dr. Michael Pawlovitch of the Iowa DOT created code to extract crash and volume data by month, starting in January 1984 and ending in December 2007. Total crashes, cross centerline crashes, and single vehicle ROR crashes were extracted from the Iowa DOT crash database for each segment by month. Crashes that corresponded to each section were selected using a manual process in a GIS, ArcView. AADT was selected for each section for each year. When AADT varied along a section, a weighted average was calculated. Monthly volume was determined by multiplying AADT by the number of days for that month. AADT was obtained from archived snapshots of the Iowa DOT's GIMS database.

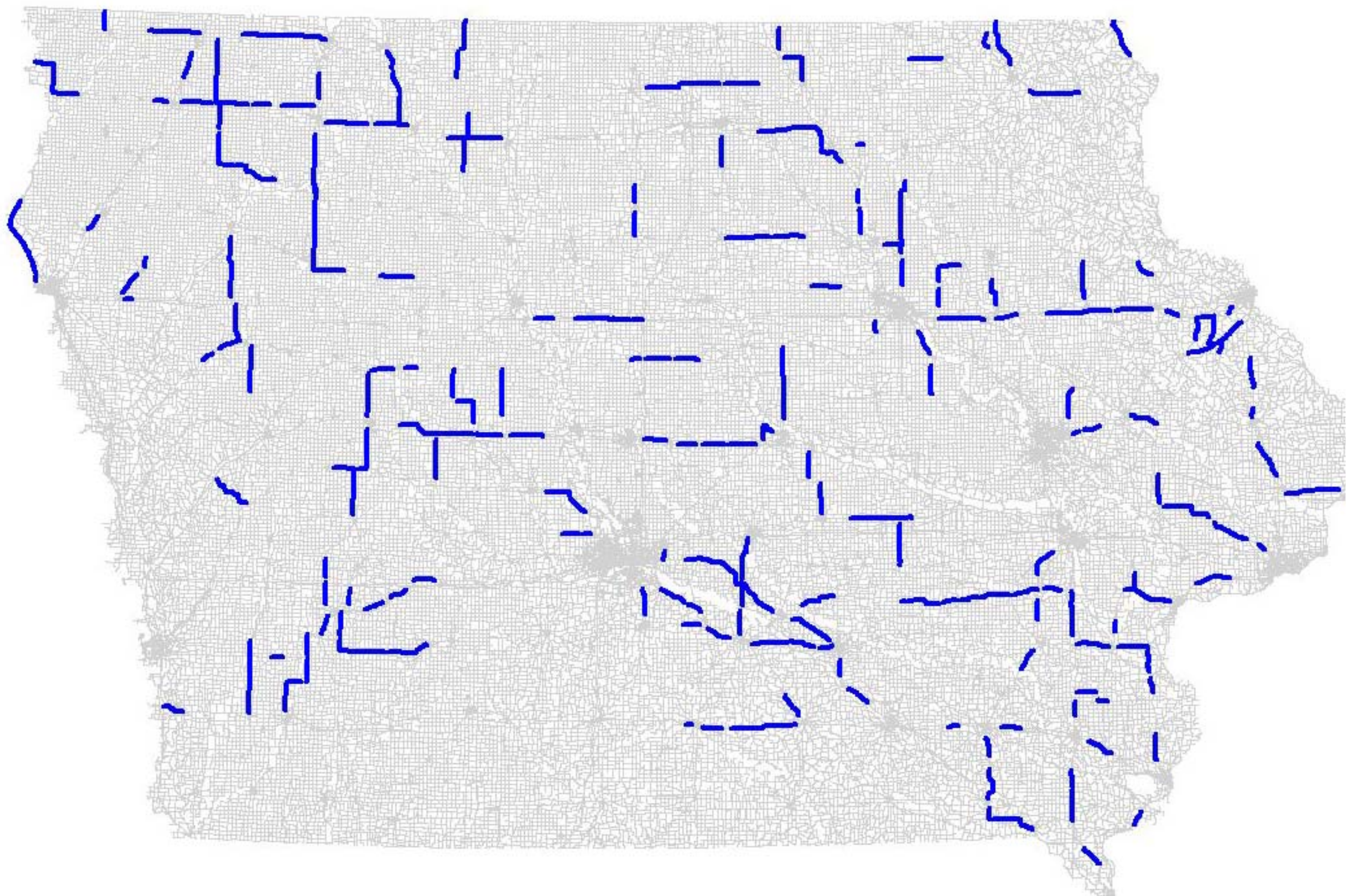


**Figure 4.10. Location of sections collected**

## 5. ANALYSIS

A generalized linear model (GLM) using a Poisson distribution with a log link function was used to investigate the relationship between crash reduction and implementation of paved shoulders. A link function is the function used in GLM to relate the mean response to the linear predictor (a linear combination of explanatory variables). In order to match the range of the predictor to that of the distribution function's mean, the concept "link function" is introduced. In our study, the canonical log link function for the Poisson distribution was chosen.

Since there may be an inherent change in crashes with time, the Poisson mean was modeled as a function of time. A set of smooth trigonometric functions with different periods were included to account for seasonal effects. It was assumed that the model on the log Poisson mean is piecewise linear, which means the slope and intercept may vary before and after the change point. Since traffic volumes are inconsistent and are assumed to have an impact on the total monthly crashes, they were taken into consideration in the analysis as offsets.

A random variable "site" was created to account for the correlation among observations made at the same site.

Site: denotes the random site effect and site ~ $N(0, \sigma^2)$

It is assumed that the number of monthly crashes y at a site is a Poisson random variable with mean $\mu=\lambda*\nu*l$ , in which $\lambda$ is the monthly crash rate, $\nu$ is the monthly traffic volume (MT), and l is the length of test road section. That is,

$$\begin{aligned} &y \sim Poisson(\mu) \\ &\mu = \lambda * \nu * l \end{aligned} \qquad (5\text{-}1)$$

The model was constructed as a rate model, in which the crash rate was modeled while still maintaining the count response (monthly crash total) for the Poisson model using the following:

$$\log \lambda = \log(\frac{\mu}{\gamma * l}) = x'\beta \qquad (5\text{-}2)$$

which is equivalent to

$$\log \mu = \log(\gamma * l) + x'\beta \qquad (5\text{-}3)$$

Since the coefficient for the term log(ν*l) is known to be 1, it was set it as an offset term.

### 5.1 Response Variable

The response variable was monthly crash frequency. Traffic volume and segment length were modeled as offsets. An attempt was made to model just ROR and cross-centerline crashes, but because individual months were modeled as the observation period, a large number of observation periods had no crashes. This limitation made it difficult to fit the crash data into an adequate model.

### 5.2 Explanatory Variables

The following variables were considered in the model as the covariates, the linear combination of which was associated to the Poisson mean. Several other explanatory variables were available but were not included because they were highly correlated to other variables. For instance, median type was highly correlated to number of lanes because most four-lane road sections were also divided roadways.

> ***Z*:** a categorical variable that indicates whether this road section was a treatment site or a control site (1 for treatment sites and 0 for control sites)
>
> ***t*:** denotes the time elapsed in months from January 1984. The variable ranges from 1 to 288. The time is calculated with the formula $t$= (year-1984)*12 + month. For example, $t$ for February 1984 is 2 and $t$ for February 1985 is 14.
>
> **$t_o$:** time in months since paved shoulders were added after the construction year, so if shoulders were constructed in 1999, $t_0$ for January 2000 would be 1.
>
> **$I_{(t>to)}$**: a categorical variable that indicates whether the time period was before or after paved shoulders were implemented (0 for a treatment section before paved shoulders were added, 0 for control sections for all periods, and 1 for treatment sections after paved shoulders were added)
>
> ***Median*:** a categorical variable that indicates presence of a median in the road section (0 for undivided roadways and 1 for divided roadways)
>
> ***RS:*** a categorical variable that indicates the presence of rumble strips in the paved shoulder (0 if no rumble strips are present and 1 if present)
>
> ***pvdwidth***: width of the paved right shoulder (in feet)
>
> ***unpvdwidth*:** width of the unpaved right shoulder (in feet)
>
> ***spdlimit***: speed limit of the road section; sections had speed limits from 45 to 65 mph

$S_1$, $S_2$, and $S_3$ are functions to express seasonality. Months are assigned to a quarter of the year using the following:

$$S_1 = \cos\left(\frac{2\pi \times S}{4}\right),\quad S_2 = \cos\left(\frac{4\pi \times S}{4}\right),\quad S_3 = \sin\left(\frac{2\pi \times S}{4}\right)$$

and

$$S = \begin{cases} 1, \text{ if t belongs to Winter (December, January, and February)} \\ 2, \text{if t belongs to Spring (March, April, and May)} \\ 3, \text{ if t belongs to Summer (June, July, and August)} \\ 4, \text{ if t belongs to Fall (September, October and November)} \end{cases} \quad (5\text{-}4)$$

The three trigonometric functions were used to model the seasonal effects smoothly and periodically.

### 5.3 Model Results

The original model with all covariates considered is given in equation 5-5:

$$\begin{aligned} \log(\lambda) =& \beta_0 + \beta_1 * Z + \beta_2 * t + \beta_3 * Z * (t - t_0) * I_{(t>t_0)} + \beta_4 * Z * t + \beta_5 * median \\ &+ \beta_6 * RS + \beta_7 * pvdwidth + \beta_8 * unpvdwidth + \beta_9 * spd\text{limit} + \beta_{10} * S_1 + \beta_{11} * S_2 \\ &+ \beta_{12} * S_3 + Site \end{aligned} \quad (5\text{-}5)$$

Results indicate that the covariate “spdlimit” (and Z) were not significant at the 0.05 confidence level and were removed from the model (Z, median, and spdlimit cannot be significant together at the 0.05 confidence level). After removing spdlimit and Z, all the variables left were significant. A final model was created with both of those covariates removed, and all covariates in the new model are significant at a confidence level of 0.05, as shown in Table 5-1. It should be noted that since the model is a generalized linear mixed model with both fixed and random effects, conventional criteria such as AIC, BIC, or deviance, which are typically used to evaluate the model, are not as useful in evaluating the model.

The final model is given as equation 5-6:

$$\begin{aligned} \log(\lambda) =& \beta_0 + \beta_1 * t + \beta_2 * Z * (t - t_0) * I_{(t>t_0)} + \beta_3 * Z * t + \\ &\beta_4 * median + \beta_5 * RS + \beta_6 * pvdwidth + \beta_7 * unpvdwidth + \beta_8 * S_1 \\ &+ \beta_9 * S_2 + \beta_{10} * S_3 + Site \end{aligned} \quad (5\text{-}6)$$

The parameter estimates for both random and fixed effects in the final model are shown below:

**Table 5.1. Estimate and standard error for $\sigma^2$, variance for random site effect**

| Cov Parm | Estimate | Standard Error |
|---|---|---|
| $\sigma^2$ | 0.2237 | 0.02301 |

**Table 5.2. Estimate and standard error for fixed effects in model 2**

| Effect | Estimate | Standard Error | DF | t Value | Pr > \|t\| |
|---|---|---|---|---|---|
| $\beta_0$ | -13.3215 | 0.07163 | 219 | -185.98 | <.0001 |
| $\beta_1$ | -0.00031 | 0.000107 | 61585 | -2.92 | 0.0036 |
| $\beta_2$ | -0.00176 | 0.000301 | 61585 | -5.84 | <.0001 |
| $\beta_3$ | 0.000492 | 0.000151 | 61585 | 3.26 | 0.0011 |
| $\beta_4$ | -0.3788 | 0.08322 | 61585 | -4.55 | <.0001 |
| $\beta_5$ | -0.1770 | 0.05201 | 61585 | -3.40 | 0.0007 |
| $\beta_6$ | -0.01872 | 0.008806 | 61585 | -2.13 | 0.0336 |
| $\beta_7$ | -0.02756 | 0.007645 | 61585 | -3.61 | 0.0003 |
| $\beta_8$ | 0.2362 | 0.007718 | 61585 | 30.60 | <.0001 |
| $\beta_9$ | 0.01579 | 0.005524 | 61585 | 2.86 | 0.0043 |
| $\beta_{10}$ | 0.2158 | 0.007908 | 61585 | 27.28 | <.0001 |

For control sites, equation 5-6 can be reduced to

$$E\{\log(\lambda) \mid control\} = \beta_0 + \beta_1 t + otherterms \tag{5-7}$$

For treatment sites, before the shoulder pavement, is

$$E\{\log(\lambda) \mid pavement, before\} = \beta_0 + (\beta_1 + \beta_3)t + otherterms \tag{5-8}$$

while the expectation of log (month crashes) for a treatment site, after the shoulder pavement, is

$$E\{\log(\lambda) \mid pavement, after\} = (\beta_0 - \beta_2 t_0) + (\beta_1 + \beta_2 + \beta_3)t + otherterms \tag{56-9}$$

The effect of adding paved shoulders is indicated by the coefficient, $\beta_2$. If $\beta_2$ is less than 0, the slope is more negative in the after period, indicating that the treatment was effective. When considering control sites as well, if the treatment was effective, we would expect that $\beta_1$ for the control sites (from equation 5-7) would be greater than $\beta_1 + \beta_2 + \beta_3$ for the treatment sites (from equation 5-9) and $\beta_1 + \beta_3$ for the before period (from equation 5-8) would be greater than $\beta_1 + \beta_2 + \beta_3$ (from equation 5-9). Thus, the slope for treatments would be more negative, indicating that the effect of adding paved shoulders resulted in fewer crashes.

Since time of year is expected to be relevant, three trigonometric functions with different periods, $S_1$–$S_3$, were used to account for the seasonal effect associated with the log crash rate. To be specific, the following convention was used:

- If time t is in winter, then $S_1$=0,$S_2$=-1,$S_3$=1
- If the time is in spring, $S_1$=-1, $S_2$=1, $S_3$=0
- If the time is in summer, $S_1$=0, $S_2$=-1, $S_3$=-1
- If the time is in fall, $S_1$=1,$S_2$=1,$S_3$=0

The confidence intervals for $\beta_2$ and ($\beta_2$+ $\beta_3$) are provided in Table 5.3. As shown, 0 is not included in the confidence interval and the estimates of both $\beta_2$ and $\beta_2$+ $\beta_3$ are negative, indicating $\beta_2<0$ and $\beta_2+\beta_3<0$, as expected. These results suggest that there is a significant difference in crash rate for the before and after periods when paved shoulders were installed for the treatment sites. The difference between the control groups and the after period of the treatment sites is also significant.

**Table 5.3. Estimates and confidence intervals for $\beta_2$ and $\beta_2$+ $\beta_3$**

| | 2.5% | Estimate | 97.5% |
|---|---|---|---|
| $\beta_2$ | -0.00234 | -0.00160 | -0.00117 |
| $\beta_2$+ $\beta_3$ | -0.00183 | -0.00126 | -0.00070 |

As indicated in Table 5.2, the variables for presence of median, presence of rumble strips, paved width, and unpaved width were shown to be significant terms at the 0.05 confidence level. The negative coefficient estimates and the confidence intervals for all these terms are negative, suggesting that the presence of a median and rumble strips or wider shoulders is correlated with a decrease in the number of crashes.

The estimates and 95% confidence intervals for the linear combinations of regression coefficients representing the seasonal effects were calculated, as shown in Table 5.4. The results show that a higher number of crashes occur in winter and fall than in spring and summer.

**Table 5.4. Estimates and 95% confidence intervals for seasonal effects**

| | 2.5% | Estimate | 97.5% |
|---|---|---|---|
| Winter ($\beta_{10}-\beta_9$) | 0.1820 | 0.2000 | 0.2179 |
| Spring ($\beta_9-\beta_8$) | -0.2403 | -0.2204 | -0.2005 |
| Summer ($-\beta_{10}-\beta_9$) | -0.2513 | -0.2315 | -0.2117 |
| Fall ($\beta_9+\beta_8$) | 0.2348 | 0.2520 | 0.2692 |

**5.4 Prediction of Monthly Crash Frequency**

According to the model shown in equation 5-6, the expected mean number of monthly crashes for a given site can be estimated by the following, including the coefficients, as shown in equation 5-10:

$$\hat{\mu} = \exp(-13.3215 - 0.00031t - 0.00176Z(t - t_0)I_{(t>t_0)} + 0.000492Zt - 0.3788median - 0.177RS$$
$$- 0.01872pvdwidth - 0.02756unpvdwidth + 0.2362S_1 + 0.01579S_2 + 0.2158S_3 + Site) * volume * length \quad (5\text{-}10)$$

In equation 5-10, the variable "Site" is a random normal variable with mean zero and variance estimate of 0.2237, which was included to account for repeated observations at the same location. The random effect for each site (PavedID) can be estimated using GLIMMIX, and the results are listed in Appendix B. These estimates can be used to estimate the monthly crashes for a specific site. Because we are interested in the general effect of paved shoulders, for simplicity if the "Site" term is not included, equation 5-10 can be simplified to equations 5-11 to 5-13, which can be used to estimate the mean number of monthly crashes at a control site, a treatment site before installation of shoulders, or a treatment site after installation of shoulders.

$$\hat{\mu} \mid control = \exp(-13.3215 - 0.00031t - 0.3788median - 0.02756unpvdwidth$$
$$+ 0.2362S_1 + 0.01579S_2 + 0.2158S_3) * volume * length \quad (5\text{-}11)$$

$$\hat{\mu} \mid treatment, before = \exp(-13.3215 - 0.000182t - 0.3788median - 0.02756unpvdwidth$$
$$+ 0.2362S_1 + 0.01579S_2 + 0.2158S_3) * volume * length \quad (5\text{-}12)$$

$$\hat{\mu} \mid treatment, after(t_0) = \exp(-13.3215 + 0.00176t_0 - 0.001578t - 0.3788median - 0.177RS$$
$$- 0.01872pvdwidth - 0.02756unpvdwidth + 0.2362S_1 + 0.01579S_2 + 0.2158S_3) * volume * length \quad (5\text{-}13)$$

The expected impact of paved shoulders can be determined by dividing the expected number of monthly crashes for one set of circumstances by the expected number of monthly crashes under a different set of circumstances. The following example can be used to estimate the impact of implementing paved shoulders. If we use a construction year of 1999 and assume construction is completed by June, then $t_o$ is 186. If a before period of March 1997 and an after period of March 2002 is selected, then t for the before period is 159 and t for the after period is 219. If all other variables are held constant, the effect of adding paved shoulders can be obtained by comparing the change in total number of monthly crashes at control sites to the change at a treatment section from before to after using the following calculation:

Change for control sections from before to after

$$= (e^{(-13.3215 - 0.00031 * 159)} - e^{(-13.3215 - 0.00031 * 219)} = 0.018 \text{ or } 1.8\%$$

Change for test sections from before to after

$$= (e^{(-13.3215 + 0.000182 * 159)} - e^{(-13.3215 + 0.00176*186 - 0.00158 * 219)}) = 0.046 \text{ or } 4.6\%$$

As a result, a 1.8% reduction in crashes would occur in control sections due to factors other than paved shoulders, and a decrease of 4.6% would occur with paved shoulders.

## 6. SUMMARY

In 2004, Iowa adopted a paved shoulder policy for higher volume roads, but a broad diversity of paved shoulder types have been utilized for many years in the state. Because the benefits of paved shoulders have not been quantified, the Iowa DOT requested a study to analyze the safety performance of various paved shoulder designs on a wide spectrum of traffic and roadway types.

The research described in this report evaluated the effectiveness of paved shoulders. As part of the research, two surveys were conducted that assessed the opinions of field maintenance personnel and law enforcement personnel about the effectiveness of paved shoulders. Most maintenance personnel felt that paved shoulders led to reduced maintenance costs. Most officers felt that the shoulders reduced ROR crashes and improved safety for officers when they have to pull over for traffic stops.

This study also included a crash analysis for non-Interstate roadways in Iowa where paved shoulders have been installed. The team made site visits and collected roadway data for 256 roadway sections in Iowa. The majority were locations where paved shoulders had been installed, but a number of control sections were collected as well. Each test segment was reviewed, and the construction year for implementation of paved shoulders was determined. In some cases, the roadway segment could not be located in the GIMS database, and in other cases the construction year could not be determined. These sections were removed from further analysis. This resulted in a total of 220 sites analyzed, including77 control sections and 143 test sections. Sections included both two- and four-lane roadways. Four-lane roadways were both divided and undivided.

A GLM using a Poisson distribution with a log link function was used to investigate the relationship between crash reduction and implementation of paved shoulders. The response variable was monthly crash frequency. Traffic volume and segment length were modeled as offsets. An attempt was made to model just ROR and cross-centerline crashes, but because individual months were modeled as the observation period, a large number of observations had no crashes. This limitation made it difficult to fit an adequate model to the data.

Model results indicated that the covariate for speed limit was not significant at the 0.05 confidence level, and was it removed from the model. All other variables that resulted in the final model were significant at the 0.05 confidence level. The final model indicated that season of the year was significant for indicating expected number of total monthly crashes, with a higher number of crashes occurring in the winter and fall than in the spring and summer. The model also indicated that the presence of rumble strips, paved shoulder width, unpaved shoulder width, and the presence of a divided median were correlated to a decrease in crashes. The model also indicated that roadway sections with paved shoulders had fewer crashes in the after period compared to both the before period and control sections.

The actual impact of paved shoulders depends on several other covariates, as indicated in the final model, such as installation year and width of paved shoulders. However, comparing the expected number of total crashes before and after installation of paved shoulders for several scenarios indicated around a 4.6% reduction in the expected number of monthly crashes in the after period.

## 7. REFERENCES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## APPENDIX A. DATA COLLECTION FORM

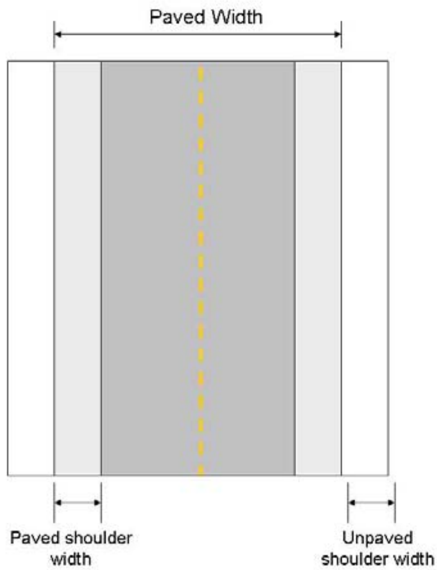
### Paved Shoulder Data Collection Form

*If this is a divided highway, note and do each direction separately*

**Date:** ____________________ **County:** _____________________________________

**Main St.** (include gov and local names): ________________________________________
**Begin cross-street:** _________________________________________________________
**End cross-street:** __________________________________________________________
*Note location on map for cross reference*
**Speed Limit:** ___________ **Orientation:** N/S E/W
Sample -

| | | | |
|---|---|---|---|
| **Pavement Type:** | Asphalt | Concrete | |
| **Shoulder:** | Fully Paved | Partially Paved | |
| **Shoulder pavement type:** | Asphalt | Concrete | |
| **Unpaved Shoulder type:** | Gravel | Earth | Mixed |

| | | |
|---|---|---|
| **West shoulder on N/S Road or North shoulder on E/W road** |  | **East shoulder on N/S Road or South shoulder on E/W road** |
| **Rumble strips**<br>None<br>Milled<br>Rolled<br><br>**RS Location:**<br>Edge of paved lane<br>Edge of paved shoulder<br>Dist from edge of paved shoulder ____________ | | **Rumble strips**<br>None<br>Milled<br>Rolled<br><br>**RS Location:**<br>Edge of paved lane<br>Edge of paved shoulder<br>Dist from edge of paved shoulder ___________ |
| **Total paved width**: | | **Total paved width**: |
| **Paved shoulder:** | | **Paved shoulder:** |
| **Unpaved shoulder:** | | **Unpaved shoulder:** |



**Note if there is anything unusual about this roadway.**
**Note if paved driveway entrances exist or widening on curves:**
**Location and type of other lane widenings**

## APPENDIX B. ESTIMATES OF RANDOM EFFECTS FOR SITES

### Table B.1. Estimates of the random effects DF = 61585

| ID | Estimate | Std Err Pred | t Value | Pr > \|t\| | ID | Estimate | Std Err Pred | t Value | Pr > \|t\| |
|---|---|---|---|---|---|---|---|---|---|
| 100 | 0.4534 | 0.09316 | 4.87 | <.0001 | 152 | -0.5514 | 0.1516 | -3.64 | 0.0003 |
| 101 | 0.1719 | 0.08856 | 1.94 | 0.0522 | 153 | -0.8855 | 0.1577 | -5.61 | <.0001 |
| 103 | -0.8699 | 0.1430 | -6.08 | <.0001 | 154 | -0.7056 | 0.1878 | -3.76 | 0.0002 |
| 104 | -0.03843 | 0.1323 | -0.29 | 0.7714 | 155 | 0.4767 | 0.06346 | 7.51 | <.0001 |
| 105 | -0.6745 | 0.1608 | -4.20 | <.0001 | 156 | -0.2754 | 0.08295 | -3.32 | 0.0009 |
| 106 | 0.01630 | 0.1316 | 0.12 | 0.9014 | 157 | -0.1369 | 0.1036 | -1.32 | 0.1865 |
| 107 | 0.02465 | 0.07241 | 0.34 | 0.7336 | 158 | 0.5022 | 0.08467 | 5.93 | <.0001 |
| 108 | -0.5324 | 0.1324 | -4.02 | <.0001 | 159 | 0.7414 | 0.07445 | 9.96 | <.0001 |
| 109 | -0.1460 | 0.08264 | -1.77 | 0.0773 | 160 | -0.1844 | 0.1284 | -1.44 | 0.1509 |
| 110 | -0.2764 | 0.08087 | -3.42 | 0.0006 | 161 | -0.2919 | 0.09835 | -2.97 | 0.0030 |
| 111 | -0.06470 | 0.1056 | -0.61 | 0.5399 | 162 | -0.4054 | 0.1008 | -4.02 | <.0001 |
| 112 | -0.06653 | 0.08965 | -0.74 | 0.4580 | 163 | -0.1142 | 0.1021 | -1.12 | 0.2635 |
| 113 | -0.6665 | 0.1004 | -6.64 | <.0001 | 164 | -0.03746 | 0.1004 | -0.37 | 0.7090 |
| 114 | -0.6270 | 0.1358 | -4.62 | <.0001 | 165 | 0.3519 | 0.07843 | 4.49 | <.0001 |
| 115 | -0.4200 | 0.09054 | -4.64 | <.0001 | 166 | -0.1162 | 0.08955 | -1.30 | 0.1944 |
| 116 | 0.1915 | 0.06325 | 3.03 | 0.0025 | 167 | -0.1837 | 0.1023 | -1.80 | 0.0724 |
| 117 | 0.4376 | 0.08611 | 5.08 | <.0001 | 168 | -0.2033 | 0.1703 | -1.19 | 0.2326 |
| 118 | 0.4015 | 0.06954 | 5.77 | <.0001 | 169 | -0.3740 | 0.1950 | -1.92 | 0.0552 |
| 119 | 1.0169 | 0.2178 | 4.67 | <.0001 | 170 | -0.03987 | 0.09926 | -0.40 | 0.6879 |
| 120 | -0.8708 | 0.1070 | -8.14 | <.0001 | 171 | 0.1893 | 0.09458 | 2.00 | 0.0454 |
| 121 | -0.5878 | 0.1413 | -4.16 | <.0001 | 172 | -0.02186 | 0.1207 | -0.18 | 0.8563 |
| 122 | -1.0117 | 0.1117 | -9.06 | <.0001 | 173 | -0.4358 | 0.07408 | -5.88 | <.0001 |
| 123 | 0.3319 | 0.1042 | 3.18 | 0.0015 | 175 | 0.3937 | 0.06684 | 5.89 | <.0001 |
| 124 | -0.3184 | 0.09926 | -3.21 | 0.0013 | 176 | 0.1254 | 0.07059 | 1.78 | 0.0756 |
| 125 | 0.1431 | 0.1001 | 1.43 | 0.1529 | 177 | -0.1727 | 0.1503 | -1.15 | 0.2507 |
| 126 | 0.2216 | 0.08463 | 2.62 | 0.0088 | 178 | 0.2743 | 0.1057 | 2.60 | 0.0095 |
| 127 | -0.1573 | 0.1326 | -1.19 | 0.2355 | 180 | -0.1956 | 0.1169 | -1.67 | 0.0943 |
| 128 | 0.1065 | 0.08031 | 1.33 | 0.1850 | 181 | 0.05028 | 0.1113 | 0.45 | 0.6516 |
| 129 | 0.01230 | 0.1239 | 0.10 | 0.9209 | 182 | 0.3515 | 0.07445 | 4.72 | <.0001 |
| 130 | 0.2714 | 0.09824 | 2.76 | 0.0057 | 183 | -0.3977 | 0.1435 | -2.77 | 0.0056 |
| 131 | -1.0423 | 0.1850 | -5.63 | <.0001 | 184 | 0.3807 | 0.07802 | 4.88 | <.0001 |
| 132 | -0.3104 | 0.1037 | -2.99 | 0.0028 | 185 | -0.00341 | 0.1151 | -0.03 | 0.9764 |
| 133 | 1.0515 | 0.1012 | 10.39 | <.0001 | 186 | -0.2095 | 0.08365 | -2.50 | 0.0123 |
| 134 | -0.1910 | 0.1128 | -1.69 | 0.0905 | 187 | -2.49E-6 | 0.08149 | -0.00 | 1.0000 |
| 136 | 0.3291 | 0.1224 | 2.69 | 0.0072 | 188 | 0.6029 | 0.1241 | 4.86 | <.0001 |
| 137 | 0.2139 | 0.1038 | 2.06 | 0.0394 | 189 | -0.3206 | 0.1213 | -2.64 | 0.0082 |
| 138 | -0.6888 | 0.1815 | -3.79 | 0.0001 | 190 | 0.3194 | 0.1037 | 3.08 | 0.0021 |
| 139 | 0.1018 | 0.08115 | 1.25 | 0.2099 | 191 | 0.5559 | 0.07973 | 6.97 | <.0001 |
| 140 | 0.1022 | 0.1173 | 0.87 | 0.3834 | 192 | -0.4614 | 0.08160 | -5.65 | <.0001 |
| 141 | 0.4757 | 0.08015 | 5.93 | <.0001 | 193 | -0.1363 | 0.08350 | -1.63 | 0.1027 |
| 142 | -0.8819 | 0.1824 | -4.84 | <.0001 | 194 | 1.0395 | 0.1371 | 7.58 | <.0001 |
| 143 | -0.3259 | 0.1013 | -3.22 | 0.0013 | 195 | 0.3791 | 0.09835 | 3.85 | 0.0001 |
| 144 | -0.6740 | 0.1766 | -3.82 | 0.0001 | 196 | 0.5204 | 0.1231 | 4.23 | <.0001 |
| 145 | -0.3342 | 0.1062 | -3.15 | 0.0016 | 197 | 0.7468 | 0.08245 | 9.06 | <.0001 |
| 146 | 0.3881 | 0.1319 | 2.94 | 0.0033 | 198 | 0.06884 | 0.1054 | 0.65 | 0.5137 |
| 147 | -0.7072 | 0.1065 | -6.64 | <.0001 | 199 | 1.0270 | 0.1296 | 7.92 | <.0001 |
| 148 | 0.03490 | 0.08806 | 0.40 | 0.6919 | 200 | -0.8372 | 0.1023 | -8.18 | <.0001 |
| 149 | 0.09594 | 0.08599 | 1.12 | 0.2645 | 201 | -0.06885 | 0.08308 | -0.83 | 0.4073 |

**Table B.2. Estimates of the random effects DF = 61585**

| ID | Estimate | Std Err Pred | t Value | Pr > \|t\| | ID | Estimate | Std Err Pred | t Value | Pr > \|t\| |
|---|---|---|---|---|---|---|---|---|---|
| 150 | -0.4129 | 0.1422 | -2.90 | 0.0037 | 202 | -0.07259 | 0.07303 | -0.99 | 0.3202 |
| 151 | -0.7490 | 0.1152 | -6.50 | <.0001 | 203 | 0.7352 | 0.09053 | 8.12 | <.0001 |
| 204 | 0.2281 | 0.1141 | 2.00 | 0.0455 | 274 | 0.3242 | 0.09230 | 3.51 | 0.0004 |
| 205 | -0.00368 | 0.07477 | -0.05 | 0.9607 | 275 | 0.1625 | 0.09009 | 1.80 | 0.0713 |
| 206 | -0.2477 | 0.1278 | -1.94 | 0.0526 | 276 | -0.04544 | 0.1521 | -0.30 | 0.7651 |
| 207 | 0.06752 | 0.1113 | 0.61 | 0.5441 | 277 | 0.7218 | 0.1126 | 6.41 | <.0001 |
| 208 | 0.5683 | 0.1340 | 4.24 | <.0001 | 278 | 0.5636 | 0.1180 | 4.77 | <.0001 |
| 209 | -0.6757 | 0.1491 | -4.53 | <.0001 | 279 | -0.01651 | 0.1253 | -0.13 | 0.8952 |
| 210 | 0.2364 | 0.1146 | 2.06 | 0.0391 | 280 | 0.08665 | 0.2528 | 0.34 | 0.7317 |
| 211 | -0.01904 | 0.1354 | -0.14 | 0.8881 | 281 | -0.4267 | 0.08606 | -4.96 | <.0001 |
| 212 | -0.1604 | 0.1072 | -1.50 | 0.1348 | 282 | 0.2866 | 0.07617 | 3.76 | 0.0002 |
| 213 | -0.2362 | 0.1690 | -1.40 | 0.1621 | 283 | -0.2273 | 0.09266 | -2.45 | 0.0142 |
| 214 | 0.1679 | 0.09559 | 1.76 | 0.0789 | 284 | -0.4488 | 0.1118 | -4.01 | <.0001 |
| 215 | 0.1540 | 0.09886 | 1.56 | 0.1193 | 285 | -0.4427 | 0.07088 | -6.25 | <.0001 |
| 216 | 0.7580 | 0.09786 | 7.75 | <.0001 | 287 | 0.04307 | 0.07218 | 0.60 | 0.5507 |
| 217 | 0.08753 | 0.1431 | 0.61 | 0.5408 | 288 | -0.3143 | 0.09687 | -3.24 | 0.0012 |
| 218 | 0.8227 | 0.09501 | 8.66 | <.0001 | 289 | 0.006303 | 0.1055 | 0.06 | 0.9524 |
| 219 | 0.02681 | 0.1229 | 0.22 | 0.8274 | 290 | -0.1508 | 0.09735 | -1.55 | 0.1214 |
| 220 | -0.6312 | 0.1494 | -4.23 | <.0001 | 291 | 0.07051 | 0.09292 | 0.76 | 0.4480 |
| 221 | 0.3423 | 0.07574 | 4.52 | <.0001 | 292 | -0.01534 | 0.07877 | -0.19 | 0.8456 |
| 222 | 0.9956 | 0.1031 | 9.65 | <.0001 | 293 | -0.05041 | 0.07201 | -0.70 | 0.4839 |
| 223 | 0.2248 | 0.1060 | 2.12 | 0.0340 | 294 | 0.1322 | 0.1355 | 0.98 | 0.3294 |
| 225 | -0.4185 | 0.1036 | -4.04 | <.0001 | 295 | 0.05096 | 0.1135 | 0.45 | 0.6534 |
| 227 | 0.3295 | 0.07205 | 4.57 | <.0001 | 296 | -0.1971 | 0.1989 | -0.99 | 0.3217 |
| 229 | -0.2431 | 0.1293 | -1.88 | 0.0602 | 297 | -0.4007 | 0.1067 | -3.76 | 0.0002 |
| 230 | -0.02700 | 0.08697 | -0.31 | 0.7563 | 298 | 0.1304 | 0.08985 | 1.45 | 0.1468 |
| 231 | -0.5385 | 0.1027 | -5.24 | <.0001 | 299 | 0.1400 | 0.1031 | 1.36 | 0.1744 |
| 232 | -0.2052 | 0.1191 | -1.72 | 0.0851 | 300 | -0.1900 | 0.1514 | -1.25 | 0.2097 |
| 233 | 1.7812 | 0.1282 | 13.89 | <.0001 | 301 | 0.09987 | 0.09815 | 1.02 | 0.3089 |
| 234 | 0.1822 | 0.09681 | 1.88 | 0.0599 | 302 | 0.2132 | 0.1150 | 1.85 | 0.0637 |
| 235 | -0.1002 | 0.09226 | -1.09 | 0.2776 | 303 | -0.1005 | 0.1681 | -0.60 | 0.5500 |
| 238 | -0.4869 | 0.1317 | -3.70 | 0.0002 | 304 | -0.2662 | 0.1368 | -1.95 | 0.0517 |
| 239 | -0.3234 | 0.08908 | -3.63 | 0.0003 | 305 | -0.5526 | 0.09032 | -6.12 | <.0001 |
| 240 | 0.06603 | 0.09734 | 0.68 | 0.4976 | 307 | 0.1589 | 0.08829 | 1.80 | 0.0719 |
| 250 | 0.4007 | 0.1155 | 3.47 | 0.0005 | 308 | 0.03921 | 0.1025 | 0.38 | 0.7021 |
| 251 | 0.2882 | 0.1451 | 1.99 | 0.0470 | 309 | -0.2608 | 0.1015 | -2.57 | 0.0102 |
| 252 | 0.4210 | 0.1115 | 3.78 | 0.0002 | 311 | -0.4968 | 0.3069 | -1.62 | 0.1055 |
| 253 | 0.2937 | 0.09406 | 3.12 | 0.0018 | 312 | 0.2963 | 0.1031 | 2.87 | 0.0041 |
| 254 | -0.2932 | 0.07836 | -3.74 | 0.0002 | 313 | 0.9750 | 0.09342 | 10.44 | <.0001 |
| 255 | 1.1625 | 0.1096 | 10.60 | <.0001 | 314 | -0.3348 | 0.1248 | -2.68 | 0.0073 |
| 256 | 1.6619 | 0.08547 | 19.44 | <.0001 | 315 | 0.1059 | 0.06735 | 1.57 | 0.1160 |
| 257 | 0.1829 | 0.1057 | 1.73 | 0.0836 | 316 | 0.008374 | 0.08727 | 0.10 | 0.9236 |
| 261 | -0.3960 | 0.1262 | -3.14 | 0.0017 | 319 | 0.6775 | 0.1471 | 4.61 | <.0001 |
| 262 | -0.7933 | 0.1114 | -7.12 | <.0001 | 320 | -0.2325 | 0.1240 | -1.87 | 0.0609 |
| 264 | -0.1070 | 0.08600 | -1.24 | 0.2134 | 321 | -0.1328 | 0.1116 | -1.19 | 0.2341 |
| 265 | -0.5125 | 0.1341 | -3.82 | 0.0001 | 322 | 0.1516 | 0.1237 | 1.23 | 0.2202 |
| 266 | -0.9382 | 0.2199 | -4.27 | <.0001 | 323 | 0.6093 | 0.1605 | 3.80 | 0.0001 |
| 267 | 0.05163 | 0.2769 | 0.19 | 0.8521 | 324 | -0.2851 | 0.08168 | -3.49 | 0.0005 |
| 268 | -0.3600 | 0.1907 | -1.89 | 0.0591 | 325 | 0.02086 | 0.1480 | 0.14 | 0.8879 |
| 269 | -0.7710 | 0.2384 | -3.23 | 0.0012 | 326 | 0.7470 | 0.08239 | 9.07 | <.0001 |

**Table B.3. Estimates of the random effects DF = 61585**

| ID | Estimate | Std Err Pred | t Value | Pr > \|t\| | ID | Estimate | Std Err Pred | t Value | Pr > \|t\| |
|---|---|---|---|---|---|---|---|---|---|
| 270 | -0.4610 | 0.1749 | -2.64 | 0.0084 | 341 | -0.04788 | 0.09016 | -0.53 | |
| 271 | -0.3739 | 0.1612 | -2.32 | 0.0204 | 342 | 0.1718 | 0.1048 | 1.64 | 0.1012 |
| 272 | 0.1624 | 0.1056 | 1.54 | 0.1241 | 343 | 0.4271 | 0.09079 | 4.70 | <.0001 |
| 273 | 0.4193 | 0.08144 | 5.15 | <.0001 | 345 | 0.3773 | 0.08896 | 4.24 | <.0001 |
| 331 | -0.7550 | 0.1568 | -4.82 | <.0001 | 346 | -0.2645 | 0.1149 | -2.30 | 0.0214 |
| 332 | 0.1241 | 0.08728 | 1.42 | 0.1551 | 347 | 0.2958 | 0.09795 | 3.02 | 0.0025 |
| 334 | 0.1176 | 0.1084 | 1.08 | 0.2783 | 350 | -0.4461 | 0.1278 | -3.49 | 0.0005 |
| 335 | 0.07873 | 0.08695 | 0.91 | 0.3652 | 351 | -0.05018 | 0.09760 | -0.51 | 0.6072 |
| 336 | 0.2414 | 0.09000 | 2.68 | 0.0073 | 370 | -0.1336 | 0.1473 | -0.91 | 0.3646 |
| 337 | 0.3805 | 0.09713 | 3.92 | <.0001 | 328 | 0.07370 | 0.07398 | 1.00 | 0.3191 |
| 338 | 0.2201 | 0.1135 | 1.94 | 0.0525 | 329 | -0.3507 | 0.1160 | -3.02 | 0.0025 |
| 340 | 0.3905 | 0.09295 | 4.20 | <.0001 | 330 | 0.1449 | 0.08221 | 1.76 | 0.0780 |
| 327 | 0.06922 | 0.06791 | 1.02 | 0.3081 | | | | | |