MINNESOTA DEPARTMENT OF TRANSPORTATION

# RESEARCH

2009-39

# Benefit:Cost Analysis of In-Vehicle Techonologies and Infrastructure Modifications as a Means to Prevent Crashes along Curves and Shoulders

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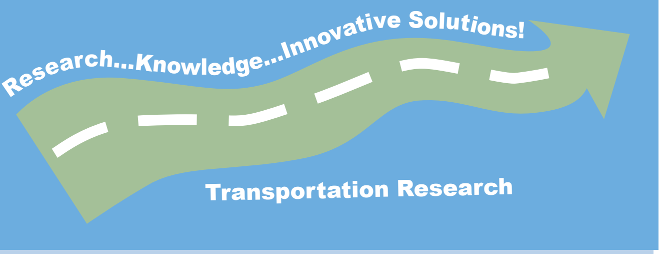

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16. Abstract (Limit: 250 words)

The State of Minnesota has under way its Toward Zero Deaths (TZD) initiative, the goal of which is to eliminate fatal traffic crashes. This is a daunting task, and with limited financial resources, optimal strategies that provide the greatest benefit for a given cost have to be utilized if the goal of TZD is to be met.

This report reviews both infrastructure and emerging in-vehicle solutions as a means to determine the optimal deployment strategy of countermeasures designed to improve highway safety. Infrastructure-based solutions are examined on two levels: 1) an analysis of a cross-section of strategies implemented throughout Minnesota, which 2) produced a before:after analysis that quantified the effectiveness of a variety of strategies utilized in Minnesota.

In addition to the standard civil engineering countermeasures studied under the before:after analysis, emerging infrastructure and in-vehicle technology-based solutions were modeled in terms of effectiveness and potential deployment schedules. These cost and effectiveness models facilitated a comparison to the results of the before:after analysis, and from the comparison, optimal strategies for improving safety with limited funds and the TZD goal are presented.

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# Benefit:Cost Analysis of In-Vehicle Technologies and Infrastructure Modifications as a Means to Prevent Crashes Along Curves and Shoulders

## Final Report

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# Table of Contents

# List of Figures

# List of Tables

# Executive Summary

Transportation is the lifeline of the state. It connects people, goods and is among the key components of the economy. A good transportation system is one that ensures safety but at the same time is not a burden on the state revenue system.

In 2007, 510 people were killed in the state of Minnesota, which costs the state more than $3.5 billion. Forty percent of these fatal crashes are road departure crashes and they mainly occur on rural curves and tangential sections. To prevent these road departure crashes, safety systems have to be implemented at these curves and tangential sections. Various safety systems were studied, and an optimal solution has been provided based on cost-effectiveness and efficiency to reduce traffic fatalities.

The study was completed in two parts:

1) The first task was completed by CH2MHill. A sample set of 204 curves and 137 tangential sections was studied.

    - A cross-sectional study was done to evaluate the effect of road geometry on the road departure crashes. Curves of different radius were evaluated for their crash rates and fatal rates. Similarly, the effects of a variety of road shoulder designs for tangential sections were studied, including narrow vs. wide, paved vs. aggregate vs. enhanced.
    - From the sample set, curves and tangential sections having some form of treatment implemented such as rumble strips, paved sections, flattened curves were identified. The effects of implementing these various treatments were quantified as the before:after analysis.

2) The second task was completed by University of Minnesota. The traditional safety treatments identified on road sections were evaluated against new technology-based safety systems.

    The technology-based safety systems consist of both infrastructure-based and in-vehicle systems. The technology-based infrastructure solutions involve radar-based advanced curve warnings where the speed of the vehicle is calculated and accordingly the driver is warned. In-vehicle technologies include both vision-based and DGPS-based lane departure warning systems. These solutions were evaluated for their cost effectiveness and the number of fatalities they potentially reduce.

    The benefit:cost analysis consisted of four components:

    - **Effectiveness** – Effectiveness of any system is the extent to which it meets the purpose, in this case, the extent to which it reduces crashes. The before:after analysis gave the crash rates along curves and tangential sections before and after the treatment was implemented. This data was used to calculate the effectiveness in reducing crashes after implementing the treatment. Effectiveness values were also obtained using the data available from FHWA or by drawing analogies to existing technologies.

- **Exposure –** Effectiveness of any technology is always a function of its exposure. This exposure is taken into account either in the form of the number of crashes per million vehicle miles traveled or the market penetration.
- **Benefit:cost analysis –**It is necessary to implement safety systems that are cost-effective for the government as well as the public. Benefit:cost ratios have been calculated to evaluate this cost-effectiveness.
- **Contribution to TZD –** The state expends a fixed amount of safety budget every year. Thus, given a fixed amount of money, the treatment giving the most reduced number of fatalities was evaluated. This was defined as the deployment factor. The treatment having the highest deployment factor was the optimal solution which would help move toward Mn/DOT's goal of Toward Zero Deaths (TZD).

## Result

In this study, new emerging technologies were studied against traditional infrastructure-based safety systems. These studies were evaluated based on their effectiveness in reducing crashes, market penetration, legal implications, cost effectiveness and their contribution to TZD and an optimum solution has been provided.

For curves, curve flattening produced the highest effectiveness of 66%. However, curve flattening is among the most expensive safety treatment. Using effectiveness numbers from the Federal Highway Administration (FHWA), static curve warning systems *would appear* to provide the highest benefit:cost ratio. However, it is important to note that as a result of the cross-sectional and before:after analyses, approximately 80% of the curves studied were already equipped with static curve warning signs, *and these intersections still had high crash and fatality rates.* To improve safety, static curve warning signs should be complemented with additional countermeasures for curves of radii between 500 and 1,500 feet. For a given fixed safety budget, adding rumble strips gives the highest reduced number of fatalities, but chevron treatments provide the highest benefit:cost ratio. Engineers have to evaluate their situation, and can use the results presented herein to implement a cost-optimal safety strategy.

The paving of road shoulders was shown to have a safety benefit when the entirety of road shoulders studied in the before:after analysis was evaluated. However, what was not clear from the data is the effect of small incremental changes in shoulder width on safety; small sample sizes for some road sections precluded a conclusive result correlating safety results with paved shoulder width. Curiously, in a small number of instances, paving shoulders actually increased crash rates. However, overall, paved shoulders do provide a safety benefit.

The results of this research effort suggest two policy issues for Mn/DOT's consideration – the first dealing with horizontal curves and the second with paved shoulders.

## Policy Strategy: Curves

There is a notion that a greater margin of safety is associated with larger curve radii. The earlier work done in Texas and these results suggest that starting at around a 2,000 radius (3 degrees), the expected crash rate in curves approximates the average system crash rate for all two-lane state highways (it should be noted that curves account for about 5% of the system mileage). Potential policy implications include discouraging designers from selecting curve radii greater than 2,000 feet, solely based on the safety of vehicles traversing the curve and encouraging designers to give greater consideration to providing a more consistent design among curves along a particular segment of road as part of a context sensitive solution.

A typical practice in the application of traffic control devices on the approaches to and through horizontal curves is to defer to the guidance in the *Minnesota Manual on Uniform Traffic Control Devices* (MMUTCD). However, it appears that there is lack of any guidance about how to identify specific curves that are candidates for the application of traffic control devices. Potential policy implications involve preparing new guidelines for the MMUTCD that would require agencies to provide a higher level of consistency by calling for proactively placing signs based on curve radius and the relative degree of risk. For example:

- Curves > 2,000 feet – Low risk (Crash Rate = System average): No Advance Warning signs, Only rumble strips
- Curves > 1,500 feet & < 2,000 feet – Moderate risk (Crash rate = 2xSystem average): Advance Warning Sign
- Curves < 1,500 feet – High risk (Crash rate > 5xSystem average & 90% of fatal crashes): Advanced Warning + Chevrons + Rumble Strips

### Policy Strategy: Shoulders

The issue of paving shoulders along two-lane rural roads (and how to pay for the improvement) is a topic being discussed across Mn/DOT and by a number of county engineers. The results of both the Cross-Sectional and before:after generally indicate reduction in crashes associated with shoulder paving. The results of this research also found similar crash reductions associated with adding shoulder enhancements – edge line rumble strips/stripEs. Thus both treatments appear to have similar crash reductions, but when construction costs are considered, a possible policy direction emerges. The cost of adding paved shoulders ($60,000 - $100,000/mile) is 20 to 30 times the cost of adding edge line rumble stripEs ($3,000/mile). The policy would encourage designers to build as much safety into their projects as possible by adding paved shoulders plus edge line rumble stripEs on all construction/reconstruction projects but to focus limited HSIP funds on the edge line rumble stripEs due to their high cost-effectiveness and lower installation costs (which allows for a wider, proactive deployment across the system, consistent with the objectives in the SHSP).

An additional policy change appears worthy of consideration based on newly documented crash statistics. A review of Mn/DOT's *Road Design Manual* indicates that paved shoulders are only a required design feature on two-lane roads with daily traffic volumes greater than 3,000 vehicles per day and it appears that this guidance is based on the issue of exposure. However, a recent review of crash statistics along almost 1,700 miles of the two-lane Trunk Highways in Districts 3 and 7 found that roads with less than 3,000 ADT were more at risk – these lower volume roads had a higher fatal crash rate and twice as many severe road departure crashes. These statistics combined with the results of this study certainly suggests re-evaluating the current approach of basing shoulder paving decisions solely on exposure.

# Chapter 1: Introduction

## 1.1 Background

"BRIDGEPORT -- *Three people were injured in a two-car, nearly head-on crash on a stretch of East Main Street locally called 'Dead Man's Curve' late Friday…….*"[1.]

"*Merritt College student Cesar Sopelario, 21, died Dec. 19, a day after he lost control of his car in an accident at 35th and Victor avenues in Oakland -- otherwise known by residents of Redwood Heights as "crash curve."…….. "He just lost control of his car, because he was going too fast."……………… "Think of a racetrack -- the road is curved outward, and it naturally pulls the cars to the right," said Wladimir Wlassowsky, transportation services director for the city of Oakland…….The Department of Traffic Engineering and Oakland's transportation services have applied for a $1.2 million state grant under the Hazard Safety Improvement Program. The money would be used to re-grade the curve at 35th Avenue and a similarly problematic intersection at 73rd and Sunkist avenues.*"[1.]

"*More fender-benders and serious crashes have occurred this year on Interstate 44 after lanes were narrowed late last year to carry\ more traffic from Highway 40……..The overall increase reflects concerns many motorists had a year ago, when the Missouri Department of Transportation trimmed one foot from I-44's lanes, making them 11 feet wide along 12 miles of interstate. Shoulders also became skinnier and speed limits dropped to 55 mph from 60 mph.*"[2.]

The above incidents represent only some of the numerous incidents regarding vehicle crashes on roads.

Traffic crashes are the leading cause of death among persons from age 1 to 34 across the US [3.]. The importance of safety has been realized by many organizations including the American Association of State Highway and Transportation Officials (AASHTO), Federal Highway Administration (FHWA), National Highway Traffic Safety Administration (NHTSA). These organizations each have started programs as a measure towards curbing crashes. AASHTO has a Strategic Highway Safety Plan which focuses on road departure crashes occurring on horizontal curves [4.]. They claim that in 1998, 207 trucks were involved in rollover crashes along curves. The aim of this AASHTO program was to suggest strategies which would help in reducing the frequency and severity of curve related crashes. The highlights of their conclusions include the results of effectiveness of traditional and non-traditional advance curve warnings. Traditional curve warnings include signs advising the driver to slow down and it has been proved that they are 22% effective. In contrast, the much expensive dynamic curve warning signs with radars are 44% effective in reducing speeds [4.]. Realigning the curve such as increasing the radius is among the high cost long-term treatments which reduces crashes by 80%.

The Federal Highway Administration (FHWA) also is involved in a safety plan signed by President Bush on 10th August 2005. The Safe, Accountable, Flexible, Efficient, Transportation Equity Act: A Legacy for Users (SAFETEA-LU) introduced strategic highway safety plans and increased the resources for safety implementation for all states. It requires all the states to have a plan for crash data analysis and accordingly establish countermeasures. As per the requirement of the federal act, the comprehensive highway safety plan (CHSP) was updated to a strategic highway safety plan (SHSP).

Minnesota's Strategic Highway Safety Plan (SHSP) [5.] adopted a number of new safety priorities as a result of a data driven analytical process. The SHSP identified reducing the number of fatal crashes as the key safety objective, with fatal crashes as the new safety performance measure. In addition, the SHSP suggested developing new processes for allocating State and Federal Highway Safety funds – to be more in line with distribution of fatal crashes across Minnesota and between State and local highway systems. Key data include:

- 70% of fatal crashes in Minnesota occur in the 80 counties that are outside the Minneapolis/St. Paul metropolitan area.
- 48% of fatal crashes occur on the local highway system.
- On Mn/DOT's system of Trunk Highways, 80% of fatal crashes occur on highways that are considered rural.
- The County Highway System, which is overwhelmingly rural, has a fatality rate (1.3 fatalities per 100 million vehicle miles of travel) that is 30% higher than on similar State highways and 44% higher than the overall State wide average.

The SHSP also identified addressing single vehicle road departure crashes as one of Minnesota's Safety Emphasis Areas based on the fact that these types of crashes account for 32% of State wide fatalities, 36% of fatalities in Greater Minnesota and 47% of fatalities on local systems in Greater Minnesota. This data clearly indicates that the large number of traffic fatalities on State and local systems in rural areas associated with road departure crashes represents a pool of crashes susceptible to correction. However, this new focus on road departure crashes along rural highways also results in the need for better information about crash causation factors and the relative effectiveness of various mitigation strategies.

### 1.2 Problem Statement

In the year 2007, 510 people died in the state of Minnesota due to traffic fatalities and 35,318 were injured in accidents. The estimated cost to Minnesota due to this was more than $3.5 billion which is an average daily cost of more than $9 million. Crashes in Minnesota are categorized into 5 types as per the crash severity and accordingly monetary values are assigned to them in Figure 1.1 where A, B and C are severity types of crashes and PDO is property damage only.

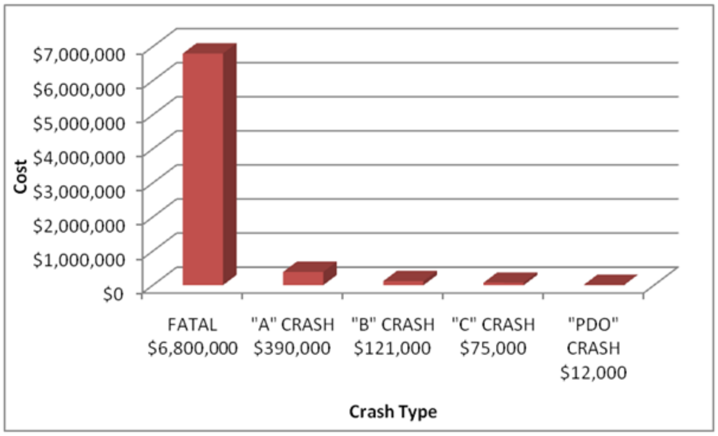


**Figure 1.1 Cost as Per Crash Severity Used in the State of Minnesota in 2009**

These values are based on the tangible and intangible consequences of crashes such as medical costs, emergency services costs, insurance payments, loss of market and household productivity, workplace costs, travel delay costs and property damage costs [6.]. The percentage of each is given in Figure 1.2 below.

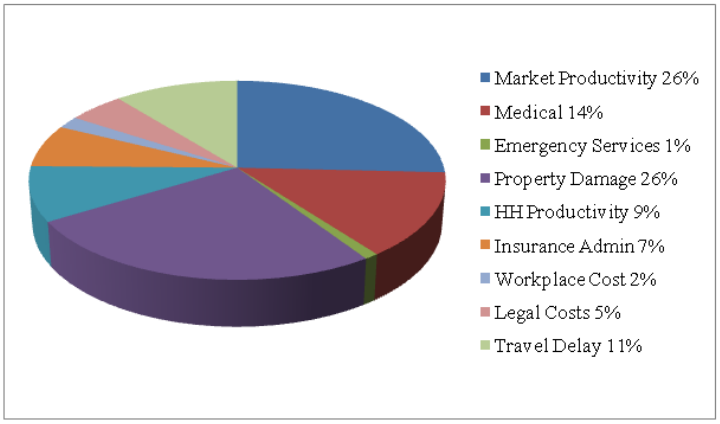


**Figure 1.2 Components of the Total Cost: Graph Created from Data in [6.]**

NHTSA has quantified the economic impact of these crashes. Public revenues pay around 9% of all these crash costs and 14% is paid by those not directly involved with these crashes, including uninvolved motorists caught up in traffic and delayed for work, health care providers and charities [6.].

Until 08 June 2009, Minnesota had no primary seat belt law. Until then the deaths due to non-restraint use were high. Seat belt usage increased in 2007 in Minnesota due to the I-35W bridge collapse [3.].

To summarize, both the 510 fatalities in MN in 2007 and the $3.5 billion economic loss need to be reduced. To reduce both, it is necessary to study the traditional infrastructure-based safety solutions and the emerging technology-based safety solutions.

The need for the day would be to install a safety technology which would be acceptable by the public and be a preventive safety device, that is, one which prevents the crash, not just reduces its impact.

### 1.3 Research Approach

The first task of this project identified the sections of the roads where road departure crashes were concentrated. There is a basic understanding in the industry that horizontal curves are more at-risk than tangent sections of highway (based on both crash rates and the over representation of crashes on a system wide basis) and that shoulders are considered to be safety features, but questions arise about details for which there are currently no good answers. These questions include:

- Are all horizontal curves equally at risk?
- Does the use of traffic control devices reduce/mitigate the risk in horizontal curves?
- Do all widths and types of shoulders equally contribute to safety?
- What are the effects of low-cost shoulder edge treatments (edge line rumble strips)?
- Do new technologies aimed at improving driver's ability to navigate along rural highways represent an opportunity to reduce road departure crashes?
- How does the expected effectiveness (based on crash reduction) of advanced technologies compare to infrastructure-based strategies?
- How much is the economic loss incurred to the state and the public due to these crashes?
- How can we reduce the frequency and severity of highway crashes and the economic losses and human suffering due to it?

The approach to conducting this phase of the research to provide answers to these questions consists of two basic components – a cross-sectional study and a before:after study of infrastructure-based components, followed by an evaluation of advanced technologies. The cross-sectional study compares different segments of roadway with similar features (for example, all 1-degree curves versus all 2-degree curves in a sample or all segments with 2-foot gravel shoulders versus all segments with 6-foot paved shoulders) and the before:after study compares the same segment of roadway in a pre- and post- implementation condition.

There are two possible approaches to conducting both the cross-sectional analysis and the before:after analysis – a census (inclusion of all possible locations) or a sampling (selection of a fraction of the possible locations). In order to be sensitive to budget and schedule constraints, it was determined that the research approach would involve identifying a sample of the possible curve and shoulder locations, with a sufficient number of locations in the sample in order to address concerns about statistical reliability.

The result of the selected research approach is the need to identify a sample of horizontal curve locations and roadway/shoulder segments. It was determined that the process for identifying the necessary samples would involve requesting the Mn/DOT Districts and the county highway departments to identify candidate locations on their systems. The Mn/DOT and county staff were asked to provide basic (location) information on a form (see Appendix A) that was included with the solicitation package. The information form was originally developed by CH2MHill staff and then refined based on review and comments provided by Mn/DOT staff. This form was sent out in December, 2007.

In an additional effort to secure candidate locations, CH2MHill conducted a field trip in Central Minnesota that resulted in adding 39 curves for the horizontal curve cross-sectional study, one curve for the before:after study, nine segments for the shoulder cross-sectional study and one segment for the shoulder before:after study. Following this field work, the candidate sites for each component of the research were tabulated. A summary is provided in Table 1.1, below and the individual sites are listed in Appendix B through Appendix E.

**Table 1.1 Site Summary**

| Research Component | Number of Sites | Goal | Appendix |
|---|---|---|---|
| Curves<br>Cross Section | 175 curves<br>Approx. 80 miles | 50 miles | B |
| Curves<br>Before:After | 21 curves | 20 curves | C |
| Shoulders<br>Cross Section | 140 Segments<br>940 miles | 200 miles | D |
| Shoulders<br>Before:After | 40 Segments<br>250 miles | 20 locations | E |

Other key points regarding the responses to the request for information include:

- Nineteen agencies provided responses – Six Mn/DOT districts and 13 county highway agencies.
- Candidate sites are located in each of Mn/DOT's eight districts and in 37 counties; as a result, it appears that the desired geographic distribution has been achieved.
- There are 52 candidate sites on the State's Trunk Highway System and 63 candidate sites on the various county highway systems; as a result, it appears that the desired distribution across road systems has been achieved.

The second set of research tasks were carried out by the University of Minnesota. Once the road sections were identified, these tasks

- Evaluated the crash effectiveness of infrastructure-based treatments
- Suggested different technology-based safety systems
- Calculated the benefits after implementing safety systems and the number of fatalities reduced due to them.

As per Figure 1.1, these crashes studied correspond to loss of money in the range of millions of dollars. Using safety systems, these fatalities can be reduced and money losses due to vehicle crashes can be avoided. However, implementing these safety solutions also requires certain amount of investment and it is desired that this money invested is less than the money saved due to reduced crashes. This is evaluating the cost effectiveness of the system. In other words, with fixed financial resources, the safety system suggested should reap the maximum benefits.

Safety systems can be broadly divided into two types

- Infrastructure-based: These include road signs, rumble strips, curve flattening, paving shoulders.
- Technology-based: Technology-based solutions are further divided in two parts- technology-based infrastructure solutions, such as dynamic curve warning signs with radar and in-vehicle technologies such as lane departure warning systems.

It is within the scope of this project to study the benefit versus cost tradeoffs for the above systems and suggest changes that can be implemented at the curves and tangential sections. This way the crashes are reduced by expending the least amount of resources.

Another criterion to consider is the contribution of the system to help Mn/DOT achieve its Toward Zero Deaths Goal. TZD has a mission statement: "To move Minnesota toward zero deaths on our roads, using education, enforcement, engineering, and emergency services." Mn/DOT has always been striving to increase the safety on roads. TZD can be conceived with use of safety solutions which are highly efficient in reducing the crashes. As per CHSP, the emphasis is to reduce the number of traffic fatalities and not just fatality rates.

It is the aim of this project to identify a system which would cost low enough to justify the benefits reaped as well as be highly efficient to take the state towards its goal of TZD.

The further sections of this paper are going to include sections on analysis conducted by CH2MHill, evaluating the efficiencies of various infrastructure and technology-based solutions and computing their benefit:cost ratios. At the same time the benefit of their state wide implementation is studied with respect to reduced number of fatalities. This would give us a preferred solution in order to avoid crashes along curves and tangential sections.

## 1.4 Overview of Previous Research

A search was conducted that identified recently published research reports that deal with safety issues associated with horizontal curves, shoulder type and width and technological based solutions. Each report is identified and an overview of the key conclusions is provided in the following paragraphs.

### 1.4.1 Low Cost Treatments for Horizontal Curve Safety, Report No. FHWA-SA-07-002[8.]

Authors – McGee, Hugh and Hanscom, Fred
Performing Organization – Vanasse Hagen Brustlin, Inc. (VHB)
Sponsoring Agency – Federal Highway Administration
Report Date – December 2006

Overview – Nearly 25% of fatal crashes occur in or near a horizontal curve, as a result, addressing safety deficiencies at horizontal curves is one of the 22 Safety Emphasis Areas identified by AASHTO in their Strategic Highway Safety Plan. In addition, crashes at horizontal curves are a factor contributing to the problem of road departure crashes, which is one of FHWA's focus areas. The document provides a synthesis of low-cost treatments that can be applied at horizontal curves to address identified or potential safety deficiencies. The treatments include:

- Basic signs and markings found in the MUTCD (curve warning signs, chevrons, edge lines, etc.)
- Enhanced traffic control devices (larger devices, multiple devices, flashing beacons and raised markings)
- Additional traffic control devices not found in the MUTCD (dynamic curve warning systems, speed advisories, barriers, etc.)
- Rumble strips (centerline and shoulder)
- Minor Roadway Improvements (shoulder and edge treatments)
- Innovative and Experimental Treatments (optical speed bars and other pavement markings)

This report provides a very thorough description of available low-cost treatments for horizontal curves including what is known regarding the relative effectiveness. However, there is no insight about the application of these treatments beyond what is already provided in the MUTCD. For example, the MUTCD is very prescriptive about using the Curve sign when the advisory speed is greater than 30 MPH and the Turn sign when the advisory speed is 30 MPH or less. However, the MUTCD provides no guidance relative to the selection of particular curves for the installation of advance warning signs and this report does not provide any additional suggestions beyond the use of engineering judgment. In addition, there is no consideration of a systematic approach to curve signing or a discussion of the potential risks of not using a systematic approach to the use of Curve signs.

### 1.4.2 Horizontal Curve Signing Handbook, Report No. FHWA/TX-07/0-5439-P1 [9.]

Authors – Bonneson, J., Pratt, M., Miles, J. and Carlson, P.
Performing Organization – Texas Transportation Institute
Sponsoring Agency – Texas Department of Transportation
Report Date – October, 2007

Overview – Horizontal curves are a necessary component of the highway alignment; however, they tend to be associated with a disproportionate number of severe crashes. Warning signs are intended to improve curve safety by alerting the driver of a change in geometry that may not be apparent or expected. However, several research projects conducted over the past 20 years have consistently shown that drivers are not responding to curve warning signs or complying with posted advisory speeds.

The Handbook was developed in order to address the fact that about 1,400 fatal crashes occur each year on horizontal curves in Texas (44%) and this frequency indicates that Texas is over-represented in terms of its proportion of fatal curve related crashes, relative to the national average.

The two most intriguing aspects of this Report include; a description of the relationship between curve radius and crash rate (Figure 1.3) – crash rates increase sharply for curves with a radius of less than 1,000 feet and the development of a set of guidelines for the selection of curve related traffic control devices based on assigning curves to a severity category determined by the speed differential between the tangent and the curve (Figure 1.4).

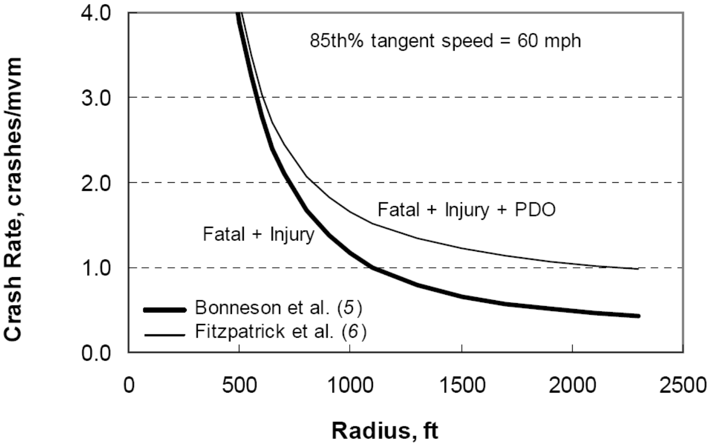
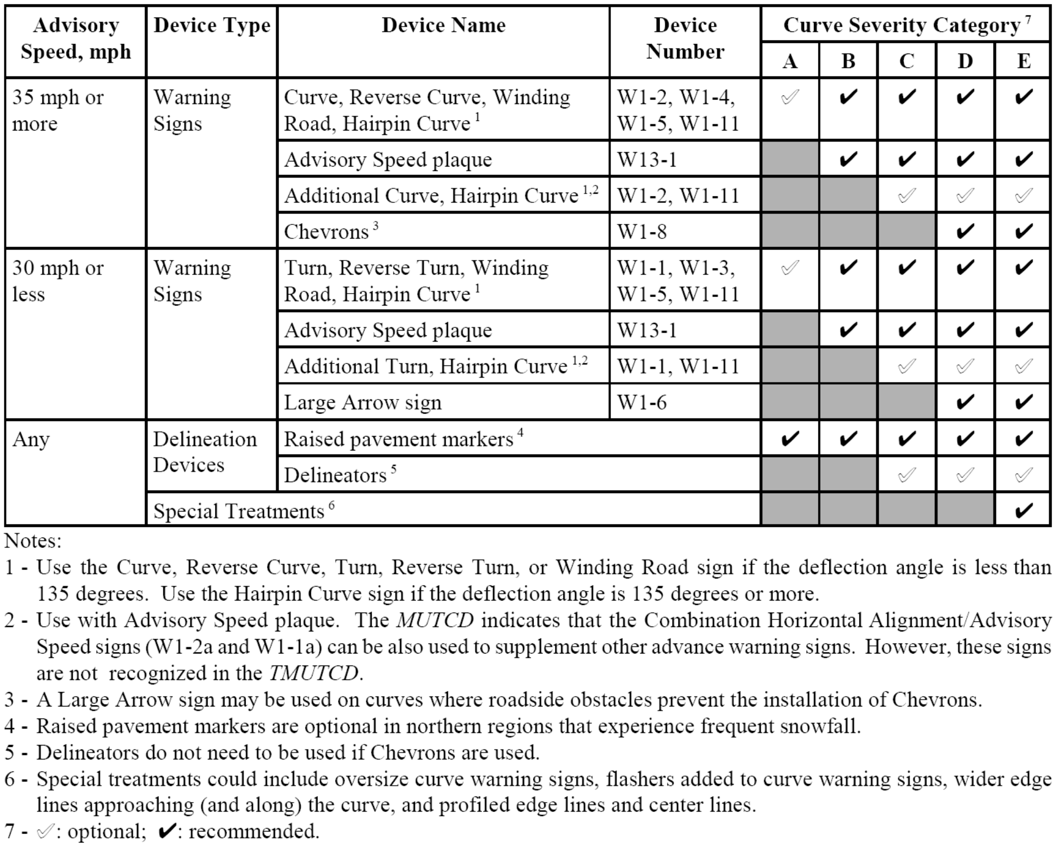


**Figure 1.3 Curve Crash Rate as a Function of Radius (Reprinted from [9.])**

**Table 1.2 Guidelines for the Selection of Curve-Related Traffic Control Devices (Reprinted from [9.])**



| Advisory Speed, mph | Device Type | Device Name | Device Number | Curve Severity Category [7] | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | A | B | C | D | E |
| 35 mph or more | Warning Signs | Curve, Reverse Curve, Winding Road, Hairpin Curve [1] | W1-2, W1-4, W1-5, W1-11 | ✓ | ✔ | ✔ | ✔ | ✔ |
| | | Advisory Speed plaque | W13-1 | ▨ | ✔ | ✔ | ✔ | ✔ |
| | | Additional Curve, Hairpin Curve [1,2] | W1-2, W1-11 | ▨ | ▨ | ✓ | ✓ | ✓ |
| | | Chevrons [3] | W1-8 | ▨ | ▨ | ▨ | ✔ | ✔ |
| 30 mph or less | Warning Signs | Turn, Reverse Turn, Winding Road, Hairpin Curve [1] | W1-1, W1-3, W1-5, W1-11 | ✓ | ✔ | ✔ | ✔ | ✔ |
| | | Advisory Speed plaque | W13-1 | ▨ | ✔ | ✔ | ✔ | ✔ |
| | | Additional Turn, Hairpin Curve [1,2] | W1-1, W1-11 | ▨ | ▨ | ✓ | ✓ | ✓ |
| | | Large Arrow sign | W1-6 | ▨ | ▨ | ▨ | ✔ | ✔ |
| Any | Delineation Devices | Raised pavement markers [4] | | ✔ | ✔ | ✔ | ✔ | ✔ |
| | | Delineators [5] | | ▨ | ▨ | ✓ | ✓ | ✓ |
| | Special Treatments [6] | | | ▨ | ▨ | ▨ | ▨ | ✔ |

Notes:

1 - Use the Curve, Reverse Curve, Turn, Reverse Turn, or Winding Road sign if the deflection angle is less than 135 degrees. Use the Hairpin Curve sign if the deflection angle is 135 degrees or more.

2 - Use with Advisory Speed plaque. The *MUTCD* indicates that the Combination Horizontal Alignment/Advisory Speed signs (W1-2a and W1-1a) can be also used to supplement other advance warning signs. However, these signs are not recognized in the *TMUTCD*.

3 - A Large Arrow sign may be used on curves where roadside obstacles prevent the installation of Chevrons.

4 - Raised pavement markers are optional in northern regions that experience frequent snowfall.

5 - Delineators do not need to be used if Chevrons are used.

6 - Special treatments could include oversize curve warning signs, flashers added to curve warning signs, wider edge lines approaching (and along) the curve, and profiled edge lines and center lines.

7 - ✓: optional; ✔: recommended.

The curve radius vs. crash rate graph appears to be the first real documentation that all curves are not equally likely to adversely affect safety: long radius curves (radii > 2,000 feet) have crash rates that are similar to tangents and short radius curves (radii < 1,00 feet) have crash rates more than twice that of the tangents. The application guidelines that provide a mapping process from a curve severity category to a short list of suggested traffic control devices is also a first and supports the notion of a systematic/proactive application of traffic control devices.

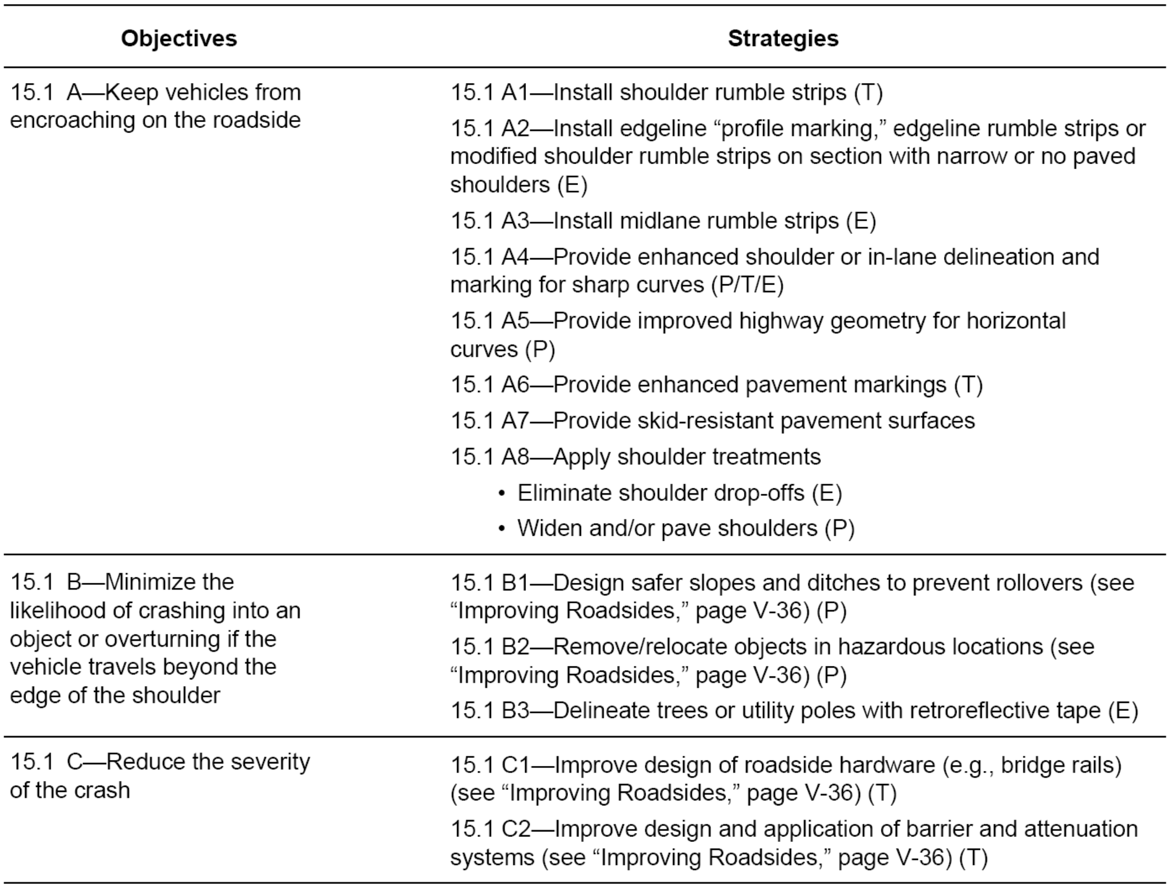
### 1.4.3 NCHRP Report 500 Volume 6: A Guide for Addressing Run-Off-Road Collisions

Authors – Neuman, T., Pfefer, R., Slack, K., Hardy, K, Council, F., McGee, H.
Performing Organization – CH2M HILL, Maron Engineering, and BMI
Sponsoring Agencies – Transportation Research Board, AASHTO and FHWA
Report Date – 2003

Overview – AASHTO's Strategic Highway Safety plan identified 22 goals to pursue in order to significantly reduce the number of highway crash fatalities. The NCHRP Series 500 Reports provide a synthesis of strategies for each of AASHTO's safety emphasis areas. The strategies were developed by and filtered through a panel of experts including both academics and practitioners. In addition, the Series 500 Reports introduce the concept of evaluating safety strategies on their effectiveness – Proven, Tried or Experimental.

Goal 15 – Keep Vehicles on the Roadway and Goal 16 – Minimize the Consequences of Leaving the Road evolved into a safety emphasis area focused on reducing the number of run–off-road crashes. The strategies documented in Volume 6 are organized into three basic objectives - Keep Vehicles on the Road, Provide Clear Recovery Areas and Improve Highway Hardware (Figure 1.5).

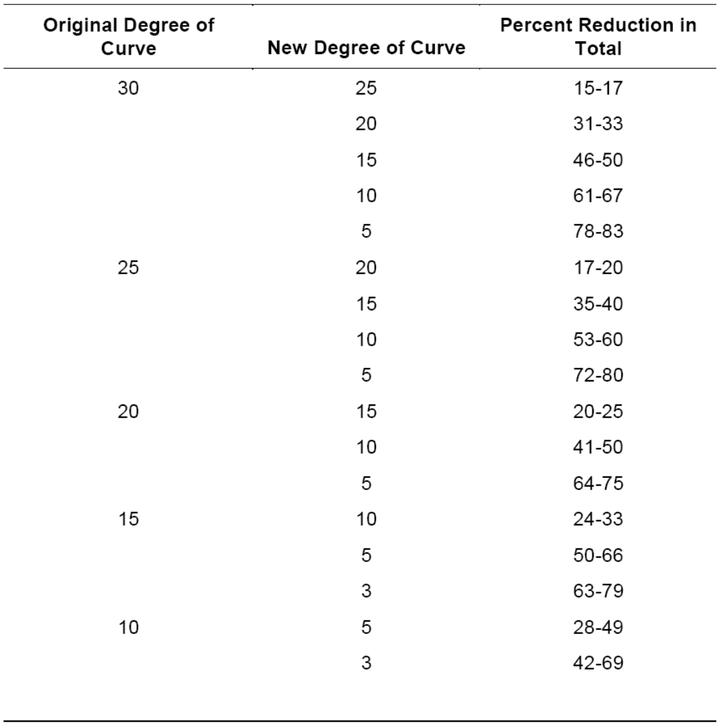
**Table 1.3 Off-Road Emphasis Area Objectives and Strategies (Reprinted with Permission from [10.])**



| Objectives | Strategies |
|---|---|
| 15.1 A—Keep vehicles from encroaching on the roadside | 15.1 A1—Install shoulder rumble strips (T) |
| | 15.1 A2—Install edgeline “profile marking,” edgeline rumble strips or modified shoulder rumble strips on section with narrow or no paved shoulders (E) |
| | 15.1 A3—Install midlane rumble strips (E) |
| | 15.1 A4—Provide enhanced shoulder or in-lane delineation and marking for sharp curves (P/T/E) |
| | 15.1 A5—Provide improved highway geometry for horizontal curves (P) |
| | 15.1 A6—Provide enhanced pavement markings (T) |
| | 15.1 A7—Provide skid-resistant pavement surfaces |
| | 15.1 A8—Apply shoulder treatments<br>• Eliminate shoulder drop-offs (E)<br>• Widen and/or pave shoulders (P) |
| 15.1 B—Minimize the likelihood of crashing into an object or overturning if the vehicle travels beyond the edge of the shoulder | 15.1 B1—Design safer slopes and ditches to prevent rollovers (see “Improving Roadsides,” page V-36) (P) |
| | 15.1 B2—Remove/relocate objects in hazardous locations (see “Improving Roadsides,” page V-36) (P) |
| | 15.1 B3—Delineate trees or utility poles with retroreflective tape (E) |
| 15.1 C—Reduce the severity of the crash | 15.1 C1—Improve design of roadside hardware (e.g., bridge rails) (see “Improving Roadsides,” page V-36) (T) |
| | 15.1 C2—Improve design and application of barrier and attenuation systems (see “Improving Roadsides,” page V-36) (T) |

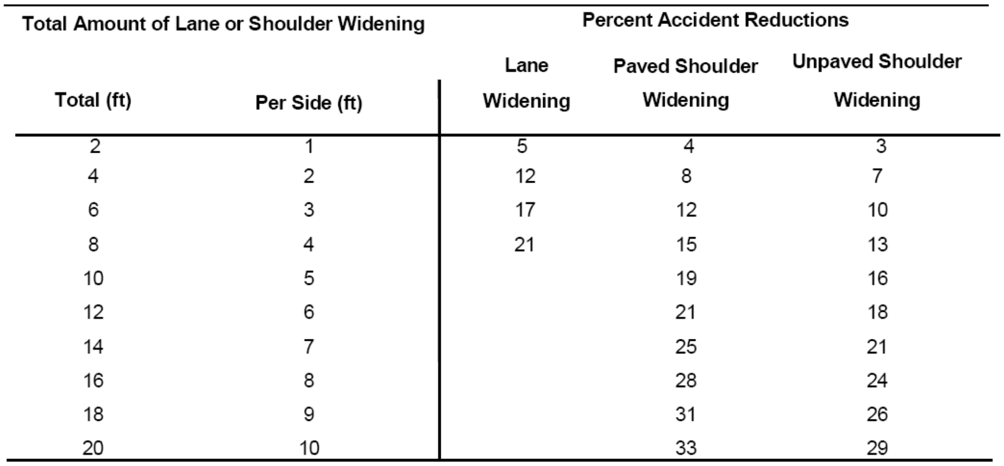
Two items in Volume 6 are of particular interest. Strategy 15.1 A5 focuses on improved highway geometry for horizontal curves. Estimate of the expected crash reduction are provided for projects that reduce the degree of curvature (Table 1.2) and for projects that widen either the lane or shoulder width (Table 1.3). The information indicates that a crash reduction in the range of 28 – 49 percent can be expected if a 10 degree curve is improved to a 5 degree curve and a crash reduction of 15% can be expected if a 4 foot paved shoulder is added.

## Table 1.4 Percentage Reduction in Total Crashes on Two-Lane Rural Roads Due to Curve Flattening (Reprinted with Permission from [10.])



| Original Degree of Curve | New Degree of Curve | Percent Reduction in Total |
|---|---|---|
| 30 | 25 | 15-17 |
| | 20 | 31-33 |
| | 15 | 46-50 |
| | 10 | 61-67 |
| | 5 | 78-83 |
| 25 | 20 | 17-20 |
| | 15 | 35-40 |
| | 10 | 53-60 |
| | 5 | 72-80 |
| 20 | 15 | 20-25 |
| | 10 | 41-50 |
| | 5 | 64-75 |
| 15 | 10 | 24-33 |
| | 5 | 50-66 |
| | 3 | 63-79 |
| 10 | 5 | 28-49 |
| | 3 | 42-69 |

## Table 1.5 Percentage Reduction in Total Crashes on Two-Lane Rural Roads Due to Shoulder Widening (Reprinted with Permission from [10.])



| Total Amount of Lane or Shoulder Widening | | Percent Accident Reductions | | |
|---|---|---|---|---|
| Total (ft) | Per Side (ft) | Lane Widening | Paved Shoulder Widening | Unpaved Shoulder Widening |
| 2 | 1 | 5 | 4 | 3 |
| 4 | 2 | 12 | 8 | 7 |
| 6 | 3 | 17 | 12 | 10 |
| 8 | 4 | 21 | 15 | 13 |
| 10 | 5 | | 19 | 16 |
| 12 | 6 | | 21 | 18 |
| 14 | 7 | | 25 | 21 |
| 16 | 8 | | 28 | 24 |
| 18 | 9 | | 31 | 26 |
| 20 | 10 | | 33 | 29 |

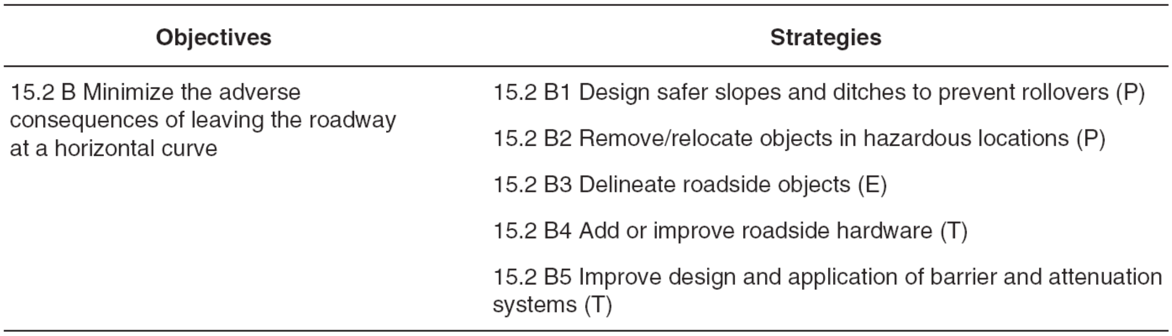
### 1.4.4 NCHRP Report 500 Volume 7: A Guide for Addressing Collisions on Horizontal Curves [11.]

Authors – Torbic, D., Harwood, D., Gilmore, D., Pfefer, R. Neuman, T., Slack, K. and Hardy, K.
Performing Organization – Midwest Research Institute, Maron Engineering, and CH2M HILL
Sponsoring Agencies - Transportation Research Board, AASHTO and FHWA

Overview – Volume 7 of the 500 Series Reports focuses on mainly low-cost strategies for addressing safety in horizontal curves (Table 1.4) that are focused on three objectives; Keep Vehicles in their Lane Provide a Clear Recovery Area and Improve Highway Hardware. These objectives are virtually identical to those in Volume 6, so there is a great deal of overlap among the strategies and the supplemental discussion of effectiveness.

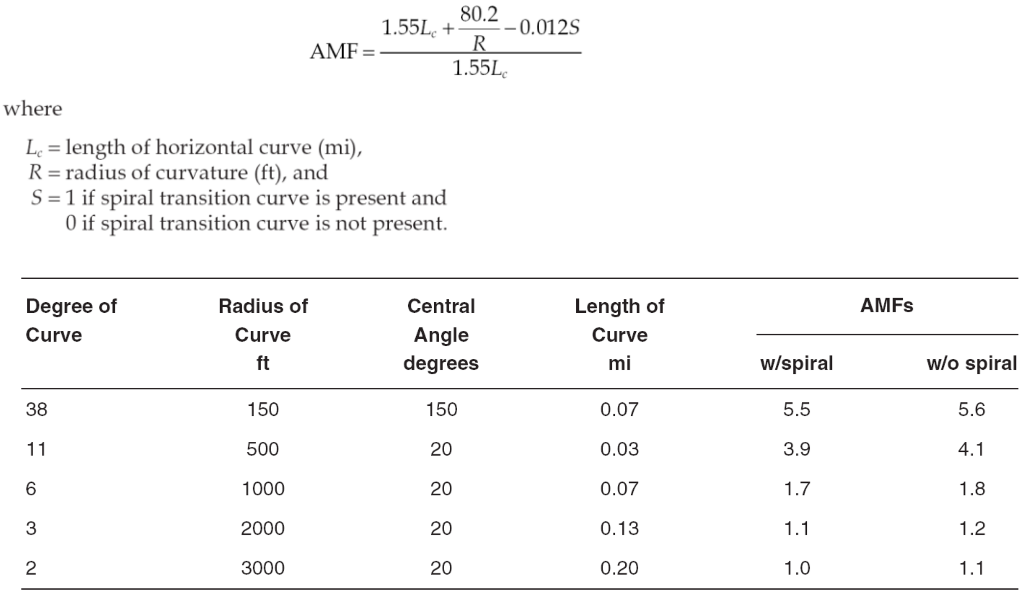
Volume 7 contains one new item; information is provided (Table 1.5) that demonstrates that spiral transitions are effective at reducing crashes.

**Table 1.6 Objectives and Strategies for Improving Safety at Horizontal Curves (Reprinted with Permission from [11.])**



| Objectives | Strategies |
|---|---|
| 15.2 B Minimize the adverse consequences of leaving the roadway at a horizontal curve | 15.2 B1 Design safer slopes and ditches to prevent rollovers (P) |
| | 15.2 B2 Remove/relocate objects in hazardous locations (P) |
| | 15.2 B3 Delineate roadside objects (E) |
| | 15.2 B4 Add or improve roadside hardware (T) |
| | 15.2 B5 Improve design and application of barrier and attenuation systems (T) |

**Table 1.7 AMFS for Horizontal Curves with and without Spiral Transitions (Reprinted with Permission from [11.])**



$$\mathrm{AMF} = \frac{1.55L_c + \dfrac{80.2}{R} - 0.012S}{1.55L_c}$$

where

$L_c$ = length of horizontal curve (mi),
$R$ = radius of curvature (ft), and
$S$ = 1 if spiral transition curve is present and 0 if spiral transition curve is not present.

| Degree of Curve | Radius of Curve ft | Central Angle degrees | Length of Curve mi | AMFs | |
|---|---|---|---|---|---|
| | | | | w/spiral | w/o spiral |
| 38 | 150 | 150 | 0.07 | 5.5 | 5.6 |
| 11 | 500 | 20 | 0.03 | 3.9 | 4.1 |
| 6 | 1000 | 20 | 0.07 | 1.7 | 1.8 |
| 3 | 2000 | 20 | 0.13 | 1.1 | 1.2 |
| 2 | 3000 | 20 | 0.20 | 1.0 | 1.1 |

### 1.4.5 ***Desktop Reference for Crash Reduction Factors,* Report No. FHWA–SA-07-015 [12.]**

Authors – Bahar, J., Masliah, M., Wolff, R., Park, P.
Performing Organizations – iTrans Consulting Ltd., Vanasse Hangen Brustlin, Inc.
Sponsoring Organization – U.S. Department of Transportation, Federal Highway Administration

Overview – The *Desktop Reference* documents the estimates of the crash reduction that might be expected if a specific countermeasure is implemented with respect to intersections, roadway departure and pedestrian crashes. The documented Crash Reduction Factors (CFR's) represent the best information assembled to date. However, the authors note that it remains necessary to apply engineering judgment and to consider site specific conditions when using the CFR's to estimate the safety effectiveness of safety improvements.

Specifically relating to road departure crashes, the *Desktop Reference* includes the following CFR's:

- Install Chevrons – three studies, 20 to 50% reduction
- Install Curve Warning signs – four studies, 10 to 30% reduction
- Shoulder improvements – four studies, 5 to 30% reduction

The *Desktop Reference* does not include any CFR's for technology applications relating to road departure crashes.

# Chapter 2: Cross-Sectional Analysis

A study was conducted by CH2MHill to assess the importance of road geometry in crashes. The road sections are divided into curves and tangential sections.

The basic objective of the cross-sectional analysis is to determine if crash characteristics of rural 2-lane highways varies as a result of differences in selected design features including:

- Curve radii
- Other curve attributes (traffic control devices)
- Shoulder width
- Shoulder material
- Shoulder enhancements (edge line rumble strips/stripes)

The approach to conducting the cross-sectional study consisted of comparing different segments of roadway with similar features; for example, all 1-degree curves versus all 2-degree curves in a sample or all segments with 2-foot gravel shoulders versus all segments with 6-foot paved shoulders. The curve locations and highway segments were identified through responses to a survey of practice that was sent to each of Mn/DOT's eight Districts and to 87 county highway engineers.

## 2.1 Cross-Sectional Study: Curves

### 2.1.1 Total Number of Curves in Data Set

The data set of curves was assembled from candidate locations submitted by Mn/DOT Districts and County Highway Departments in response to a survey of practice and was then supplemented with curves that were reviewed as part of countywide road safety audit reviews in three Counties – Freeborn, Meeker and Koochiching. The complete data set includes 204 curves, all of which are located along rural two-lane State (57 curves) and County Highways (147 curves). The curves on the State system represent six of Mn/DOT's eight Districts (1, 2, 4, 6, 8 and Metro) and the curves on the County system represent 16 Counties that are generally distributed around the State (Figure 2.1 and Table 2.1). It should be noted that curves on expressways, freeways and in urban areas were excluded from the sample because of documented differences in crash characteristics among the various highway facility types and between rural and urban areas.

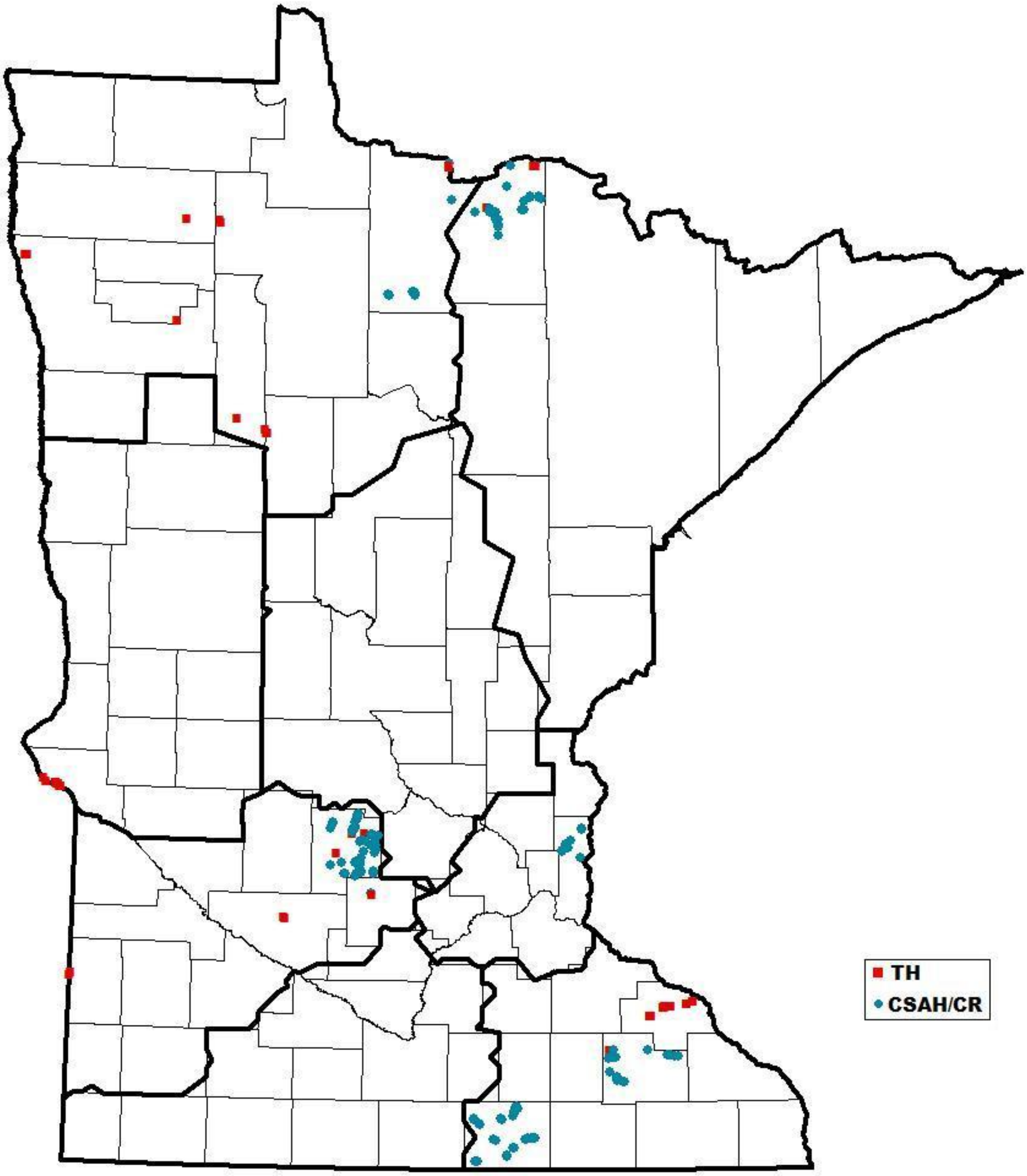


Figure 2.1 Map of Curve Locations

## Table 2.1 Curves by County and District

| | | ***# Curves*** | | | ***Miles*** | | |
|---|---|---|---|---|---|---|---|
| | | *Total* | *State* | *County* | *Total* | *State* | *County* |
| ***County*** | Red Lake | 1 | 1 | | 0.40 | 0.40 | |
| | Marshall | 1 | 1 | | 0.40 | 0.40 | |
| | Clearwater | 1 | 1 | | 0.30 | 0.30 | |
| | Polk | 2 | 2 | | 1.10 | 1.10 | |
| | Beltrami | 2 | 2 | | 0.80 | 0.80 | |
| | McLeod | 2 | 2 | | 0.45 | 0.45 | |
| | Lincoln | 2 | 2 | | 0.56 | 0.56 | |
| | Renville | 2 | 2 | | 0.62 | 0.62 | |
| | Hubbard | 3 | 3 | | 2.10 | 2.10 | |
| | Washington | 8 | | 8 | 1.48 | | 1.48 |
| | Big Stone | 11 | 11 | | 1.70 | 1.70 | |
| | Olmsted | 19 | | 19 | 2.86 | | 2.86 |
| | Wabasha | 19 | 19 | | 1.52 | 1.52 | |
| | Freeborn | 28 | | 28 | 4.70 | | 4.70 |
| | Koochiching | 49 | 9 | 40 | 6.57 | 0.92 | 5.65 |
| | Meeker | 54 | 2 | 52 | 8.96 | 0.50 | 8.46 |
| | *Total* | *204* | *57* | *147* | 34.52 | 11.37 | 23.15 |
| ***Mn/DOT District*** | 1 | 49 | 9 | 40 | 6.57 | 0.92 | 5.65 |
| | 2 | 10 | 10 | | 5.10 | 5.10 | |
| | 4 | 11 | 11 | | 1.70 | 1.70 | |
| | 6 | 66 | 19 | 47 | 9.08 | 1.52 | 7.56 |
| | 8 | 60 | 8 | 52 | 10.59 | 2.13 | 8.46 |
| | M | 8 | | 8 | 1.48 | | 1.48 |
| | *Total* | *204* | *57* | *147* | 34.52 | *11.37* | *23.15* |

### 2.1.2 Total Length of Curves in Data Set

The average length and the total length of the 204 curves were computed (Length = 100 x Delta Angle/Degree of Curve) to be 0.17 miles per curve and 35 miles, respectively. This total length is less than the 50 mile goal suggested in the Work Scope; however, the 50 mile goal was included in order to create a data set with a sufficient number of curve candidates and a sufficient number of crashes. When the Work Scope was written, it was assumed that the curves would be between 0.25 and 0.5 miles in length and that 50 miles of curves would result in between 100 and 200 curves. Given that the data set includes 204 curves, it was concluded that the intent of the goal is effectively met.

### 2.1.3 Daily Traffic Volume

The average daily traffic volume in the curves was 860 vehicles per day and the range was 50 to 6,900 vehicles per day. This range of volume is representative of rural roads in Minnesota and is consistent with the objective to focus this research on roadways considered rural.

### 2.1.4 Curve Radii

The average radius of the 204 curves was approximately 1,200 feet (4.8 degrees) and the range was 100 feet (57 degrees) to 5,600 feet (1 degree). Disaggregating the data set into 500-foot subsets (Figure 2.2) indicates the distribution across the range of curve radii. Each subset contains between 9 and 55 curves and suggests that there is sufficient number of curves to determine the curve radii/crash rate relationship.

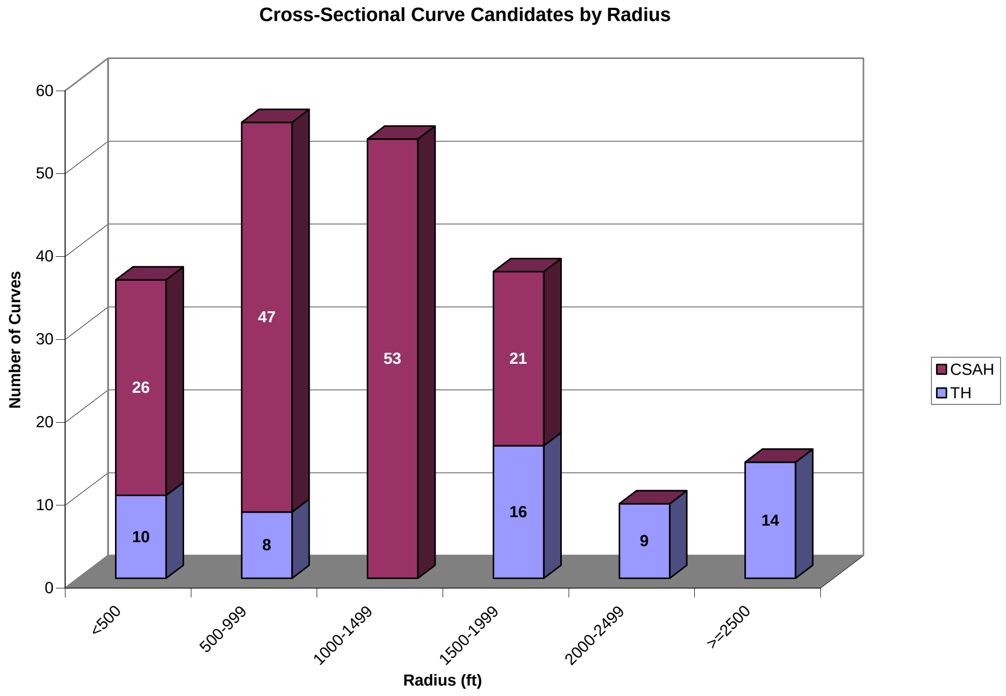


Figure 2.2 Distribution of Curves by Radii

### 2.1.5 Number of Crashes

There were a total of 262 crashes in the 204 curves in the data set. The average number of crashes per curve is between 0.1 to 0.2 crashes per curve per year. Computing a more exact average is not entirely straight forward because the number of years of data for each curve varies from 5 to 10 years. The total number of crashes at individual curves varied from zero (111 curves or 55% of the data set) to one location (TH 7 East of TH 22 in McLeod County) with 15 crashes in a 10 year period (Figure 2.3). This data supports the idea that crashes in curves are rare – the highest crash frequency curve averages just 1.5 crashes per year. This in turn suggests that the most effective method of dealing with crashes in curves is a systematic approach because there are just too few crashes (even at the worst locations) to identify potentially at-risk curves using a traditional Black Spot approach. It should be noted that this finding, supporting a systematic approach to addressing crashes in curves, is consistent with results of countywide safety studies (in Freeborn, Meeker and Koochiching Counties) that identified proactively addressing curve safety across their system of County highways as a top priority based on documenting 40 to 50% of all road departure crashes occurring in curves.

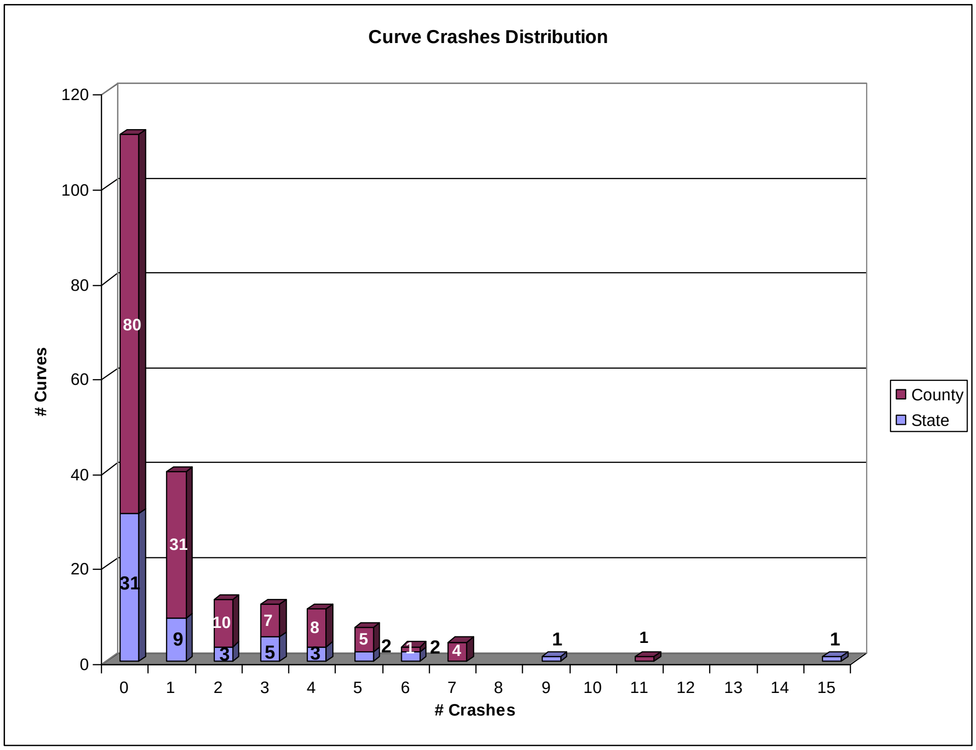


Figure 2.3 Distribution of Curves by Number of Crashes

### 2.1.6 Crash Severity

The crashes in the data set included 9 fatal crashes (3%), 115 injury crashes (44%) and 138 property damage crashes (53%). This distribution is more severe than the average for all crashes in Minnesota, where less than 1% of crashes are fatal and approximately 30% involve injuries. Disaggregating the crash severity by radii (Figures 2.4 and 2.5) indicates that crashes tend to be more severe in curves with shorter radii. For example, the curves with radii greater than 2,500 feet had 90% property damage crashes, 10% injury crashes and no fatal crashes. This compares to curves with radii less than 2,500 feet that had 50% property damage crashes, 47% injury crashes and 3% fatal crashes. In addition, all of the fatal crashes occurred in curves with radii less than 2,000 feet and of these fatal crashes, curves with radii between 1,000 and 1,499 feet had the highest number (4) and curves with radii less than 500 had the highest percentage (5%).

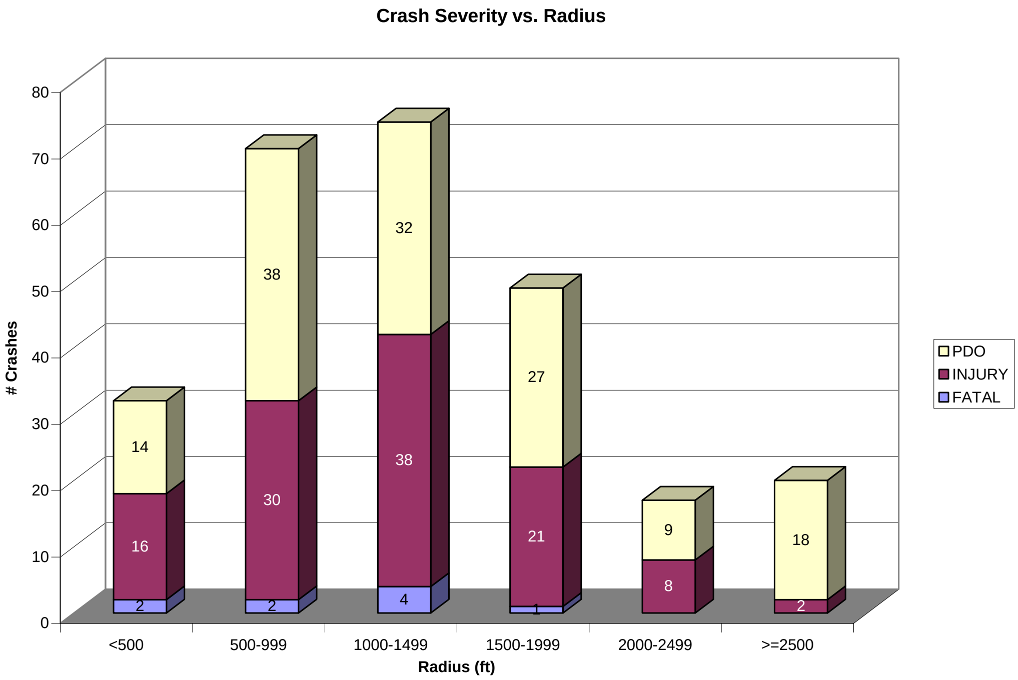


Figure 2.4 Distribution of Crash Severity by Radii

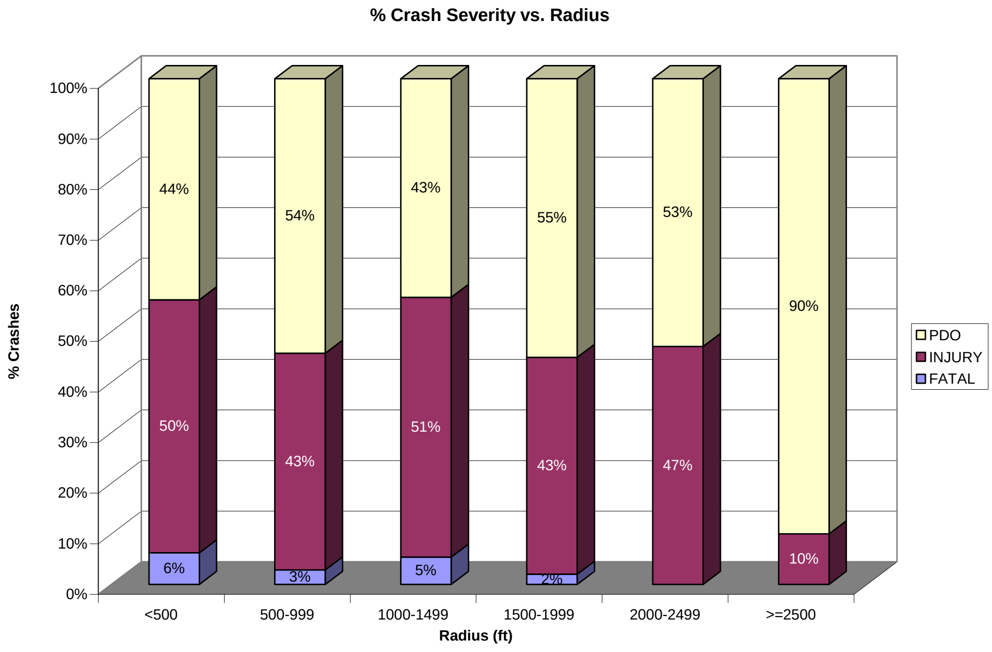


Figure 2.5 Crash Severity Percentages by Radii

### 2.1.7 Crash Type

The crashes in the data set were disaggregated by crash type (Figure 2.6) and the results were then compared to expected values for all crashes on rural roads. The results indicate that road departure crashes, particularly to the right, are over represented. The percentages for all other crash types are below expected values.

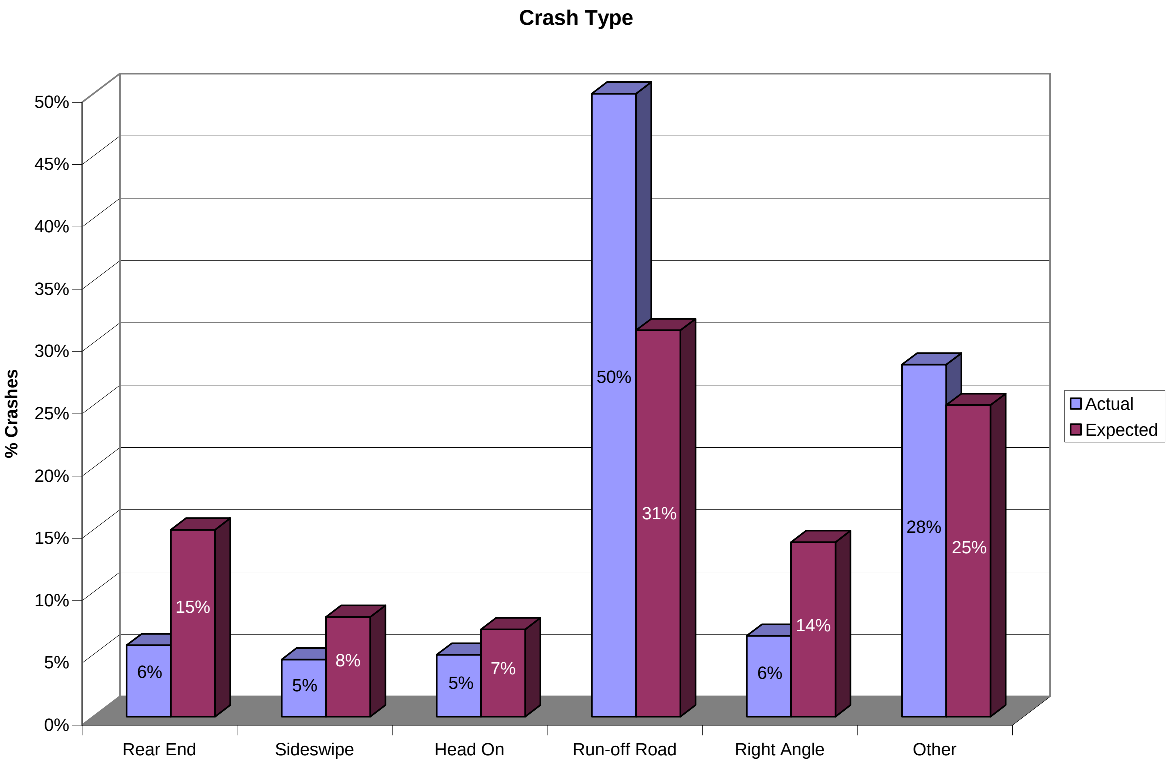


**Figure 2.6 Percentages of Crash Types**

### 2.1.8 Crash Rate

Crash rates were computed for the each of the 93 curves with crashes, using the formula:

Crash Rate = Number of Crashes/Exposure in Millions of Vehicle Miles Annually

The computed rates varied widely, from less than 1 crash/MVM to more than 50 crashes/MVM (Figure 2.7). A wide variation in crash rates was expected and the very high rates are likely due to the combination of a few crashes, low volumes and the very short length of most of the curves. The calculated crash rates were then plotted against the curve radius (Figure 2.8) and a least squares trend line was fit to the data (Figure 2.9). The results indicate that crash rates increase greatly as curve radii decrease, beginning at curves with radii around 2,000 feet. At curve radii of 1,500 feet, the crash rate increases by a factor of two; at1,000 feet, the rate increases by a factor of five; and at 500 feet, the rate increases by a factor of eleven. It should be noted that the shape of this trend line is similar to the one in the Research Report prepare by Texas Transportation Institute that was discussed in Chapter 1 – Overview of previous research.

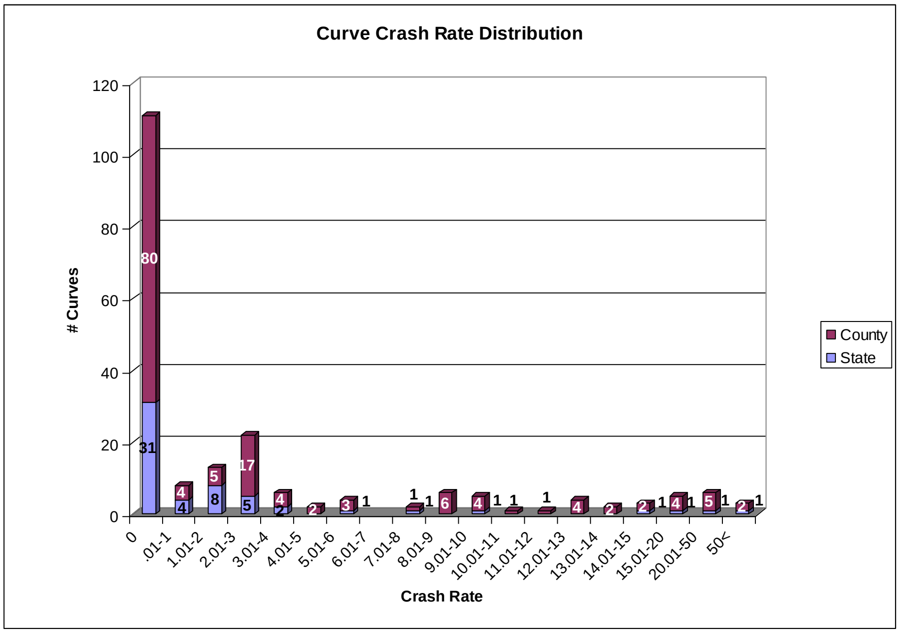


Figure 2.7 Distribution of Curves by Crash Rate

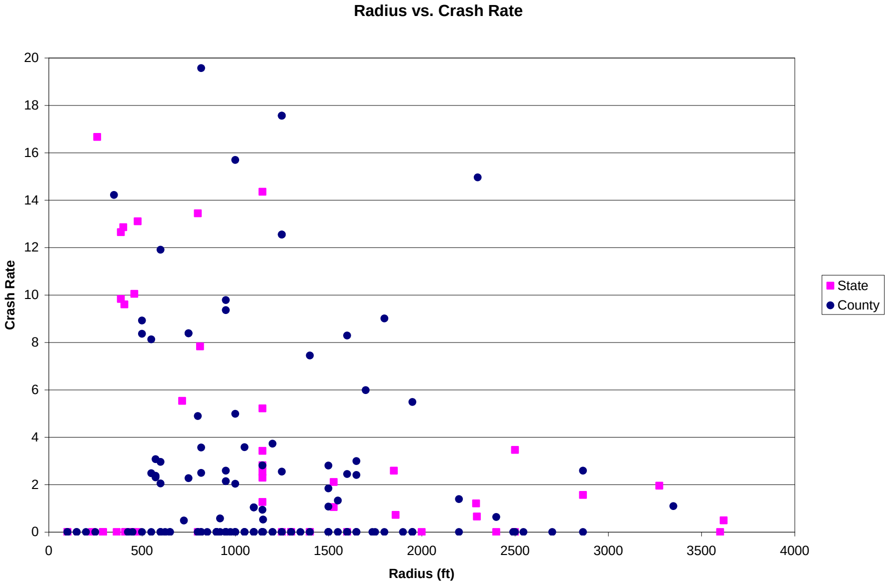


Figure 2.8 Crash Rate by Radii

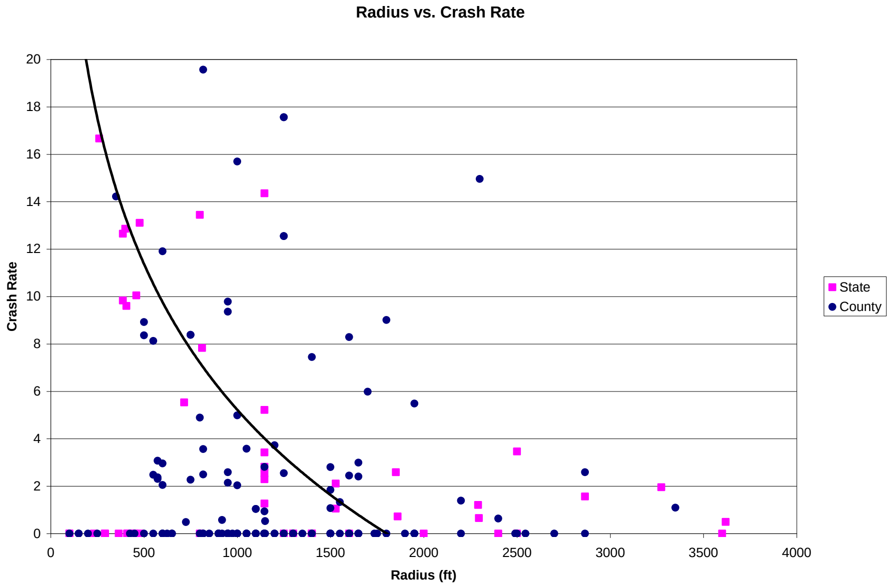


Figure 2.9 Crash Rate by Radii with Trend Line

Severity rates (Figures 2.10 and 2.11) and Fatal Crash rates (Figure 2.12 and 2.13) were also computed and then plotted against the curve radii. These data indicate a similar trend as for all crashes, rates rise as curve radii decreases, starting at radii around 2,000 feet.

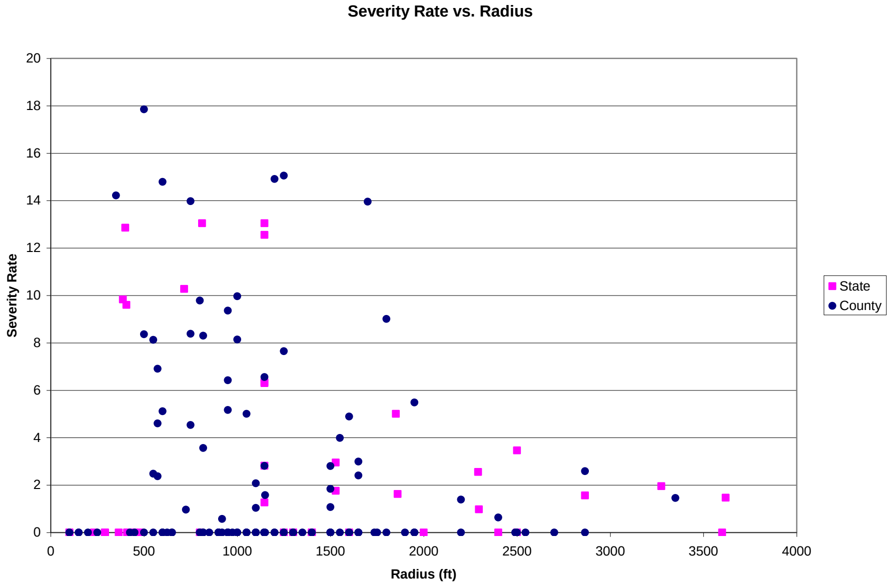


Figure 2.10 Severity Rate by Radii

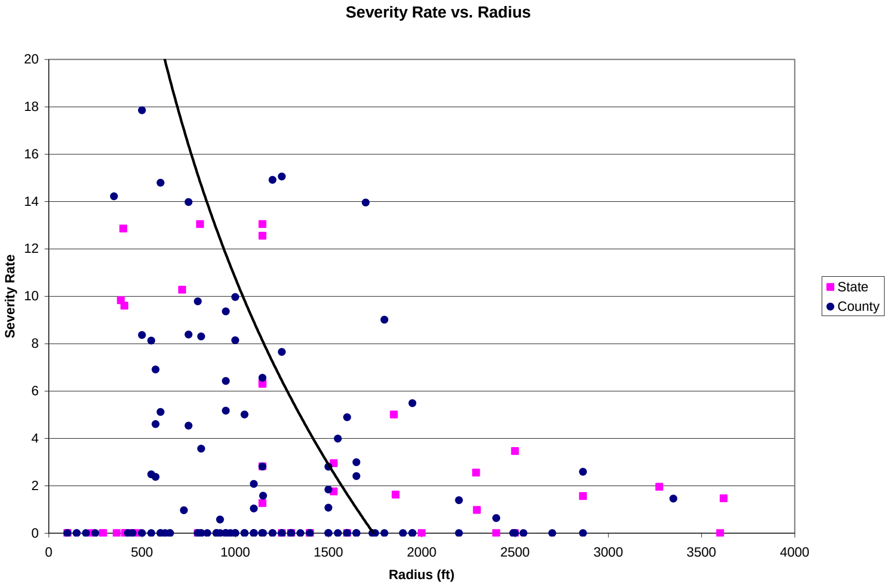


Figure 2.11 Severity Rate by Radii with Trend Line

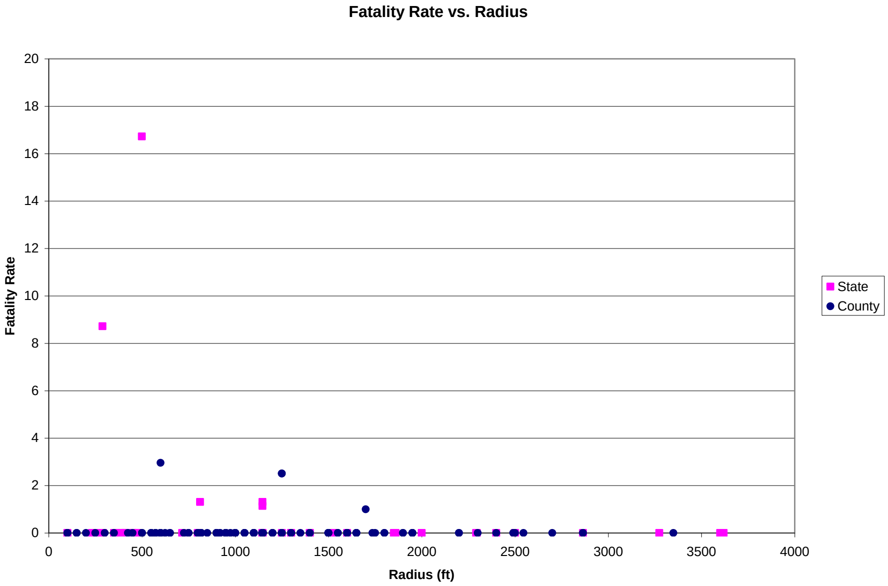


Figure 2.12 Fatality Rate by Radii

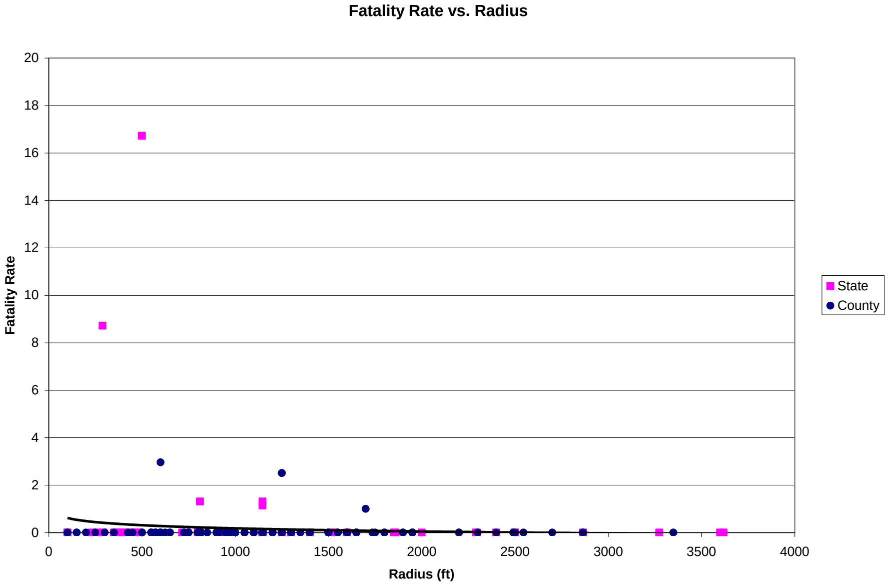


**Figure 2.13 Fatality Rate by Radii with Trend Line**

### 2.1.9 Effect of Warning Signs

The highway agencies submitting candidates for this study were asked to indicate the use of warning signs in each of the curves. The usage of the traffic control devices was plotted against curve radii (Figure 2.14) and the data indicate a level of inconsistency in the application of warning devices in the data set of curves from around the State – each of the six radius categories included some curves with no warning signs and some with warning signs. The use of chevrons in the data set was limited to curves with radii less than 2,500 feet. Other key points include

- The percentage of curves with no treatment was highest (43 – 56%) in long radius curves (over 2,000 feet)
- The use of the typical static curve warning sign was highest (70 – 76%) in curves with radii between 500 and 1,999 feet
- The use of chevrons was highest (13 -26%) in curves with radii less than 1,000 feet.

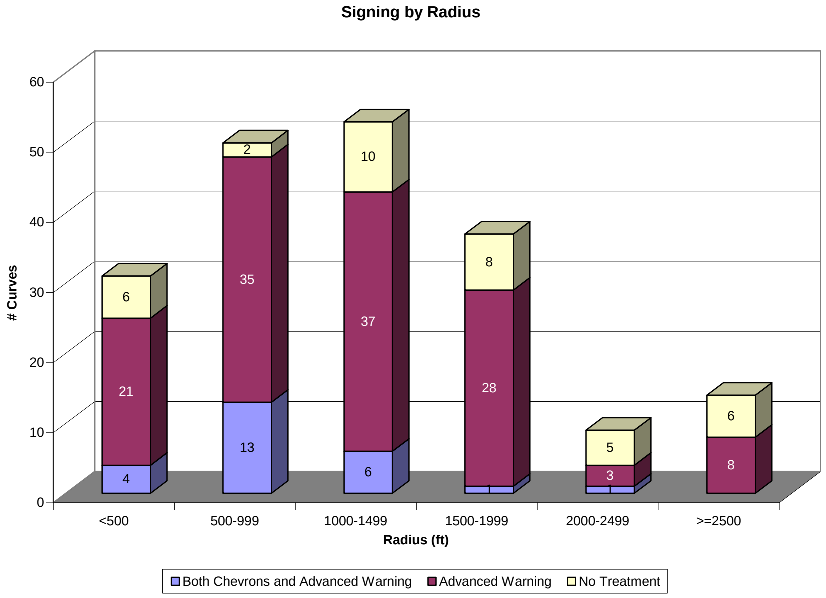


**Figure 2.14 Signing by Curve Radii**

It should be noted that both curve warning signs and chevrons are considered to be optional based on the guidance in the Minnesota MUTCD. Moreover, the entire document is in fact based on deference to engineering judgment. However, the inconsistent application of warning signs across a system of highways can increase the risk for an agency being accused of negligence – why did Curve A have a sign and an identical Curve B did not?

Crash rates were also plotted for the curves with warning signs (Figures 2.15 and 2.16) and those with Warning signs plus chevrons (Figures 2.17 and 2.18). Please note that the trendlines for the crash rates at curves with warning signs (Figure 2.16) and chevrons (Figure 2.18) are shown in solid lines and the crash rate trend line for the total dataset (Figure 2.9) is shown as a dashed line for comparison. These data indicate that the use of typical static curve warning signs had an observable positive effect (a crash reduction) on crashes only in the curves with radii between 1,000 and 1,800 feet, and that the use of chevrons appears to only have an effect on curves with radii less than 500 feet. However, the number of locations in the data set with chevrons is very small. Thus the data with respect to chevrons might be statistically insignificant.

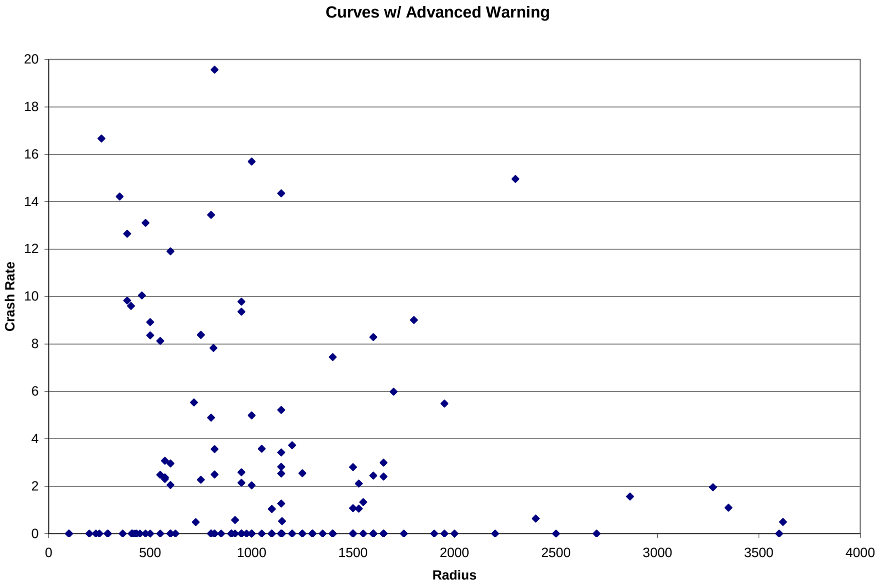


Figure 2.15 Crash Rate by Radii of Curves with Advanced Warning

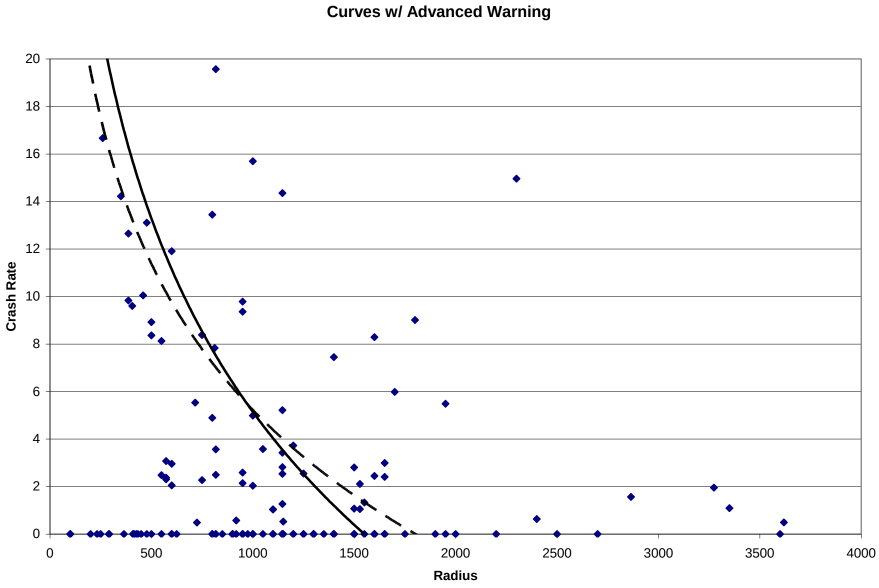


Figure 2.16 Crash Rate by Radii of Curves with Advanced Warning with Trend Line

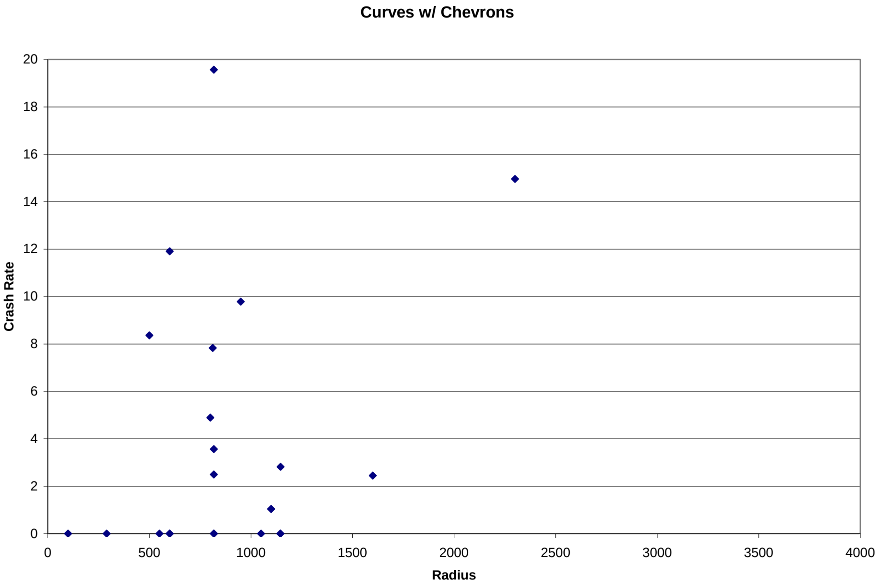


Figure 2.17 Crash Rate by Radii of Curves with Chevrons

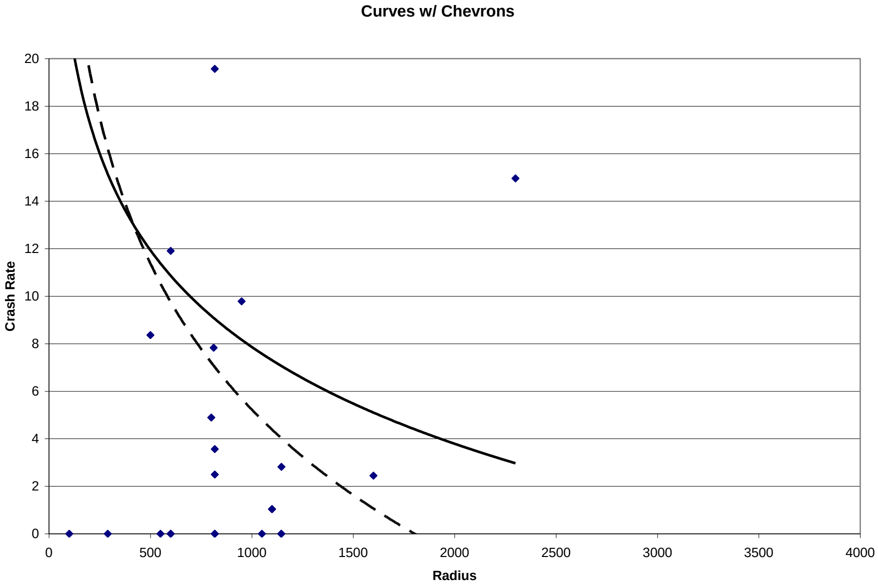


Figure 2.18 Crash Rate by Radii of Curves with Chevrons with Trend Line

### 2.1.10 Cross-Sectional Study Curves – Conclusions

The key questions relative to curves include:

- Does Minnesota data support the theory that the risk of a crash in a curve increases as the radius of the curve decreases?
- Does the use of traffic control devices (the typical static curve warning sign and chevrons) reduce the risk of a crash?

The analysis of the curves in the Minnesota data set appears to support the first theory. Crash rates in the curves in the data set do increase as the curve radius decreases, in a similar fashion to the data for curves in Texas. In addition, there appears to be a relationship between curve radii and crash severity. At the 204 curves in the Study sample, approximately 90% of the fatal crashes and 75% of the injury crashes occurred in curves with radii less than 1,500 feet.

The data regarding the use of traffic control devices is not as conclusive. The data indicates that the use of static curve warning signs has little noticeable effect on crashes and only on curves within a fairly narrow range of curve radii (1,000 to 1,800 feet). In addition, the use of chevrons appears to suggest a positive effect (a reduction in crashes) only when used on very short radius curves (radii less than 500 feet). However, because of the small number of locations in the data set (25) and the small number of crashes at these locations, there is not sufficient information to support a conclusion about the safety effectiveness associated with the placement of chevrons at short radius curves. Due to the size of the data it may be possible that there is a contrast between the effectiveness shown by road signs with respect to the sample set to that shown by FHWA. The effectiveness as per FHWA is 18% to 22% for advanced curve warning signs and 20% for chevrons.

Two other key points should be noted. First, crashes in curves are rare, over one-half of the curves in the data set had NO crashes during its study period and the worst curve averaged around 1.5 crashes per year – yet, none of these curves in the data set were previously identified as being at-risk using a traditional Black Spot approach. This data along with the results of a number of countywide safety studies that found a high fraction of road departure crashes in curves across the Counties system of highways suggests a need to approach curve safety from a proactive systematic perspective. The countywide studies also suggest a need to prioritize curves based on more than just crashes - curve radii, a particular range of traffic volume, the presence of visual traps, intersections and proximity to other high priority curves (Table 2.2) all appear to add to the level of risk for road departure crashes at any given curve.

## Table 2.2 Freeborn County Road Safety Audit Review

| | | | | Crashes | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Seg # | Corridor | Description | Curve | K | A | B | C | PDO | Visual Trap | Estimated Radius |
| 1 | CSAH 4 | Iowa - I-90 | 1 | | | | | | Yes | 600 |
| | | | 2 | 1 | | | | | Yes | 600 |
| | | | 3 | | | | | | Yes | 850 |
| 5 | CSAH 29 | CSAH 10 - Hwy 13 | 1 | | | | | 1 | | 650 |
| | | | 2 | | | | | | Yes | 600 |
| | | | 3 | 1 | 1 | | | 1 | Yes | 850 |
| 8 | CSAH 35 | Hwy 13 - Mower Co | 1 | | 2 | | 1 | | Yes | 950 |
| | | | 2 | | | 1 | | | Yes | 950 |
| | | | 3 | | | 1 | | | | 950 |
| | | | 4 | | | | | | | 950 |
| | | | 5 | | 1 | | | | | 1,000 |
| | | | 6 | | | | | | | 1,000 |
| | | | 7 | | | | | 1 | | 700 |
| | | | 8 | | 1 | | | 1 | | 800 |
| 13 | CSAH 1 | US 69 - US 65 | 1 | | | | | | Yes | 850 |
| | | | 2 | | | | | | Yes | 850 |
| 14 | CSAH 34 | CSAH 13 - CSAH 35 | 2 | | | | | | Yes | 700 |
| | | | 3 | | | | | | Yes | 650 |
| | | | 4 | | | | | | Yes | 700 |
| | | | 5 | | | | | | Yes | 625 |
| | | | 6 | | | | | | | 700 |
| | | | 7 | | | | | | | 700 |
| 21 | CSAH 6 | CR 109 - CSAH 29 | 1 | | | | | 1 | | 850 |
| | | | 2 | | | | | | | 850 |
| | | | 3 | | | | 1 | | | 800 |
| | | | 4 | | | 1 | | | | 1,250 |
| | | | 5 | | | | 1 | | | 500 |

(Source: Freeborn County Road Safety Audit Review, 2007)

## 2.2 Cross-Sectional Study: Tangential Sections

### 2.2.1 Total Number of Segments in Data Set

The data set of segments for the cross-sectional analysis of shoulders was assembled from candidate locations submitted by Mn/DOT District and County Highway Departments in response to the same survey of practice that was used for the cross-sectional analysis of curves. The complete data set includes 137 segments, all of which are located along rural two-lane State (80 segments) and County Highways (57 segments). The shoulder candidates represent all eight Mn/DOT Districts and 38 Counties that are distributed around the State (Figure 2.19 and Table 2.3). As was the case in the cross-sectional analysis of curves, segments along expressways, freeways and in urban areas were not included in the shoulder data set.

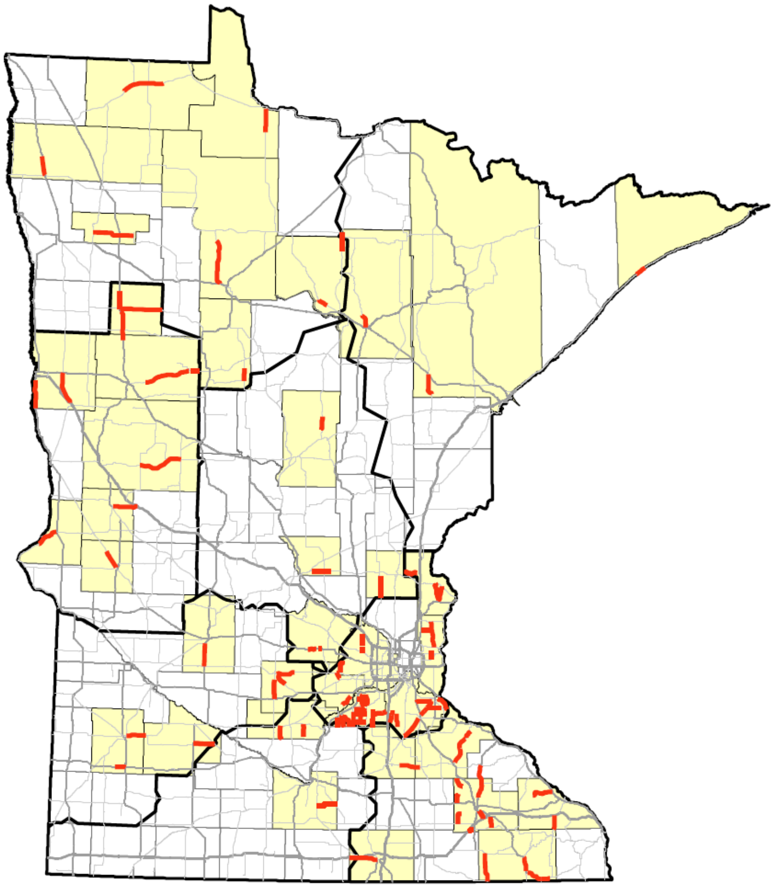
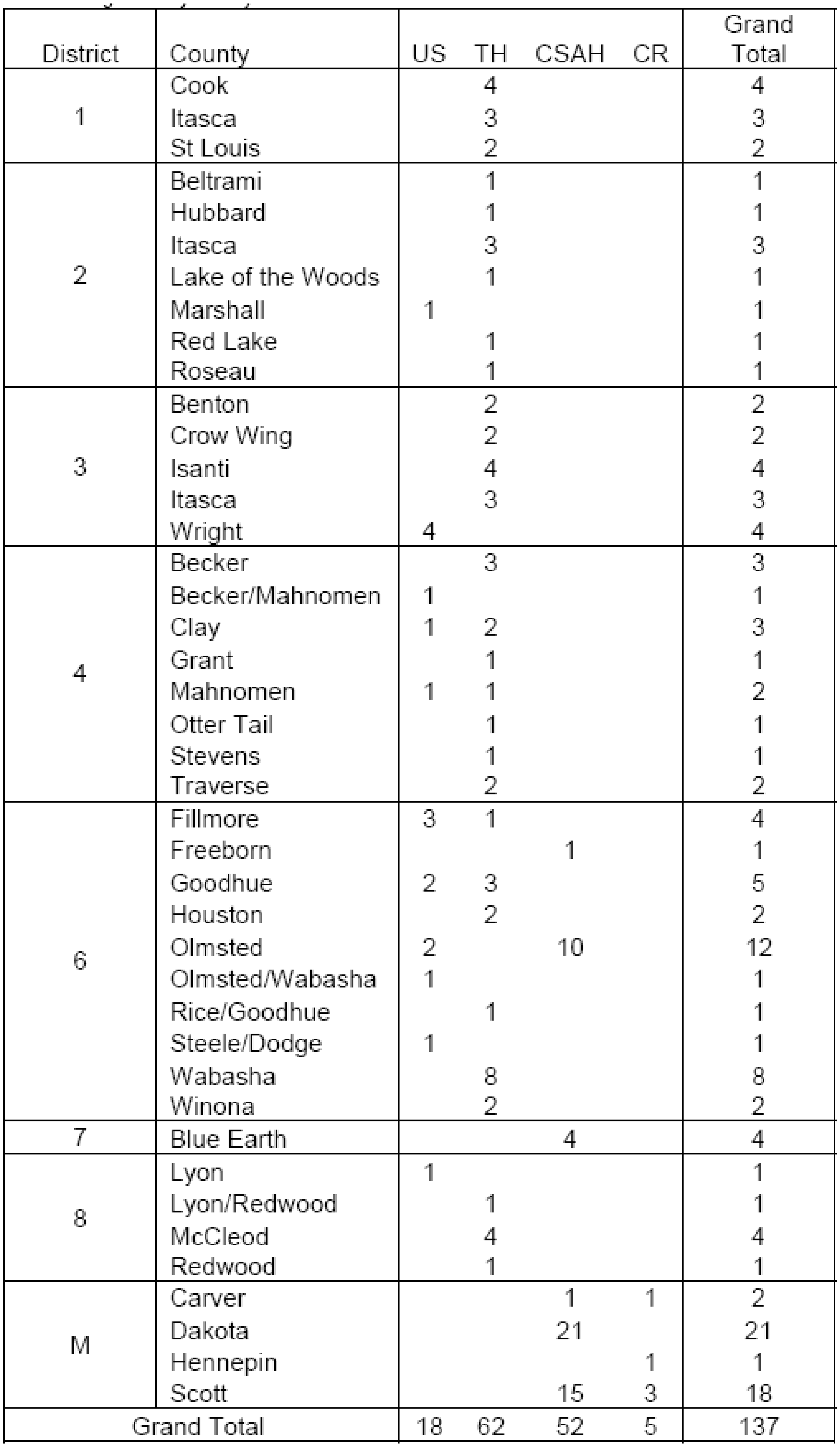


Figure 2.19 Map of Shoulder Locations

## Table 2.3 Count of Segments by County and District



| District | County | US | TH | CSAH | CR | Grand Total |
|---|---|---|---|---|---|---|
| 1 | Cook |  | 4 |  |  | 4 |
|  | Itasca |  | 3 |  |  | 3 |
|  | St Louis |  | 2 |  |  | 2 |
| 2 | Beltrami |  | 1 |  |  | 1 |
|  | Hubbard |  | 1 |  |  | 1 |
|  | Itasca |  | 3 |  |  | 3 |
|  | Lake of the Woods |  | 1 |  |  | 1 |
|  | Marshall | 1 |  |  |  | 1 |
|  | Red Lake |  | 1 |  |  | 1 |
|  | Roseau |  | 1 |  |  | 1 |
| 3 | Benton |  | 2 |  |  | 2 |
|  | Crow Wing |  | 2 |  |  | 2 |
|  | Isanti |  | 4 |  |  | 4 |
|  | Itasca |  | 3 |  |  | 3 |
|  | Wright | 4 |  |  |  | 4 |
| 4 | Becker |  | 3 |  |  | 3 |
|  | Becker/Mahnomen | 1 |  |  |  | 1 |
|  | Clay | 1 | 2 |  |  | 3 |
|  | Grant |  | 1 |  |  | 1 |
|  | Mahnomen | 1 | 1 |  |  | 2 |
|  | Otter Tail |  | 1 |  |  | 1 |
|  | Stevens |  | 1 |  |  | 1 |
|  | Traverse |  | 2 |  |  | 2 |
| 6 | Fillmore | 3 | 1 |  |  | 4 |
|  | Freeborn |  |  | 1 |  | 1 |
|  | Goodhue | 2 | 3 |  |  | 5 |
|  | Houston |  | 2 |  |  | 2 |
|  | Olmsted | 2 |  | 10 |  | 12 |
|  | Olmsted/Wabasha | 1 |  |  |  | 1 |
|  | Rice/Goodhue |  | 1 |  |  | 1 |
|  | Steele/Dodge | 1 |  |  |  | 1 |
|  | Wabasha |  | 8 |  |  | 8 |
|  | Winona |  | 2 |  |  | 2 |
| 7 | Blue Earth |  |  | 4 |  | 4 |
| 8 | Lyon | 1 |  |  |  | 1 |
|  | Lyon/Redwood |  | 1 |  |  | 1 |
|  | McCleod |  | 4 |  |  | 4 |
|  | Redwood |  | 1 |  |  | 1 |
| M | Carver |  |  | 1 | 1 | 2 |
|  | Dakota |  |  | 21 |  | 21 |
|  | Hennepin |  |  |  | 1 | 1 |
|  | Scott |  |  | 15 | 3 | 18 |
| Grand Total |  | 18 | 62 | 52 | 5 | 137 |

### 2.2.2 Total Length of Segments in Data Set

The total length of the segments included in the data set is approximately 930 miles, of which 660 miles is on the State system and 270 miles is on the County system (Figure 2.20). The average length of the individual segments is 7 miles and range in length varies from slightly less than 1 mile to more than 20 miles. The total length included in the cross-sectional analysis exceeds the goal suggested in the Work Scope which was 200 miles with at least 100 miles on both the State and County systems.

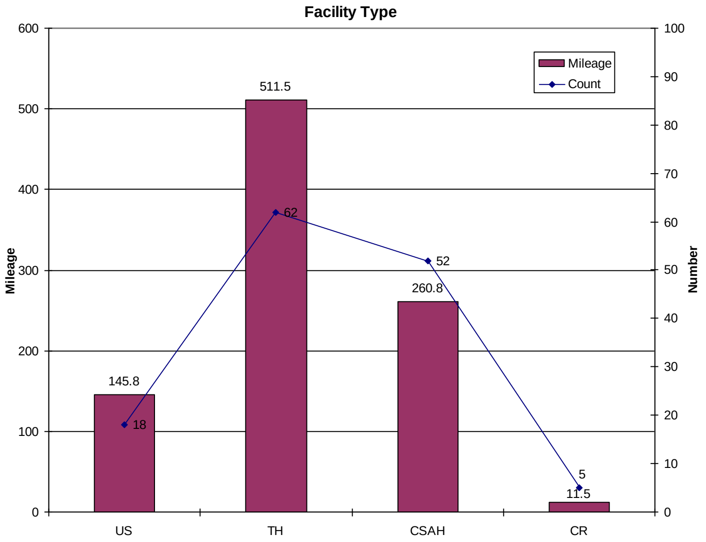


Figure 2.20 State and County Split of Shoulder Locations

### 2.2.3 Daily Traffic Volume

The average daily traffic volumes ranged from 175 vehicles per day on Olmsted County Highway 7 to 12,000 vpd on TH 12 in Wright County. This range of volume is generally representative of rural roads and the fact that two-lane highways on the State system generally carry more traffic than similar facilities on the County system.

### 2.2.4 Tangential Section Categories for Analysis

The general theories regarding the relationship between safety and shoulders is that wider is safer than narrower since it provides additional room for errant vehicles to recover if they leave the travel lanes. Also paved tangential sections are presumed safer than gravel as the edge drop-off is moved further away from the travel lanes and this reduces the chances of a tire scrubbing crash. In addition, there has been a recent focus on low cost shoulder enhancements such as Edge Line Rumble Strips/StripEs. Rumble StripEs (Figure 2.22) have the edge line painted over the grooves in the pavement. In order to adequately test these theories regarding the safety-shoulder relationship, the candidate segments were assigned to one of nine categories based on shoulder type (Aggregate, Paved, Composite or Enhanced). Composite shoulders are comprised of a paved shoulder adjacent to the lane of travel, and an aggregate shoulder adjacent to the paved component of the shoulder. Enhanced shoulders are shoulders with rumble strips/StripEs.(For cost analysis, they do not include the process of paving the shoulders first). These categories are further divided into width (0-2 feet, 2-4 feet, 4-6 feet or 8-10 feet). These categories were selected because they were expected to represent the range of conditions found along typical two-lane facilities and this proved to be the case with the segments in the data set. The distribution of the segments in the data set across these categories (Table2.4, Figure 2.23 and 2.24) indicates:

- About 35% of the sample has aggregate shoulders
- About 50% has paved shoulders
- About 15% are enhanced
- About 60% of the data set has shoulders 4 foot or narrower
- About 25% have shoulders between 4 and 8 feet in width
- About 15% have shoulders wider than 8 feet

**Figure 2.21 Example of Rumble Strip**

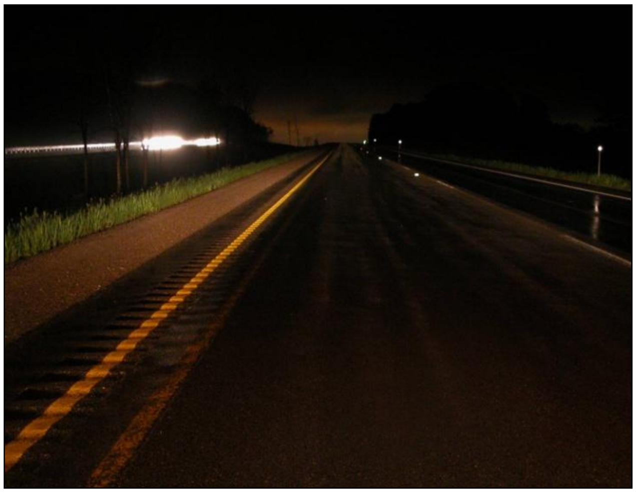


**Figure 2.22 Example of Rumble StripEs and Additional Paving**

## Table 2.4 Disaggregating Shoulder Segments by Width and Type

| | | Shoulder Type | | | | | |
|---|---|---|---|---|---|---|---|
| | | Aggregate | Paved | Composite | Enhanced | Total | |
| **Width (ft)** | >0 to 2 | 19 | 3 | 24 | 1 | 47 | Segments |
| | | 115.8 | 13.1 | 221.5 | 6.0 | 356.5 | Miles |
| | >2 to 4 | 17 | 6 | 4 | 6 | 33 | Segments |
| | | 86.9 | 23.4 | 39.6 | 36.5 | 186.3 | Miles |
| | >4 to 6 | 6 | 2 | 5 | 2 | 15 | Segments |
| | | 39.9 | 8.6 | 32.0 | 31.1 | 111.7 | Miles |
| | >6 to 8 | 8 | 9 | 2 | 3 | 22 | Segments |
| | | 60.8 | 63.6 | 4.9 | 14.6 | 143.9 | Miles |
| | >8 to 10 | 3 | 6 | 3 | 8 | 20 | Segments |
| | | 12.0 | 55.9 | 19.4 | 44.0 | 131.4 | Miles |
| | Total | 53 | 26 | 38 | 20 | | Segments |
| | | 315.5 | 164.7 | 317.5 | 132.1 | | Miles |

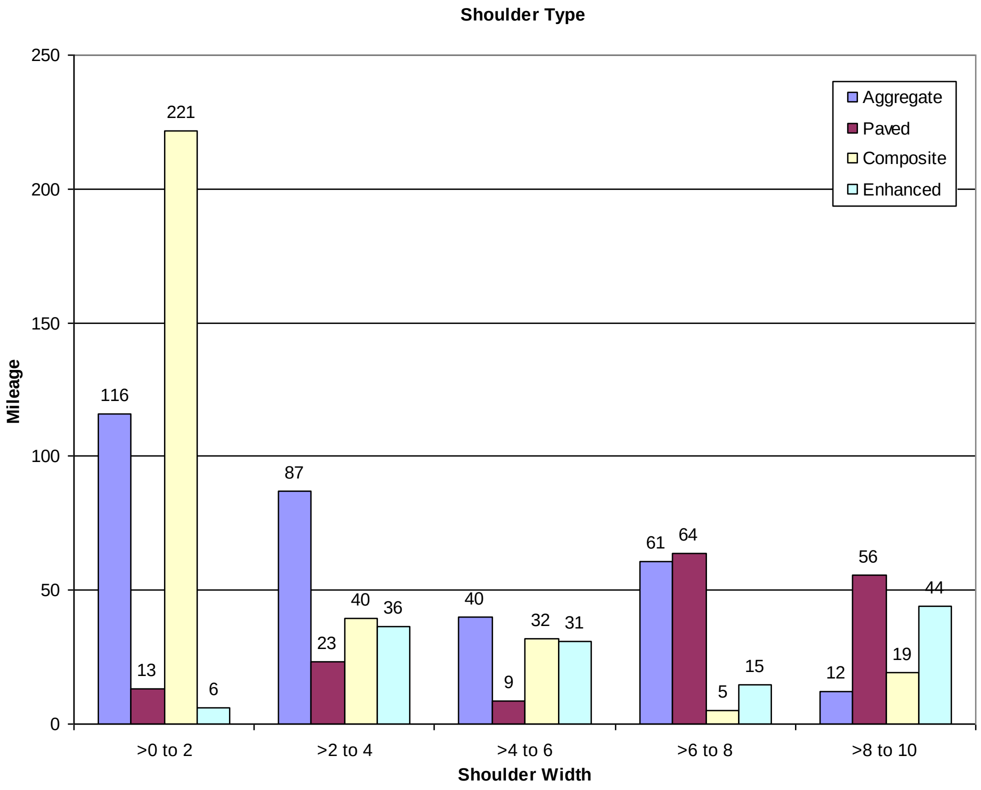


Figure 2.23 Mileage of Shoulder Type

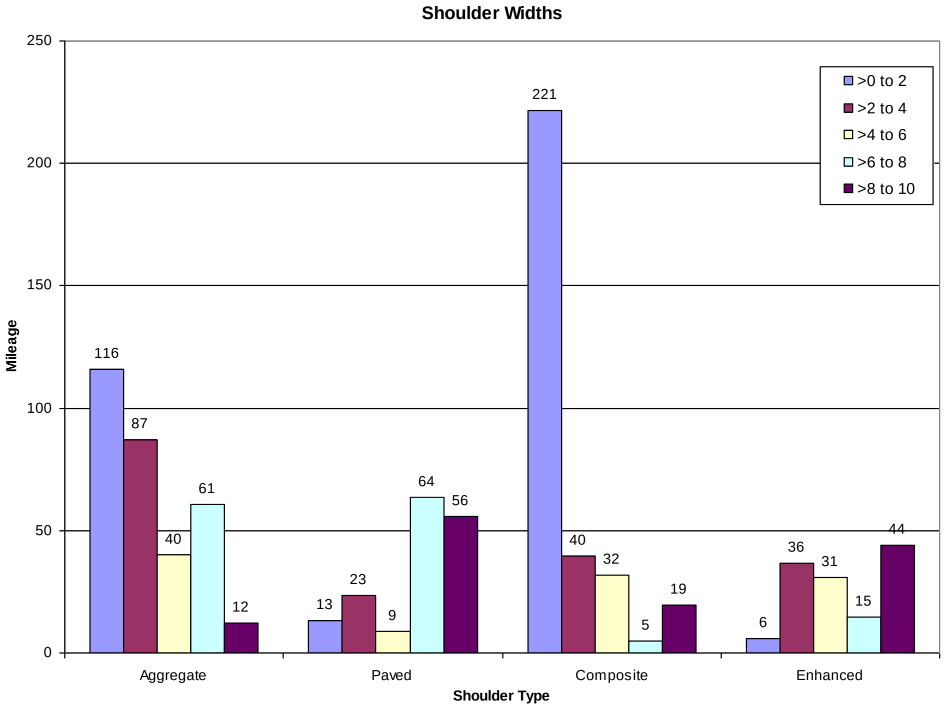


Figure 2.24 Mileage of Shoulder Width

### 2.2.5 Number of Crashes

There were a total of slightly fewer than 7,000 crashes in the data set. The predominant type of crash in the data set is a single vehicle road departure - approximately 1,700 crashes which is about 26% of the total. This percentage of road departure crashes is slightly less than the State wide average (31%) for similar two-lane rural highways and this difference may be due to the segments in the data set not exactly representing the actual distribution of shoulder width and type across the system of two-lane highways in Minnesota.

Disaggregating the crashes across the shoulder categories (Table 2.5) identified the following results:

- The percentage of road departure crashes is highest for segments with aggregate shoulders (30%) and lowest for segments with some type of improved shoulder (24%).
- The percentage of road departure crashes is highest for the narrowest shoulders (36% for 0-2 feet), is lower for the mid range of widths (31% for 2-6 feet) and is the lowest for widest shoulders (19% for greater than 6 feet).
- The effects of shoulder type and width on road departure crashes across the cells of the matrix are less obvious and in a number of cases appear to be influenced by the small number of segments and crashes in a few specific categories.

**Table 2.5 Crashes and Percentage of Road Departure Crashes**

|  |  | Shoulder Type |  |  |  |  |  |
|---|---|---|---|---|---|---|---|
|  |  | Aggregate | Paved | Composite | Enhanced | Total |  |
| Width (ft) | >0 to 2 | 739<br>34% | 174<br>46% | 789<br>35% | 5<br>40% | 1707<br>36% | Crashes<br>Road |
|  | >2 to 4 | 435<br>41% | 159<br>21% | 388<br>14% | 179<br>35% | 1161<br>31% | Crashes<br>Road |
|  | >4 to 6 | 327<br>27% | 26<br>50% | 158<br>28% | 116<br>36% | 627<br>30% | Crashes<br>Road |
|  | >6 to 8 | 238<br>27% | 707<br>22% | 21<br>43% | 167<br>18% | 1133<br>23% | Crashes<br>Road |
|  | >8 to 10 | 322<br>13% | 764<br>17% | 187<br>26% | 651<br>17% | 1924<br>17% | Crashes<br>Road |
|  | Total | 2061<br>30% | 1830<br>23% | 1543<br>28% | 1118<br>22% |  | Crashes<br>Road |

### 2.2.6 Crash Rates

Crash, severity and fatal crash rates were computed for each of the 137 segments in the data set. Disaggregating the rates across the shoulder categories (Table 2.6) identified the following results:

- Crash and severity rates were highest for segments with aggregate shoulders (1.3 and 2.9) and lowest for segments with some type of improved shoulder (1.1 and 2.4)
- These differences represent about 15% reductions in the rates)
- Crash, severity and fatal crash rates were highest for the narrowest shoulders (1.5, 3.4 and 0.03), were lower for the mid range of widths (1.1, 2.6 and 0.025) and were lowest for the widest shoulder widths (1.0. 2.2 and 0.015).
- The effect of shoulder type and width on crash, severity and fatal crash rates across the cells of the matrix are less obvious and appear to be influenced by small number of segments and crashes in a few specific cases.

**Table 2.6 Various Rates for Shoulder Type and Width**

| | | **Shoulder Type** | | | | | |
|---|---|---|---|---|---|---|---|
| | | Aggregate | Paved | Composite | Enhanced | Total | |
| **Width (ft)** | >0 to 2 | 1.8 | 1.7 | 1.2 | 1.1 | 1.5 | Crash Rate |
| | | 4.2 | 3.8 | 2.8 | 3.2 | 3.4 | Severity Rate |
| | | 0.03 | 0.04 | 0.03 | 0.00 | 0.03 | Fatal Crash Rate |
| | >2 to 4 | 1.0 | 1.4 | 1.6 | 1.7 | 1.3 | Crash Rate |
| | | 2.3 | 3.3 | 3.4 | 3.6 | 2.8 | Severity Rate |
| | | 0.01 | 0.04 | 0.02 | 0.03 | 0.02 | Fatal Crash Rate |
| | >4 to 6 | 1.1 | 1.4 | 0.8 | 0.8 | 0.9 | Crash Rate |
| | | 2.5 | 3.6 | 2.3 | 1.9 | 2.3 | Severity Rate |
| | | 0.02 | 0.00 | 0.05 | 0.02 | 0.03 | Fatal Crash Rate |
| | >6 to 8 | 0.9 | 1.0 | 0.5 | 1.2 | 1.0 | Crash Rate |
| | | 2.1 | 2.3 | 1.1 | 2.3 | 2.2 | Severity Rate |
| | | 0.01 | 0.02 | 0.00 | 0.02 | 0.02 | Fatal Crash Rate |
| | >8 to 10 | 1.7 | 0.9 | 0.7 | 1.2 | 1.0 | Crash Rate |
| | | 3.7 | 1.8 | 1.5 | 2.5 | 2.2 | Severity Rate |
| | | 0.02 | 0.01 | 0.02 | 0.01 | 0.01 | Fatal Crash Rate |
| Total | | 1.3 | 1.0 | 1.1 | 1.2 | | Crash Rate |
| | | 2.9 | 2.2 | 2.5 | 2.5 | | Severity Rate |
| | | 0.02 | 0.02 | 0.03 | 0.02 | | Fatal Crash Rate |

### 2.2.7 Cross-Sectional Study Shoulders – Conclusions

The key questions relative to shoulders include:

- Do all widths and types of shoulders equally contribute to safety?
- What are the effects of low cost shoulder edge treatments?

The results of the analysis of shoulders in the Minnesota data set generally support the basic theories regarding the relationship between shoulders and safety. First, wider shoulders have lower crash rates, severity rates, fatal crash rates and a lower percentage of single vehicle road departure crashes. Second, improved shoulders have lower crash rates, severity rates and a lower percentage of road departure crashes. Finally, the data also indicate that the segments where low cost edge treatments have been installed have lower crash and severity rates and a lower percentage of road departure crashes.

# Chapter 3: Before:After Analysis

The before:after study compares crash characteristics before versus after a shoulder treatment or additional curve delineation has been installed. The after conditions for curves include curve flattening, paving shoulders or adding edgeline rumble strips. The after conditions for shoulder improvements include paving shoulders, widening of narrow paved shoulders or additional enhancements, such as rumble strips.

## 3.1 Before:After Study – Curves

### 3.1.1 Total Number of Curves in Data Set

The data set of curves was assembled from candidate locations submitted by Mn/DOT Districts and County Highway Departments in response to a survey of practice. The complete data set includes 39 curves, all of which are located along two-lane State (37 curves) and County (2 curves) Highways. The general location of the curves in the before versus after dataset are documented in Figure 3.1.

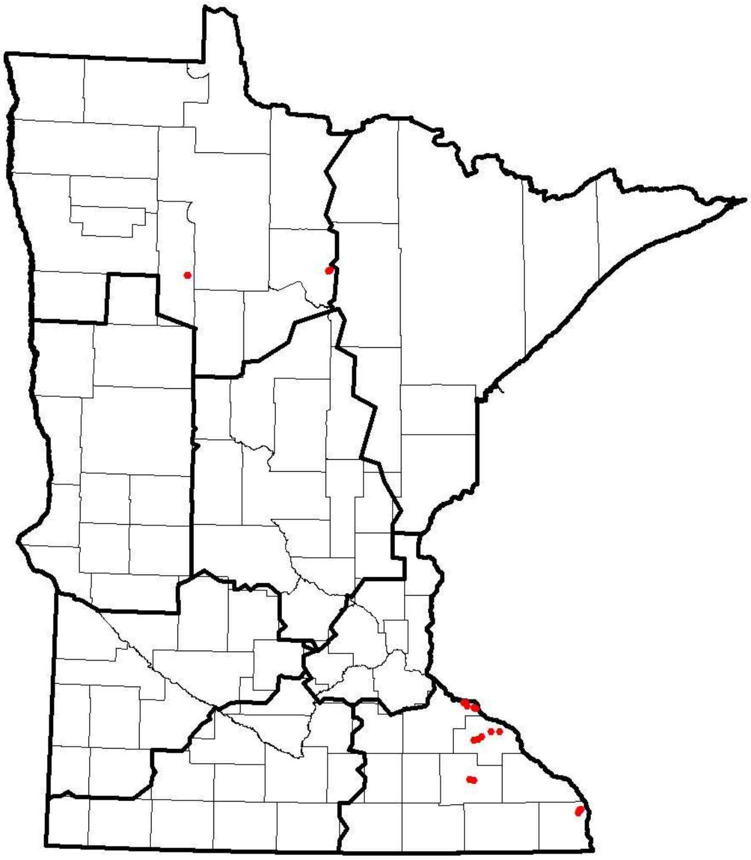


**Figure 3.1 Curve Locations for Before:After Study**

It should be noted that curves on expressways, freeways and in urban areas were excluded from the sample because of documented differences in crash characteristics among the various highway facility types and between rural and urban areas. In addition, it should also be noted that the number of curves (39) exceeds the goal of 20 curves suggested in the Work Scope.

The improvements to the curves included in this data set consist of three basic strategies:

- Flattening the curves (increasing the radius)
- Paving narrow shoulders through the curves
- Adding edge line rumble strips

### 3.1.2 Curve Flattening

The four curves that were flattened consisted of two along CSAH 2 in Clearwater County (Figure 3.2 Aerial View of Flattened Curve on CSAH 2) and two more along TH 6 in Itasca County (Figure 3.3). The radii of the curves along CH 2 were increased from 573 feet (10 degrees) to 1,109 feet (5.2 degrees). The radii of the curves along TH 6 were increased from 880 feet (6.5 degrees) to 1,919 feet (3 degrees).

**Figure 3.2 Aerial View of Flattened Curve on CSAH 2 (Source: Google Maps, ©2009 Google-Imagery ©Digital Globe, GeoEye, USDA Farm Service Agency, TerraMetrics Map data ©2009 Google). The 90 degree curve has been flattened; the former sharp curve is visible to the north east of the curve apex.**

**Figure 3.3 Aerial View of Flattened Curve on TH 6 (Source: Google Maps, ©2009 Google-Imagery ©Digital Globe, GeoEye, USDA Farm Service Agency, TerraMetrics Map data ©2009 Google). Both curves have been flattened; the former roadway is visible in both instances.**

The annual crash frequency and crash rate for these four curves are documented in Table 3.1. This data indicates:

- The total number of crashes was extremely low – only two crashes in a 1 to 3 year before period and only three crashes in a 6 to 8 year after period.
- The annual average number of crashes per curve dropped from 0.25 in the before period to 0.11 in the after period, a +50% reduction.
- The annual average crash rate dropped from 1.2 crashes per million vehicle miles in the before period to 0.4 in the after period, a +60% reduction.
- The crash reduction is interesting, but needs to be used with caution because the changes are not statistically significant due to the low number of crashes.
- These results are consistent with the cross-sectional study which documented an inverse relationship between curve radius and crash rate.

**Table 3.1 Crash Summary for Flattened Curves**

| | # Crashes | | Crash Rate | | Years of Data | |
|---|---|---|---|---|---|---|
| Curve | Before | After | Before | After | Before | After |
| 1 | 0 | 1 | 0.0 | 0.3 | 1 | 8 |
| 2 | 0 | 0 | 0.0 | 0.0 | 1 | 8 |
| 3 | 1 | 2 | 1.5 | 1.4 | 3 | 6 |
| 4 | 1 | 0 | 1.7 | 0.0 | 3 | 6 |
| | Per Year | | Average | | | |
| | 0.25 | 0.11 | 1.2 | 0.4 | | |

### 3.1.3 Paving Narrow Shoulders Through Curves

The segment of Minnesota TH 60 shown in Figure 3.4 is considered to be geometrically deficient due to a number of factors such as a large number of sharp curves (radii between 288 and 499 feet), narrow shoulders, steep slopes, variations in the design speed, and steep grades. These geometric deficiencies contribute to the segment being considered dangerous. Hence narrow (2-foot) shoulders (Figure 3.5) were paved through 25 curves along this segment in District 6 as part of a mill and overlay project in 2001. The crash rate on the segment was 2.5 crashes per million vehicle miles in the before condition, which is about 2.5 times the statewide average for similar two-lane rural roads. The segment crash rate increased in the after condition to 3.8 crashes per million vehicle miles. The District implemented the paving of the narrow shoulders as a low-cost interim measure as part of the overlay project to address the unusually high crash rate and frequency of road departure crashes. Unfortunately, this interim measure proves to increase, rather than decrease, the crash rate on this road.

**Figure 3.4 Curvilinear Alignment of TH 60 (Source: Google Maps, ©2009 Google-Imagery ©Digital Globe, GeoEye, USDA Farm Service Agency, TerraMetrics Map data ©2009 Google)**

**Figure 3.5 Two-Foot Paved Shoulders on TH 60**

The annual crash frequency and crash rate for these 25 curves are documented in Table 3.2. The data indicates:

- The total number of crashes was very low – only 10 crashes in the before period and 30 crashes in the after period.
- The annual average number of crashes per curve increased from 0.1 in the before period to 0.2 in the after period, an increase of 100%.

- The annual average crash rate increased from an average of 5.4 crashes per million vehicle miles to 11.0, an increase of 100%.
- In the before condition, 20% of all crashes involved a motorcycle, where as in the after condition 47% of crashes involved a motorcycle.
- The data certainly suggest that paving narrow shoulders along this particular segment of TH was not successful in addressing a safety deficiency and conceivably contributed to making conditions worse – a smoother riding road with an increased offset to the shoulder drop off may have influenced drivers to increase their speed.
- These results are not consistent with the cross-sectional study which documented modest (5 to 10%) reductions in both crash and severity rates associated with paving 2 foot shoulders. As a result, it appears reasonable to conclude that this data documents the ineffectiveness of merely paving a narrow shoulder through extremely short radius curves along this geometrically deficient segment of TH 60 but it does not prove that paving narrow shoulders along a different segment of rural highway would likely have a similar outcome.

**Table 3.2 Crash Summary for Curves with Narrow Aggregate Shoulders (Before) and 2-Foot Paved Shoulders (After)**

| | # Crashes | | Crash Rate | | Years of Data | |
|---|---|---|---|---|---|---|
| Curve | Before | After | Before | After | Before | After |
| 1 | 0 | 2 | 0.0 | 22.1 | 4 | 5 |
| 2 | 0 | 0 | 0.0 | 0.0 | 4 | 5 |
| 3 | 2 | 2 | 11.2 | 7.7 | 4 | 5 |
| 4 | 0 | 1 | 0.0 | 8.0 | 4 | 5 |
| 5 | 0 | 1 | 0.0 | 2.3 | 4 | 5 |
| 6 | 1 | 1 | 24.4 | 16.7 | 4 | 5 |
| 7 | 0 | 0 | 0.0 | 0.0 | 4 | 5 |
| 8 | 1 | 0 | 32.8 | 0.0 | 4 | 5 |
| 9 | 0 | 1 | 0.0 | 9.6 | 4 | 5 |
| 10 | 0 | 4 | 0.0 | 34.9 | 4 | 5 |
| 11 | 0 | 0 | 0.0 | 0.0 | 4 | 5 |
| 12 | 1 | 0 | 24.9 | 0.0 | 4 | 5 |
| 13 | 0 | 0 | 0.0 | 0.0 | 4 | 5 |
| 14 | 0 | 3 | 0.0 | 106.1 | 4 | 5 |
| 15 | 1 | 0 | 25.8 | 0.0 | 4 | 5 |
| 16 | 0 | 2 | 0.0 | 26.2 | 4 | 5 |
| 17 | 0 | 4 | 0.0 | 66.9 | 4 | 5 |
| 18 | 1 | 0 | 12.7 | 0.0 | 4 | 5 |
| 19 | 0 | 0 | 0.0 | 0.0 | 4 | 5 |
| 20 | 2 | 2 | 14.7 | 10.0 | 4 | 5 |
| 21 | 0 | 1 | 0.0 | 12.6 | 4 | 5 |
| 22 | 1 | 0 | 11.1 | 0.0 | 4 | 5 |
| 23 | 0 | 1 | 0.0 | 14.3 | 4 | 5 |
| 24 | 0 | 5 | 0.0 | 53.8 | 4 | 5 |
| | Per Year | | Average | | | |
| | 0.10 | 0.25 | 5.4 | 11.0 | | |

### 3.1.4 Adding Edge Line Rumble Strips

Edge line rumble strips were added through 11 curves (Figure 3.6) along Trunk Highways 14, 16 and 61 in Mn/DOT's District 6. Curves in this data set had radii ranging from 2,000 to 4,000 feet and shoulder widths between 6 and 10 feet.

**Figure 3.6 On TH 61, Paved Shoulder Through Curve (Before); Paved Shoulder with Rumble Strips Through Curve (After)**

The annual crash frequency and crash rate for these 11 curves are documented in Table 3.3. The data indicates:

- The total number of crashes dropped from 58 in the before period to 46 in the after period, a 20% reduction.
- The annual average number of crashes per curve dropped from 1.12 in the before period to 0.98 in the after period, a +10% reduction.
- The annual average crash rate dropped from 1.26 crashes per million vehicle miles in the before period to 1.07 in the after period, a reduction of 15%.
- These results are consistent with the results of the cross-sectional study which documented modest (about 10%) reductions in crash rates for segments with edge line rumble strips.

**Table 3.3 Crash Summary for Curves with Enhanced Shoulders in the After Condition**

| | # Crashes | | Crash Rate | | Years of Data | |
|---|---|---|---|---|---|---|
| Curve | Before | After | Before | After | Before | After |
| 1 | 1 | 1 | 0.3 | 0.3 | 4 | 5 |
| 2 | 1 | 1 | 0.5 | 0.5 | 4 | 5 |
| 3 | 5 | 9 | 1.3 | 1.8 | 4 | 5 |
| 4 | 5 | 2 | 4.5 | 1.4 | 4 | 5 |
| 5 | 6 | 5 | 1.4 | 0.9 | 4 | 5 |
| 6 | 7 | 13 | 1.0 | 1.3 | 4 | 5 |
| 7 | 14 | 2 | 3.6 | 0.4 | 4 | 5 |
| 8 | 4 | 3 | 1.1 | 1.5 | 6 | 3 |
| 9 | 10 | 6 | 1.0 | 1.1 | 6 | 3 |
| 10 | 2 | 1 | 0.6 | 0.6 | 6 | 3 |
| 11 | 3 | 3 | 0.9 | 1.6 | 6 | 3 |
| | Per Year | | Average | | | |
| | 1.12 | 0.98 | 1.3 | 1.1 | | |

### 3.1.5 Summary of Conclusions

#### *3.1.5.1 Curve Flattening*

The results of the before:after study indicate a substantial reduction in crashes and crash rates, on the order of 50 to 60% when curve radii are increased. These reductions are not statistically significant but they are generally consistent with the results of the cross-sectional study that indicate an inverse relationship between curve radii and crash rate – as curve radii increase, crash rates decrease.

#### *3.1.5.2 Paving Narrow Shoulders Through Curves*

The results of the before:after study indicate a substantial increase in the number of crashes and the crash rates associated with paving a 2-foot shoulder in the segment of TH 60 between Zumbro Falls and Wabasha. However, it appears that these results should be limited to the specific highway in question – TH 60 – because of the unique character of the highway (a high frequency of very short radius curves) which makes it unlike most other rural highways in Minnesota.

#### *3.1.5.3 Adding Edge Line Rumble Strips*

The results of the before:after study indicate a modest decrease in the number of crashes and the crash rate associated with adding an edge line rumble strip/stripe. These results are consistent with the cross-sectional study. However, it should be noted that the curves in the before:after study all had long radii (between 2,000 and 4,000 feet) and wide shoulders (between 6 and 10 feet).

## 3.2 Before:After Study – Tangential Sections

### 3.2.1 Total Number of Shoulder Segments in Data Set

The data set of shoulder segments was assembled from candidate locations submitted by Mn/DOT Districts and County Highway Departments in response to a survey of practice. The complete data set includes 34 segments, all of which are located along two-lane State (20 segments) and County (14) Highways. The general location of the shoulder segments in the before:after data set are documented in Figure 3.7.

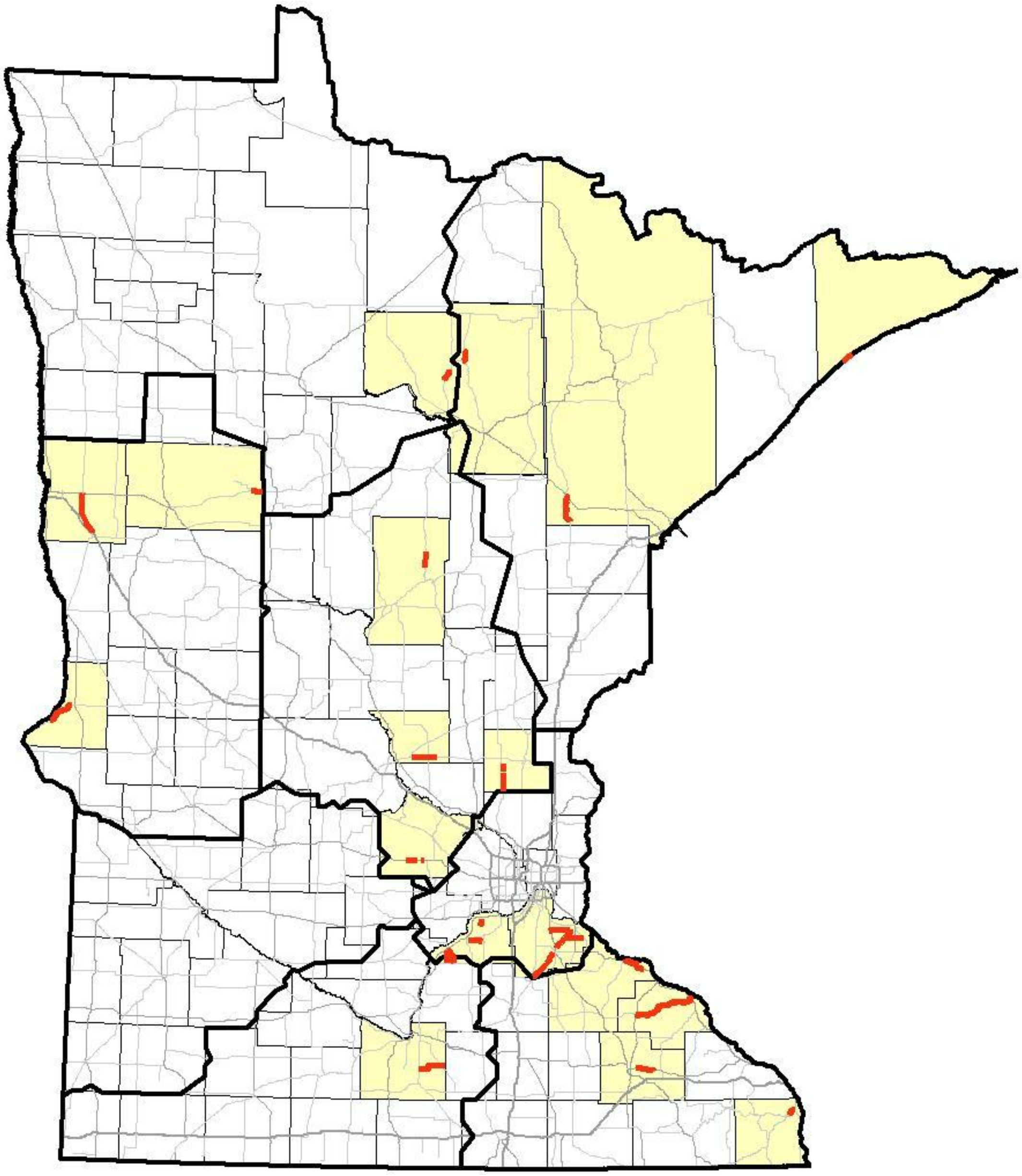


Figure 3.7 Shoulder Segment Locations for Before:After Study

The improvements to the shoulders included in the data set consist of four basic strategies:

- Paving aggregate shoulders
- Widening narrow paved shoulders
- Adding enhancements to aggregate shoulders – rumble strips/stripes
- Adding enhancements to paved shoulders – rumble strips/stripes

### 3.2.2 Paving Aggregate Shoulders

A total of 21 segments (12 County and 9 Mn/DOT) are included in the before:after data set that documents the effect of paving aggregate shoulders (Figure 4.8). The individual segments, before and after crash rates and a crash summary are documented in Table 4.4. The data indicates:

- The average crash rate dropped from 1.4 crashes per million vehicle miles of travel in the before period to 1.2 in the after period, a reduction of 16%.
- This crash reduction is consistent with the results of the cross-sectional study that found a 23% reduction in crash rates associated with paving aggregate shoulders.

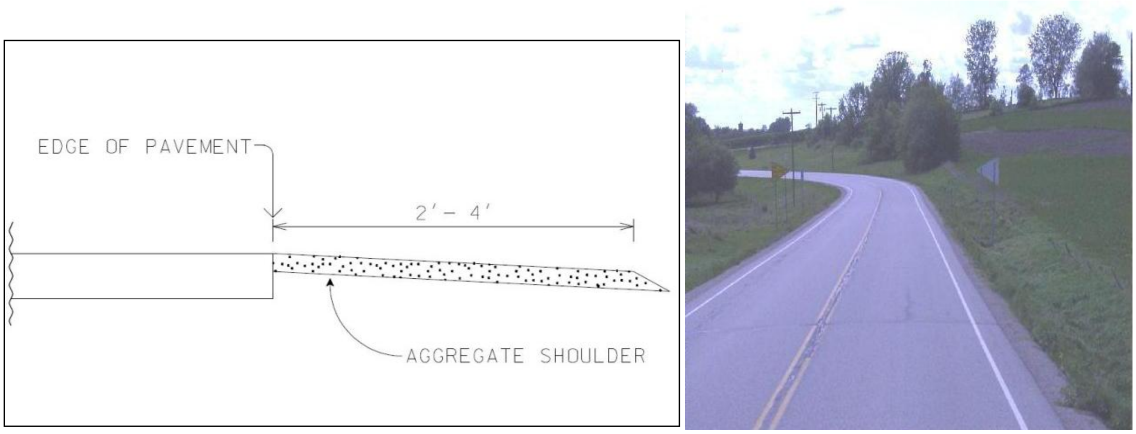


**Figure 3.8 Before Condition: Aggregate Shoulder; After Condition: Paved or Partially-Paved Shoulder**

**Table 3.4 Crash Summary of Before: Aggregate; After: Paved or Partially-Paved**

| | | | | Before | | After | |
|---|---|---|---|---|---|---|---|
| Route | Begin | End | Length | Shoulder Type | Crash Rate | Shoulder Type | Crash Rate |
| CSAH 10 | Curves | TH 22 | 2.9 | A.0-2 | 3.4 | C.0-2 | 1.6 |
| CSAH 10 | East county line | Curves | 5.7 | A.0-2 | 1.2 | C.0-2 | 1.8 |
| TH 6 | CR 136 | CSAH 35 | 2.7 | A.0-2 | 2.2 | C.0-2 | 1.1 |
| TH 60 | US 63 | CSAH 2 | 5.0 | A.0-2 | 4.1 | C.0-2 | 4.3 |
| TH 60 | Farm, 1 mile east | House, 0.4 miles west of 310th Ave | 1.0 | A.0-2 | 0.0 | C.0-2 | 2.7 |
| TH 60 | 0.2 miles east of 310th Ave | US 61 | 16.7 | A.0-2 | 2.0 | C.0-2 | 3.3 |
| TH 27 | CSAH 6 | CSAH 9 | 10.6 | A.0-2 | 1.4 | C.0-2 | 1.0 |
| TH 9 | Interstate 94 | USTH 10 | 14.9 | A.0-2 | 1.6 | C.0-2 | 1.8 |
| CSAH 3 | TH 19 | 240th St E | 4.0 | A.8-10 | 1.1 | C.2-4 | 0.2 |
| TH 60 | CSAH 2 | Farm, 1 mile east | 1.0 | A.0-2 | 1.3 | C.4-6 | 3.5 |
| TH 34 | CSAH 48 | County Line | 4.1 | A.4-6 | 0.7 | C.4-6 | 0.7 |
| CSAH 47 | 205th St | CSAH 62 Rt | 2.0 | A.2-4 | 3.8 | P.2-4 | 1.7 |
| CSAH 47 | 225th St | CSAH 85 | 2.7 | A.2-4 | 1.0 | P.2-4 | 1.1 |
| CSAH 47 | CSAH 86 | Hampton City Limits | 5.8 | A.2-4 | 1.2 | P.2-4 | 0.9 |
| CSAH 62 | USTH 61 | MNTH 316 | 2.8 | A.2-4 | 5.8 | P.2-4 | 3.0 |
| CSAH 47 | TH 3 | CSAH 86 | 4.8 | A.2-4 | 2.0 | P.2-4 | 2.4 |
| CSAH 5 | TH 19 | 240th St E | 5.2 | A.6-8 | 2.8 | P.2-4 | 0.2 |
| TH 95 | T-39 X-ing, 65th Ave NE | CSAH 6 | 9.9 | A.6-8 | 0.8 | P.6-8 | 0.3 |
| CSAH 46 | US 52 | Hastings City Limits | 7.2 | A.6-8 | 1.0 | P.6-8 | 1.5 |
| CSAH 47 | CSAH 62 Lt | CSAH 46 | 3.7 | A.6-8 | 0.7 | P.6-8 | 1.3 |
| CSAH 62 | CSAH 47 | USTH 61 | 3.6 | A.6-8 | 2.2 | P.6-8 | 2.7 |
| | | | | Average | 1.4 | | 1.2 |

### 3.2.3 Widening Narrow Paved Shoulders

Only one segment (TH 6) was found that involved widening an existing paved shoulder from two feet to four feet (Figure 3.9). The segment, before and after crash rates and a crash summary are documented in Table 3.5. The data indicate:

- The average crash rate dropped from 0.9 crashes per million vehicle miles in the before period to 0.8 in the after period, a reduction of 7%.
- This crash reduction is consistent with the results of the cross-sectional study that found that widening paved shoulders resulted in crash reductions in the range of 10 to 47%.

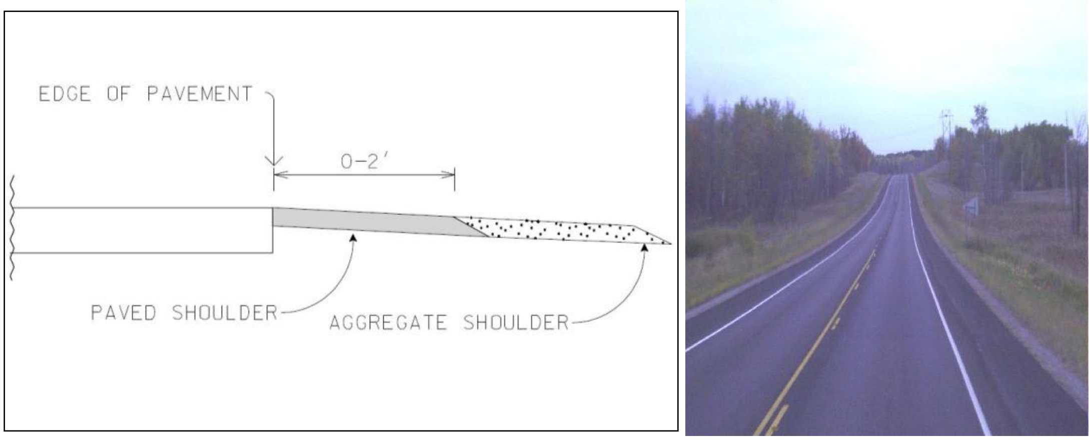


**Figure 3.9 Before Condition: Partially-Paved Shoulder; After Condition: Wider Paved**

**Table 3.5 Crash Summary of Before: Partially-Paved; After: Wider Paved**

|  |  |  |  | Before |  | After |  |
|---|---|---|---|---|---|---|---|
| Route | Begin | End | Length | Shoulder Type | Crash Rate | Shoulder Type | Crash Rate |
| TH 6 | End Bridge over MS River | T-247 RT, Fairfield TWP | 5.7 | C.0-2 | 0.9 | C.4-6 | 0.8 |

### 3.2.4 Adding Paved Shoulders Plus Enhancements to Aggregate Shoulders

A total of 7 segments (5 Mn/DOT and 2 County) are included in the before versus after data set that documents the effects of adding paved shoulders plus enhancements (rumble strips/stripes) to aggregate shoulders (Figure 3.10). The individual segments, before and after crash rates and a crash summary are documented in Table 3.6. The data indicates:

- The average crash rate dropped from 1.6 crashes per million vehicle miles in the before period to 1.0 in the after, a reduction of 37%.
- This crash reduction is consistent with the general results of the cross-sectional study that found shoulder segments with enhancements had crash rates approximately 10% lower than comparable segments with only aggregate shoulders.

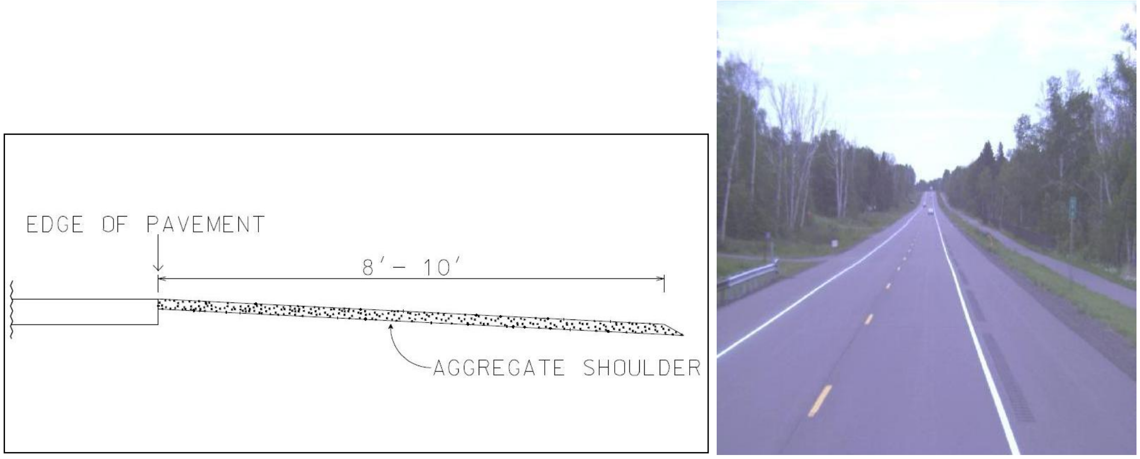


**Figure 3.10 Before Condition: Aggregate Shoulder; After Condition: Paved Shoulder with Rumble Strips**

### Table 3.6 Crash Summary of Before: Aggregate; After: Paved with Rumble Strips

| | | | | Before | | After | |
|---|---|---|---|---|---|---|---|
| Route | Begin | End | Length | Shoulder Type | Crash Rate | Shoulder Type | Crash Rate |
| CSAH 10 | Sand Creek Dr | TH 13 | 6.0 | A.2-4 | 2.9 | E.0-2 | 1.1 |
| CR 79 | CSAH 14 | Londonderry Ct | 1.3 | A.2-4 | 2.1 | E.2-4 | 1.0 |
| TH 73 | CSAH 86 | US 2 | 10.2 | A.0-2 | 1.1 | E.4-6 | 0.6 |
| TH 47 | Anoka/Isanti Co Line | Commercial Entrance Left, After 299th Ave | 7.1 | A.0-2 | 1.7 | E.6-8 | 1.2 |
| TH 47 | Commercial Entrance Left, Prior to 307th Ln | CSAH 1 | 2.0 | A.0-2 | 0.5 | E.6-8 | 1.3 |
| TH 16 | North Limit Hokah | MNTH 26 | 2.6 | A.8-10 | 1.7 | E.8-10 | 0.8 |
| TH 61 | CSAH 2 | CR 79 | 2.6 | A.0-2 | 2.1 | E.8-10 | 1.6 |
| | | | | Average | 1.6 | | 1.0 |

Key: Shoulder Type followed by Overall Width, A=Aggregate, E=Enhanced (Paved plus Rumble strips/stripes)

### 3.2.5 Adding Enhancements to Paved Shoulders

A total of 5 segments (all on the State system) are included in the before versus after data set that documents the effects of adding enhancements (rumble strips/stripes) to paved shoulders (Figure 3.11). The individual segments, before and after crash rates and a crash summary are documented in Table 3.7. The data indicates:

- The average crash rate dropped from 1.3 crashes per million vehicle miles in the before period to 1.1 in the after, a reduction of 15%.
- This crash reduction is not consistent with the results of the cross-sectional study that found a 20 to 30% increase in crash rate for segments with wide paved shoulders (6 to 10 feet) plus enhancements.

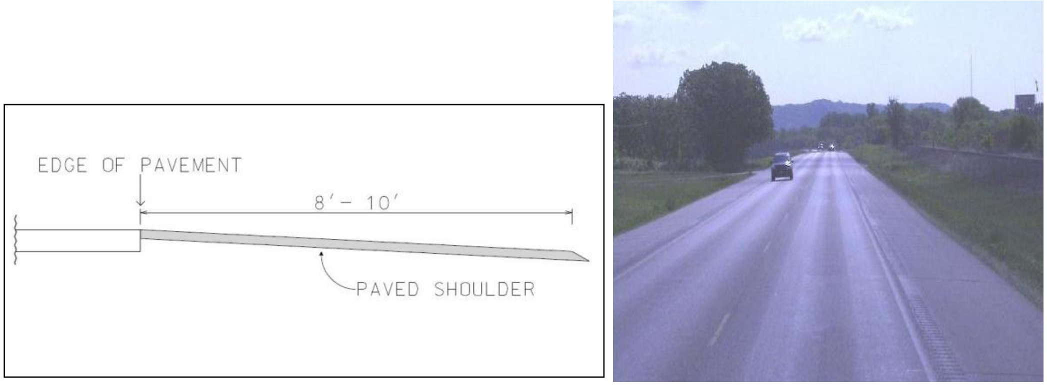


**Figure 3.11 Before Condition: Paved Shoulder; After Condition: Paved Shoulder with Rumble Strips**

### Table 3.7 Crash Summary of Before: Paved with Rumble Strips

| | | | | Before | | After | |
|---|---|---|---|---|---|---|---|
| Route | Begin | End | Length | Shoulder Type | Crash Rate | Shoulder Type | Crash Rate |
| TH 38 | CSAH 45 | North of Curve past CSAH 43 | 4.4 | P.0-2 | 2.1 | E.2-4 | 0.9 |
| US 12 | CSAH 7 LT | Emerson Ave SW | 3.7 | C.6-8 | 0.5 | E.8-10 | 0.3 |
| US 12 | Devitt Ave | Clementa Ave SW | 1.2 | C.6-8 | 0.3 | E.8-10 | 0.5 |
| US 14 | CSAH 22 | CR 102 Lt | 4.6 | P.8-10 | 2.5 | E.8-10 | 2.8 |
| US 61 | CSAH 2 | MNTH 292 East | 9.4 | P.8-10 | 0.9 | E.8-10 | 0.7 |
| | | | | Average | 1.3 | | 1.1 |

### 3.2.6 Summary of Conclusions

#### *3.2.6.1 Paving Aggregate Shoulders*

The results of the before:after study indicates a 16% crash reduction associated with paving aggregate shoulders. This is consistent with the results of the cross-sectional study.

#### *3.2.6.2 Widening Narrow Paved Shoulders*

The results of the before:after study indicates a small decrease in crash rate, about 7%, associated with widening narrow paved shoulders. This result should be used with caution because it is based on only one segment and a small number of crashes. However, this result is generally consistent with the results of the cross-sectional study that found segments with wide paved shoulders had crash rates between 10 and 47% lower than segments with narrow paved shoulders.

#### *3.2.6.3 Adding Paved Shoulders Plus Enhancements (Rumble Strips/Stripes) to Aggregate Shoulders*

The results of the before:after study indicates a 37% reduction in crash rates associated with adding enhancements to segments with aggregate shoulders. This result is consistent with the results of the cross-sectional study that found segments with enhancements had about 8% lower crash rates than comparable segments with aggregate shoulders.

#### *3.2.6.4 Adding Enhancements to Paved Shoulders*

The results of the before:after study indicates a 15% decrease in crash rates associated with adding enhancements to segments with paved shoulders. This is not consistent with the results of the cross-sectional study that found about a 20% increase in crash rates in segments with enhancements compared to segments with just paved shoulders.

## 3.3 Final Thoughts

The overall results of the before:after study suggests that paving shoulders, adding shoulder enhancements (rumble strips/stripes) and flattening curves result in safety improvements by reducing crash rates. There is one noted exception – paving narrow shoulders in very short radius curves (radii less than 500 feet) is not sufficient to mitigate the factors contributing to unusually high crash frequencies.

These results, in some cases, should be used with caution because of concerns for statistical reliability due to small sample sizes for the crash totals. However, the results are generally consistent with the cross-sectional study – paving shoulders, adding rumble strips/stripes and flattening curves appear to be reliable safety strategies.

In Chapter 5, the before:after analysis results have been used to calculate the effectiveness of infrastructure-based treatments. For tangential sections, additional sectional efficiency has been defined which has values different than the ones stated in the summary.

# Chapter 4: Countermeasures – Descriptions and Cost Base

The last chapter has mentioned the curves which have undergone some infrastructure-based treatments such as curve flattening, rumble strips. A before:after analysis has been provided for them. Along with traditional infrastructure-based treatments, certain technology-based safety systems can also be used to reduce fatalities. This chapter provides a description of the various countermeasures that have been proposed for curves and for tangential sections. Each of these have been classified into infrastructure-based civil engineering treatments, infrastructure-based technology treatments and in-vehicle technologies.

## 4.1 Infrastructure-Based: Civil Engineering

### 4.1.1 Rumble Strips (and Rumble StripEs)

The number of crashes in 2007 in Minnesota due to fatigued or drivers who were asleep were 423 of which 7 were fatal. Also, 13.5% of the crashes were due to inattentiveness of the driver or due to some kind of distraction [3.]. All these crashes could be avoided by rumble strips.

There are three types of rumble strips: milled, rolled and formed. They differ in the way they are installed, their size and shape. We are going to just concentrate on milled rumble strips since they are the most preferred type of rumble strip and produce the most vibrations and noise. Milled rumble strips are cut into existing asphalt shoulders and require narrow shoulders to install compared to rolled rumble strips. They are usually not affected by snow and ice. Life of rumble strips is generally between 10 to 15 years. [12.]

Similar to rumble strips (which are generally outboard of the outer fogline), a Rumble StripE is a grooved pattern in the pavement that is painted with durable, highly reflective paint. Like a rumble strip, the grooves make noise and cause vehicles to vibrate when they leave the driving lane. The painted edgeline marking visibly shows where the lane ends, and the shoulder begins. The primary advantages of the Rumble StripE are that it provides better wet weather/nighttime performance of the edge line and that it provides a longer lifetime for the painted fogline.

As provided by Mn/DOT the cost for milling rumble strips is $3,000 and hence this is the value used for our analysis.

### 4.1.2 Curve Flattening

Curves are defined by their length or equivalently the curve radius and the degree of the curve. Curve flattening is changing the alignment of the curves and completely reconstructing them so as to change their radius and degree.

Though highly efficient (efficiency is computed in Chapter 5) curve flattening is one of the most expensive safety implementations. As per Mn/DOT, the cost of reconstructing a rural road is $1,000,000 per mile. Since most of the curves are about a quarter of a mile in length, the reconstructing cost would be $250,000. Accounting for the cost of acquiring additional right of way, the total assumed cost to flatten a curve is $300,000.

### 4.1.3 Chevrons

Chevrons are supplemental warnings signs which are placed along a curve. Chevrons tell the driver the shape of the curve and accordingly drivers are warned when there is a change of the road from a tangential section to a horizontal curve. Chevrons can be used at any curve location; the decision to use chevrons is based on engineering judgment.

**Figure 4.1 Chevron**

Retroreflectivity of signs is necessary so that they can be visible during the day as well as at night time [15.]. Minimum retroreflectivity levels are established by FHWA. Minnesota typically uses the highest grade of reflective material for chevrons (DG3), and this material has a warranted life of twelve years, and is on a fifteen year replacement cycle.

The total cost of chevrons depends on the cost of installation, labor, sign reflective material and equipment used. In case of chevrons, it also depends on the number of signs used on the curve as per the required spacing which itself depends on the advisory speed.

**Table 4.1 Required Chevron Spacing as per Speed Limit [8.]**

| Advisory Speed Limit (mi/h) | Chevron Spacing (ft) |
|---|---|
| 15 | 40 |
| 20 | 80 |
| 25 | 80 |
| 30 | 80 |
| 35 | 120 |
| 40 | 120 |
| 45 | 160 |
| 50 | 160 |
| 55 | 160 |
| 60 | 200 |
| 65 | 200 |

On an average, the cost of installing chevrons along curves can be assumed to be $ 1,000. The efficiency of chevrons is estimated to be about 20% [8.].

### 4.1.4 Road Signs

Road signs can be as simple as a curve warning sign, speed advisory sign or technology-based as a changeable message sign. Curve warning signs are placed at least 50 feet before a horizontal curve. They are preferably to be used when the advisory speed on the curve is 30 mi/h or less [8.].

**Figure 4.2 Curve Warning Sign**

When the advisory speed is greater than 6 mi/h than the posted speed limit an advisory speed sign is coupled along with the curve warning sign [14.].

**Figure 4.3 Curve Warning Sign with Advisory Speed**

Almost 25% of the crashes occur due to speeding [3.] and hence it is more efficient to use a curve speed warning sign. Though the advisory speed is not the legal speed, it is the safe speed to travel the horizontal curve. As per FHWA, the speed warning sign coupled with the static curve warning sign increases the efficiency to 22% from 18% of a standard curve warning sign [16.]. These are the efficiency values that are used in our analysis.

The cost and life of these signs are based on similar parameters as the chevrons. A curve warning sign costs $120 and the speed advisory sign costs an additional $60. Assuming $50 for installation, a static curve warning sign and a curve warning sign along with advisory speed sign cost $170 and $230 respectively.

### 4.1.5 Paving Shoulders

The safety on shoulders is based upon whether they are wide or narrow and whether they are aggregate, paved, enhanced and composite. Paved shoulders include reconstructing the shoulder and overlaying it with hot-mix asphalt. The shoulder can be half aggregate and half paved which are referred to as composite shoulders. This shoulder paving can either be along horizontal curves or along tangential sections.

As per Mn/DOT the cost of paving shoulders is $60,000 to $100,000 per curve, given the average path lengths of curves studied in the before:after analysis. .

## 4.2 Infrastructure-Based Technology Safety Systems

### 4.2.1 Dynamic Curve Warning Signs

Owing to the fact that almost 25 % of the crashes occur due to speeding, it is justified to use more advanced curve warning signs. Also, almost 80% of the curves in Minnesota already have static curve warning signs and there is a need for further enhancements in these signs to be more effective in reducing crashes.

These signs mainly do the following:

- Detect the speed of the oncoming vehicle

- Warn the driver if he/she is speeding

Radar is used in all of them for speed detection. The driver can be warned in different ways. Flashing beacons are attached to the sign as shown in Figure 4.4. These beacons flash light to communicate to the driver to reduce speed before the curve approaches.

**Figure 4.4 Dynamic Curve Speed Warning Sign (with a Flashing Beacon and Radar Detection)**

A solar beacon could be used which consists of an array which converts sunlight to electricity which is used for powering up the LED lights in the flasher circuit.

The cost of this system ranges from $9,000 to about $14,000 per installation [8.] depending on the design. For the benefit:cost analysis, an average cost of $12,000 is used. The maintenance work consists of cleaning the solar array, checking whether the electric connections are secured, battery maintenance. The maintenance costs are mainly associated with the battery maintenance in the system. The battery needs to be changed after every 4 to 7 years depending on the weather conditions and costs $160 [17.]. The battery lasts longer in cold weather conditions. The LED lamps used have high reliability and a long life and this makes the solar beacon very economical. Except for incidents like lightning striking the panel, the dynamic curve warning sign has a life of around 20 years.

As per a study conducted, this sign is to be used when there have been more than 10 accidents in 2 years along that section of the road.

They have high efficiency value of 30% [16.].

### 4.2.2 DGPS-Based Lane Departure Warning Systems

A DGPS-based lane departure system consists of three primary components:

- A dual frequency, carrier phase Differential correction capable Global Positioning System receiver capable of providing accurate (5-8cm position errors) position measurements at high data rates (10 Hz),
- A source of differential corrections (from ground-based GPS base stations), and
- A map database which stores the presence and location of all lane boundaries on the road network.

Figure 4.6 illustrates how the DGPS system functions (in a survey context, but replacing “user” with “vehicle” accurately represents system functionality):

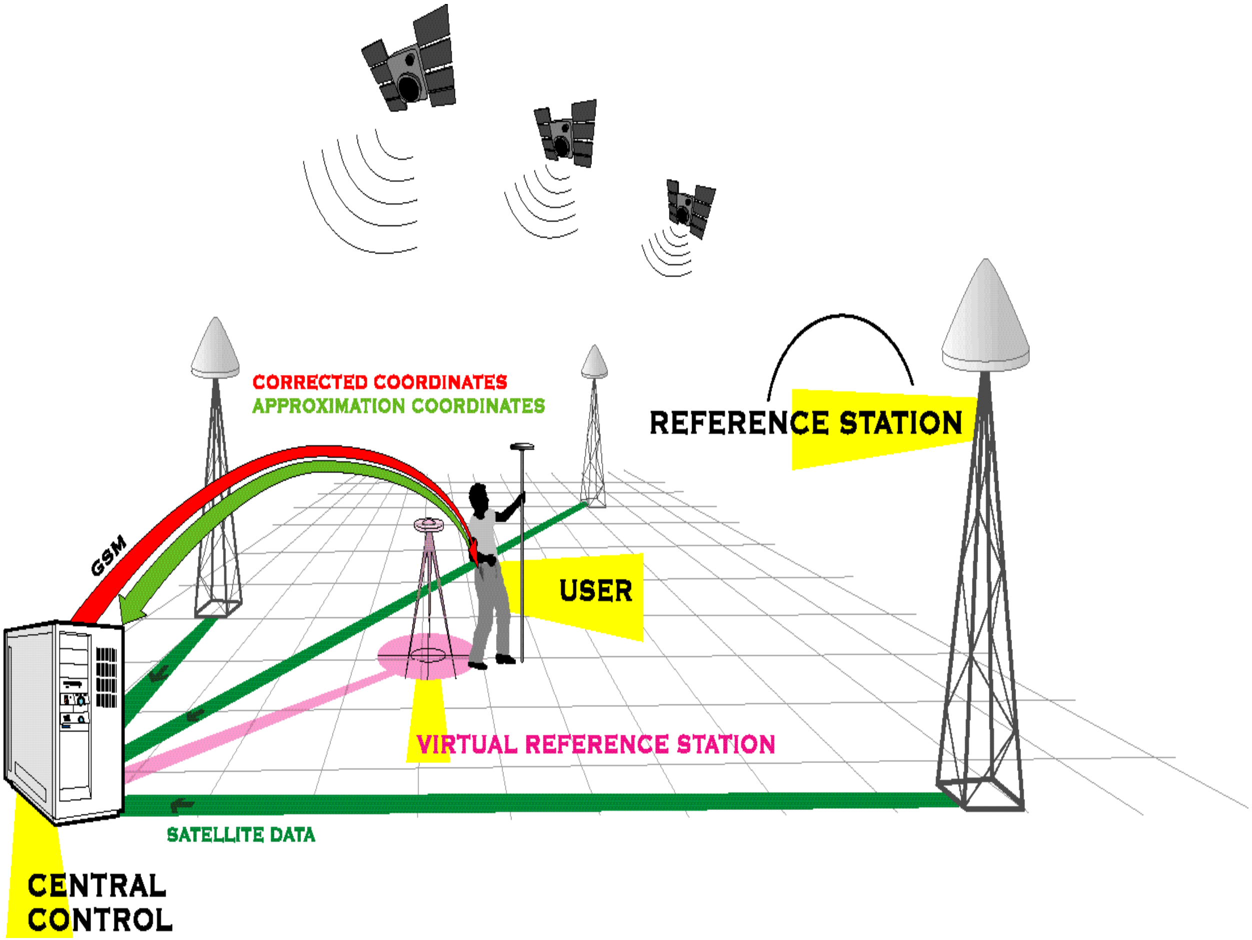


**Figure 4.5 Block Diagram of a DGPS System**

The moving vehicle requests for a correction signal from the base reference server using a data-capable cell phone. This signal is received by the data-capable cell phone which feeds it into the GPS receiver in the vehicle. The error correction provided by the server is applied by the GPS receiver in the vehicle. By applying this correction, the roving GPS receiver can achieve position solutions with errors in the range of 5-8 cms [18.].

Once the vehicle has an accurate position, the on-board map database is queried (with the query based on the present position of the vehicle as determined by the GPS system), and the query returns the global position of the lane boundaries for the present lane of travel. The position and speed of the vehicle arising from the GPS measurements is compared to the geometry of the road being travelled, and the likelihood of a lane departure event is computed. If the likelihood of a lane departure event is sufficiently great, the driver is issued a warning through an audible

The state of Minnesota operates a GPS network throughout the state; this network is shown in Figure 4.7.

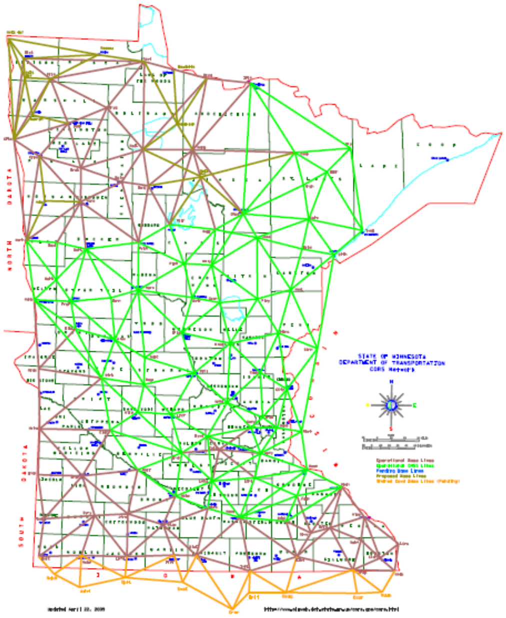


**Figure 4.6 VRS Network in MN**

The Minnesota VRS system represents the primary piece of infrastructure needed to support a DGPS-based lane departure warning system. This technology is not unique to Minnesota; other states, including Ohio, Texas, and Iowa (to name a few) are implementing state-wide VRS networks. High accuracy map databases of roads for lane departure warning purposes can be generated for approximately $100 per mile. Considering the 53,000-mile of two-lane highway in the state of Minnesota, the map database could be generated for a cost of $53,000,000.

### 4.2.3 Vision-Based Lane Departure Warning Systems (LDWS)

Vision-based lane Departure Warning Systems are another example of in vehicle technology to increase the safety of drivers while driving along tangential sections. These are already offered by certain cars manufacturers. Vision-based LDWS were seen in the American market first around 2000 by Iteris. Toyota, Nissan, General Motors, Audi started with the lane monitoring system where in the system provides an audible warning signal or a vibratory signal, but does not interfere with the driving controls. The lane departure warning system offered by Lexus uses the electric power steering system which also applies a counter torque to retain the driver within the lane [19.].

Figure 4.7 Vision-Based LDWS

The system consists of a forward looking camera which tracks the lane markings. The image processing software in the system analyzes this to track the position of the vehicle with respect to the lane markings and this is shown to the driver on an onboard screen. As the driver crosses these lane markings without activating the turn signal or at speeds greater than 25 mph, this is interpreted by the system as unintentional lane change and the driver is alerted by visual and haptic (i.e., Lexus with steering torque) or tactile (BMW, Infiniti) signals.

Field operational tests have been conducted to evaluate the efficiency of these systems. It was noticed that on freeways LDWS are available for generally 75% of the time. This availability is constrained due to visibility of the lane markings [20.].

Vision-based lane Departure warning systems are now offered by different car companies at varied prices depending on the functionalities offered in the safety package and the vehicle on which it is offered. Surprisingly, General Motors is the price leader, with a vision-based lane departure warning system available for less than $300. Table 2.4 summarizes the present market availability and prices for vision-based lane departure warning systems:

**Table 4.2 Vision-Based LDWS Offered by Different Car Companies**

| COMPANY | PACKAGE | COST |
|---|---|---|
| Volvo | Collision avoidance package, Adaptive Cruise Control, Collision Warning with Auto Brake, Distance Alert<br>Lane Departure Warning, Driver Alert Control | $ 1,695 |
| Cadillac | Lane departure warning system | $ 295 |
| Infinity | Bose® Studio Surround® sound system with digital 5.1-channel decoding, 14 speakers and multi-media drive<br>Intelligent Cruise Control<br>Brake Assist with Preview<br>Lane Departure Prevention and Lane Departure Warning systems | $ 2,800 |
| BMW | BMW Driver Assistance Package –Blind spot detection, Lane departure warning, High beam assistant | $ 1,350 |

Table 4.3 summarizes the safety countermeasures for which benefit:cost analyses will be performed in the sequel. The analysis will cover the range from traditional civil engineering countermeasures, advanced infrastructure-based technologies, and in-vehicle emerging technologies.

**Table 4.3 Safety Systems for Curves and Tangential Sections**

| **FOR CURVES** | | **FOR TANGENTIAL SECTIONS** | |
|---|---|---|---|
| **Infrastructure-Based Civil Engineering Treatments** | **Infrastructure-Based Technological Safety Systems** | **Infrastructure-Based Civil Engineering Treatments** | **In-vehicle Safety Systems** |
| • Rumble strips<br>• Curve flattening<br>• Paving shoulders along curves<br>• Chevrons | • Dynamic curve speed warning signs | • Rumble strips<br>• Paving shoulders along tangential sections<br>• Pavement widening | • Vision-based LDWS<br>• DGPS-based LDWS |

# Chapter 5: Effectiveness of Infrastructure-Based Treatments

## 5.1 Definition

Effectiveness of any product or technology is based on how useful it is. The purpose of safety solutions is to avoid crashes. The effectiveness of the infrastructure and technology-based solutions is thus based on the reduced number of crashes after implementing.

In case of solutions which have already been implemented, the effectiveness is calculated based on the before:after analysis and a formula proposed by Evans in calculation of effectiveness of seat belts[21.].

## 5.2 Infrastructure-Based Treatments for Curves

There are five infrastructure-based treatments that have been tried for curves; adding rumble strips, curve flattening, paving of shoulders along curves, adding chevrons, static curve warning signs and static curve warning signs along with advisory speed warning signs. For the road signs, efficiency values have been mentioned in Chapter 4 in their descriptions. For the other three treatments; rumble strips, paving shoulders and curve flattening; effectiveness has been calculated based on the before:after analysis. Number of crashes and the vehicle miles traveled was recorded before and after the treatment was implemented and based on these, the before and after crash rate were calculated as:

Equation 5.1:

$$Average\ Crash\ Rate\ Before = \frac{Total\ Number\ of\ crashes\ before}{Total\ VMT\ before} \times 1{,}000{,}000,$$

where VMT is the vehicle miles traveled.

Equation 5.2:

$$Average\ Crash\ Rate\ After = \frac{Total\ Number\ of\ crashes\ after}{Total\ VMT\ after} \times 1{,}000{,}000.$$

The crash rates are in units of number of crashes per million vehicle miles traveled per year

Equation 5.3:

$$Crash\ Ratio = \frac{Average\ crash\ rate\ after}{Average\ crash\ rate\ before}$$

Equation 5.4:

$$Effectiveness\ =\ 1 - CrashRatio$$

The effectiveness in percentages for implementations on curves is given below.

**Table 5.1 Effectiveness for Infrastructure-Based Treatments for Curves Based on Before:After Analysis**

| Curve Treatment | Average crash rate before | Average crash rate after | Crash ratio | Effectiveness | Percent effectiveness |
|---|---|---|---|---|---|
| Curve flattening | 1.23 | 0.42 | 0.34 | 0.66 | 66 % |
| Rumble strips | 1.26 | 1.07 | 0.85 | 0.15 | 15 % |
| Shoulder paving | 5.35 | 10.97 | 2.05 | Crash Rate Increased (not computed) | Crash Rate Increased (not computed) |

Surprisingly, the crash rate after paving shoulders along curves is higher than crash rate before. Thus this is not at all a favorable option.

Curve flattening is seen to have a very high effectiveness value of almost 66 % as compared to rumble strips which show effectiveness of 15 %. However, curve flattening is among the most expensive treatments. Hence, just knowing the effectiveness is not enough to decide which treatment to apply; the costs also have to be deduced.

The other infrastructure-based treatments for curves include chevrons, static curve warning signs and static curve speed warning signs whose effectiveness has been mentioned in Chapter 4 while describing all countermeasures. Table 5.2 lists the effectiveness values for all the civil engineering infrastructure-based treatments for curves:

It is important to note that the last two rows of Table 5.2 represent data from the FHWA *Desktop Reference* [12.]. As previously noted, approximately 80% of the curves in the cross-sectional analysis and before:after analysis were provided with either Static Curve Warning signs or Static curve Speed warning signs. Even with these signs present, these intersections were subject to high crash rates. The FHWA likely represent the effectiveness of moving from no sign to either of these two signs; however, *in practice*, most curves have these signs, and still experience a high crash rate. Therefore, in the sequel, these two treatments will be considered to be the baseline, leaving rumble strips, curve flattening, and chevrons as the options considered to improve curve safety.

**Table 5.2 Effectiveness of Infrastructure-Based Treatments for Curves**

| Treatment | Effectiveness (%) |
|---|---|
| Rumble strips | 15 |
| Curve flattening | 66 |
| Chevrons | 20 |
| Static curve warning signs | 18 |
| Static curve Speed warning signs | 22 |

## 5.3 Infrastructure-Based Treatments for Tangential Sections

There are four treatments for tangential sections- aggregate to paved (AP), aggregate to enhanced (AE), pavement widening (PWid), and paved to enhanced (PE). 930 miles of tangential sections have been considered, with categories drawn as per aggregate, paved, composite, and enhanced which are further divided as per their widths, them been from 0 to 2 ft, 2 to 4 ft, 4 to 6 ft, 6 to 8 ft, and 8 to 10 ft. There is just one example of pavement widening in the data set. Since this makes the sample set for pavement widening statistically insignificant, this treatment is not considered in our analysis.

For calculation of effectiveness for tangential sections, there are two methods that are used. Two terms- group efficiency and sectional efficiency - have been defined. These two efficiencies are listed for the different tangential sections as per the treatment given to them. The effectiveness is estimated as the average sectional efficiency.

### 5.3.1 Aggregate to Paved Treatment (AP)

#### *5.3.1.1 Group Efficiency*

For before:after analysis, tangential sections with similar treatments are grouped together. For aggregate to paved, the sum of the total number of crashes has been calculated. There are 21 tangential sections which have undergone this treatment. The number of crashes and VMT before and after treatment for each of these sections is considered.

Table 1 in Appendix F lists the crash rates and the vehicle miles travelled before and after the aggregate sections have been paved. The equations below are used to evaluate the group efficiency for the AP tangential sections.

**Group Efficiency for AP Tangential Sections**

Total number of crashes before = 477

Total number of crashes after = 537

Total VMT before = 334,000,000 miles

Total VMT after = 450,000,000 miles

Using Equation 5.1,

$$Crash\ Rate\ Before = \frac{477}{3.34 \times 10^{8}} \times 1{,}000{,}000$$

=1.4 crashes per million vehicle miles.

Using Equation 5.2,

$$Crash\ Rate\ After = \frac{537}{4.5 \times 10^{8}} \times 1{,}000{,}000$$

=1.2 crashes per million vehicle miles.

$$Group\ Efficiency = 1 - \frac{Total\ Crash\ Rate\ After}{Total\ Crash\ Rate\ Before} = 1 - \frac{1.2}{1.4} = 0.1429 = 14.29\%$$

### *5.3.1.2 Sectional Efficiency*

The second method calculates the crash rates and efficiencies for each individual section. These are called sectional efficiencies. The following equations are used. A sample calculation is shown for one section of AP tangential section (Appendix F Table 1).

**Sectional Efficiency for AP Tangential Sections**

$$\begin{aligned} Sectional\ Crash\ Rate\ Before \\ &= \frac{No.of\ crashes\ before\ for\ the\ section}{VMT\ before\ for\ the\ section} \times 1{,}000{,}000 \\ &= \frac{7}{2{,}088{,}968} \times 1{,}000{,}000 \end{aligned}$$

= 3.4 crashes per million vehicle miles travelled.

$$Sectional\ Crash\ Rate\ After = \frac{No.of\ crashes\ after\ for\ the\ section}{VMT\ after\ for\ the\ section} \times 1{,}000{,}000$$

$$= \frac{5}{3{,}037{,}530} \times 1{,}000{,}000$$

=1.6 crashes per million vehicle miles

$$Sectional\ Efficiency = 1 - \frac{Sectional\ crash\ rate\ after}{Sectional\ crash\ rate\ before} = 1 - \frac{1.6}{3.4} = 0.529 = \mathbf{52.94}\%$$

The actual sectional efficiencies are calculated for each of the tangential sections in the data set for AP sections. These are listed in table 1 in Appendix F.

The average of each of these sectional efficiencies gives the average sectional efficiency as 0.36%.

There is a huge difference in the values of the efficiencies found by the two methods. The reason for this is that there is a big range of VMT for the individual AP sections – for example, VMT before has a range from 4,245,972 miles to 102,623,400 miles. While calculating the group efficiency, in equations 5.1 and 5.2, the before and after crash rates are calculated by adding the varied VMT for all individual sections.

The difference in the distribution of the sectional efficiencies is shown by the histogram below in Figure 5.1.

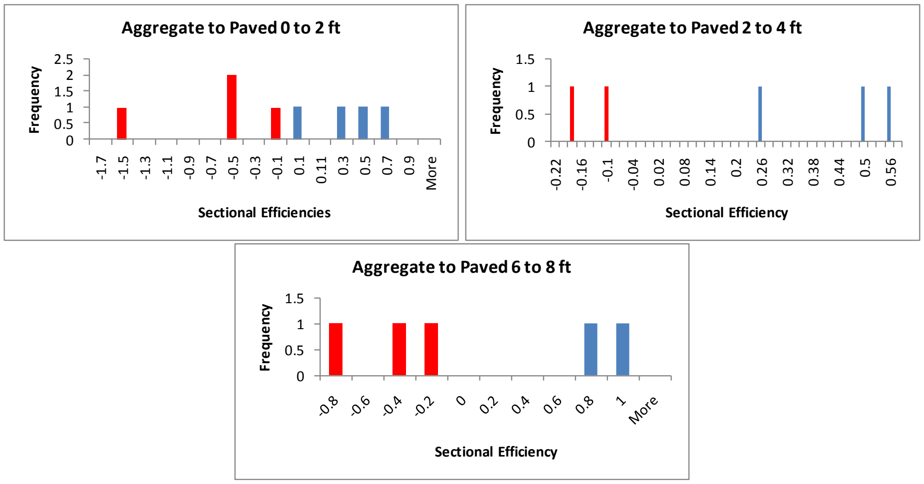


**Figure 5.1 Distribution of Sectional Efficiencies for Aggregate to Paved Sections**

The histograms show the varying range of the sectional efficiencies and also the large number of efficiencies which lie in the negative range (marked in red). The integrated results show that paved shoulders provide higher degrees of safety than aggregate shoulders. However, the data fails to indicate which pavement width is optimal.  This failure of the data is caused by the wide variation in VMT experience by the various sections of roadway.

### 5.3.2 Enhancing Aggregate and Paved Tangential Sections (AE)

Similarly, two efficiencies are calculated for enhancing aggregate and paved tangential sections. The histograms for the distribution of the sectional efficiencies are shown for both with the outliers marked in red. These outliers are discarded for calculating the average sectional efficiency.

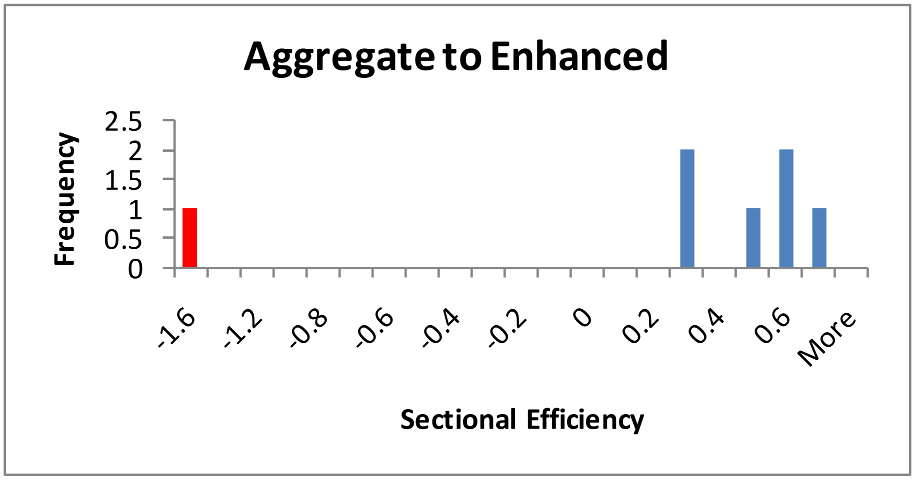


**Figure 5.2 Distribution of Sectional Efficiencies of Aggregate to Enhanced (AE) Tangential Sections**

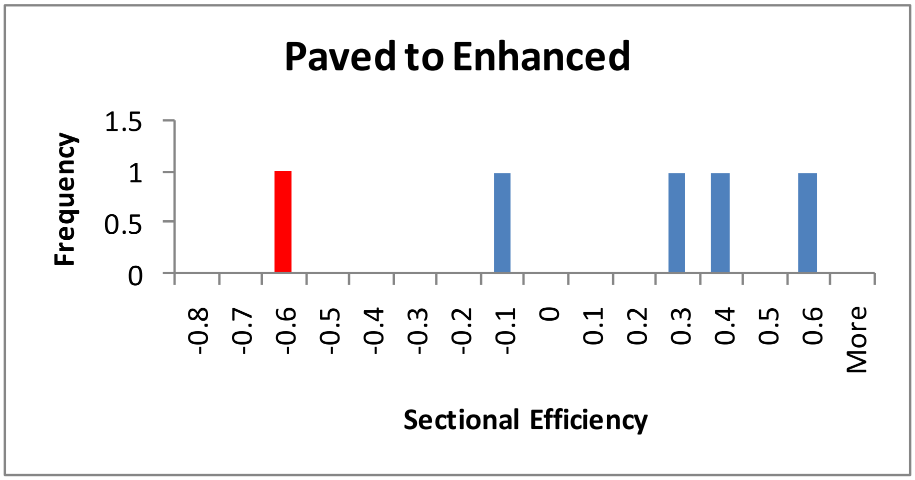


**Figure 5.3 Distribution of Sectional Efficiencies for Paved to Enhanced (PE) Tangential Sections**

The efficiencies for enhancing tangential sections can be listed in this table below:

**Table 5.3 Efficiencies for Enhancing Aggregate and Paved Tangential Sections**

| | **Aggregate to Enhanced** | **Paved to Enhanced** |
|---|---|---|
| **Group Efficiency** | 37.5% | 15.38% |
| **Average Sectional Efficiency** | 44% | 26.75% |

The average sectional efficiency has been considered as the effectiveness for enhancing the aggregate and paved tangential shoulders.

## 5.4 Summary

### 5.4.1 Safety Benefits for Countermeasures Implemented on Curves

Curve flattening shows the highest efficiency of 66%. Adding rumble strips along the curves is 15% efficient. Paving shoulders along the curve is not beneficial as the crash rate after paving increases on the curves in the data set.

### 5.4.2 Safety Benefits for Countermeasures Implemented on Tangential Sections

Average sectional efficiency is considered as the effectiveness of the infrastructure-based treatments for tangential sections. Most of the sectional efficiencies for paving shoulders are negative. Hence, it is not recommended that shoulders be paved as a means to improve safety. If shoulders are paved, then to improve safety, the shoulder should be enhanced with either rumble strips or rumble stripes. For tangential sections it is beneficial to enhance shoulders. For both categories of sections; aggregate and paved showed reduction in crash rate when rumble strips/stripEs were added to them.

# Chapter 6: Effectiveness of Technology-Based Safety Systems

The potential of any technology should be evaluated before implementing it. The technology-based treatments for curves are dynamic curve warning signs with a radar and a flashing beacon. Their effectiveness values have been mentioned in Chapter 4.

For tangential sections, in-vehicle technologies have been analyzed. Unlike infrastructure-based solutions where they have already been implemented, there is no such implemented history available for in-vehicle technologies. Their efficiency thus has to be modeled by studying previous trends and deriving conclusions based on that.

The primary goal of applying safety technologies is to reduce the fatalities caused due to crashes, thus the effectiveness of the technology would directly translate to reduction in the rate of fatal crashes. For this purpose, the fatality rate in Minnesota was studied from 1975 to now.

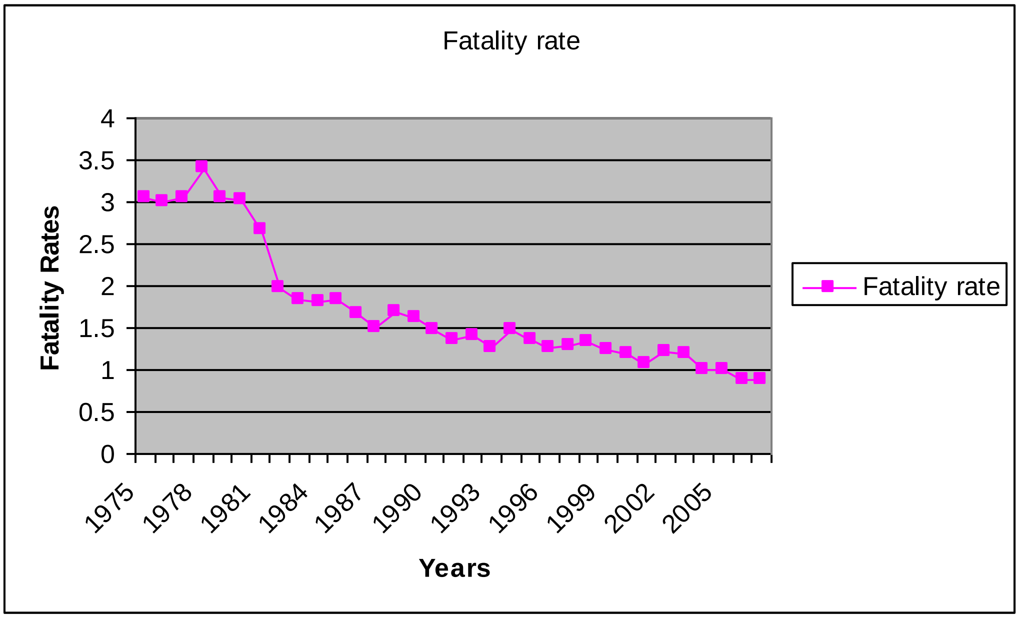


**Figure 6.1 Fatality Rate in MN [3.]**

In Figure 6.1, a sudden reduction in the fatality rate occurs between 1981 and 1984. This was mainly due to the National Minimum Drinking Age Act of 1984 in which the legal drinking age was increased from 18 to 21 [22.]. The states refusing to comply with this act would have had a reduction in their highway funds. By end of 4 years, that is by 1988 all the 50 states changed their legal drinking age to 21.

Another factor to be considered for reduction in fatality rates is the use of safety systems. One of the most common safety systems which has been used in the past in vehicles are restraint systems including seat belts. Seat belts were introduced in automobiles in 1956 by Volvo, Ford and Chrysler in some of their models. In 1971, NHTSA amended FMVSS 208 to require passive restraints in front [23.]. The 1974 models had a feature of ignition interlock; the car didn’t start without the driver being belted and also gave some warning sounds. These warnings were lessened by 1975 to only a warning light of 4-8 seconds. According to NHTSA, seat belt usage until about 1984 was only 14%. By 1992, it increased to 62% and by 2002 to 75%. In 2002, NHTSA urged auto companies to introduce belt warnings.

New York was the first state to make belt use as a mandatory law in 1985 and other states followed. The mandatory laws in each state after 1984 increased the seat belt usage rate by about 15%. States having primary seat belt laws show higher usage rates than those having secondary or no laws [24.]. Seat belt usage was made mandatory in Minnesota in 1986. The belt usage rate prior to that was 20%, and after that increased by 65% to 33% [3.]. June 9th 2009 onwards Minnesota too will have a primary seat belt law.

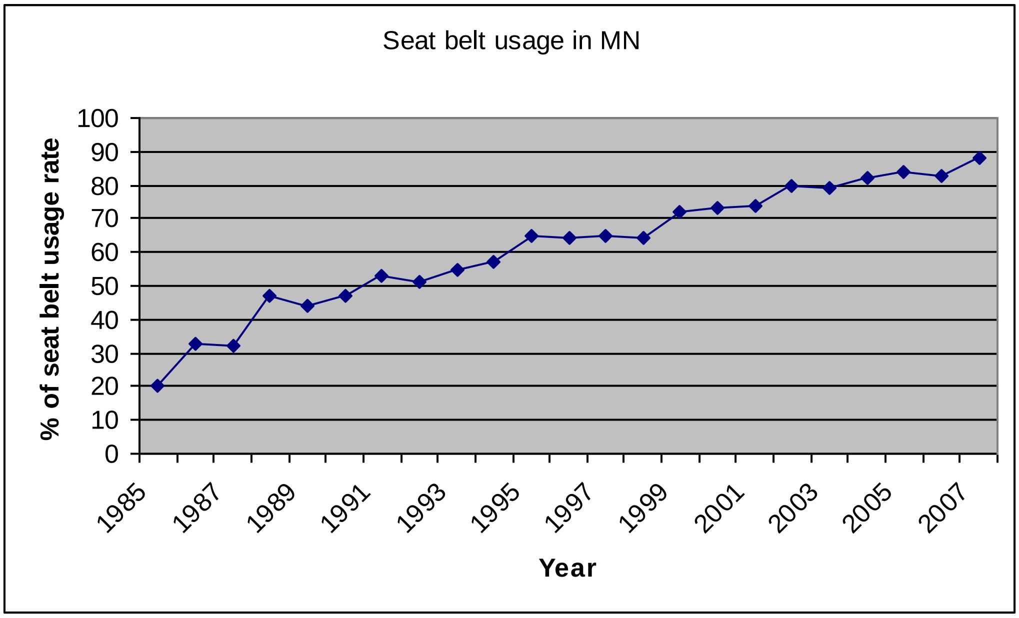


**Figure 6.2 Seat Belt Usages in MN [4.]**

Comparing Figures 6.1 and 6.2, we can assume the reduction in fatality rate in Minnesota to be a factor of the seat belt usage in the state. One of the factors that decide the usage is the purchasing power of the people. The purchasing power is reflected by the general economy and can be quantified using the inflation rate or the consumer price index. As the purchasing power of the people increases, the willingness to pay for technology increases and thus the usage increases. The inflation rate is however used to discount the costs and hence wouldn’t be considered in the efficiency modeling.

Age of the driver can also be a deciding factor for usage of safety systems. The tendency of people to use restraint systems depends on their age. The graph below shows that generally people in between age group 16-25 are not in the habit of using safety devices.

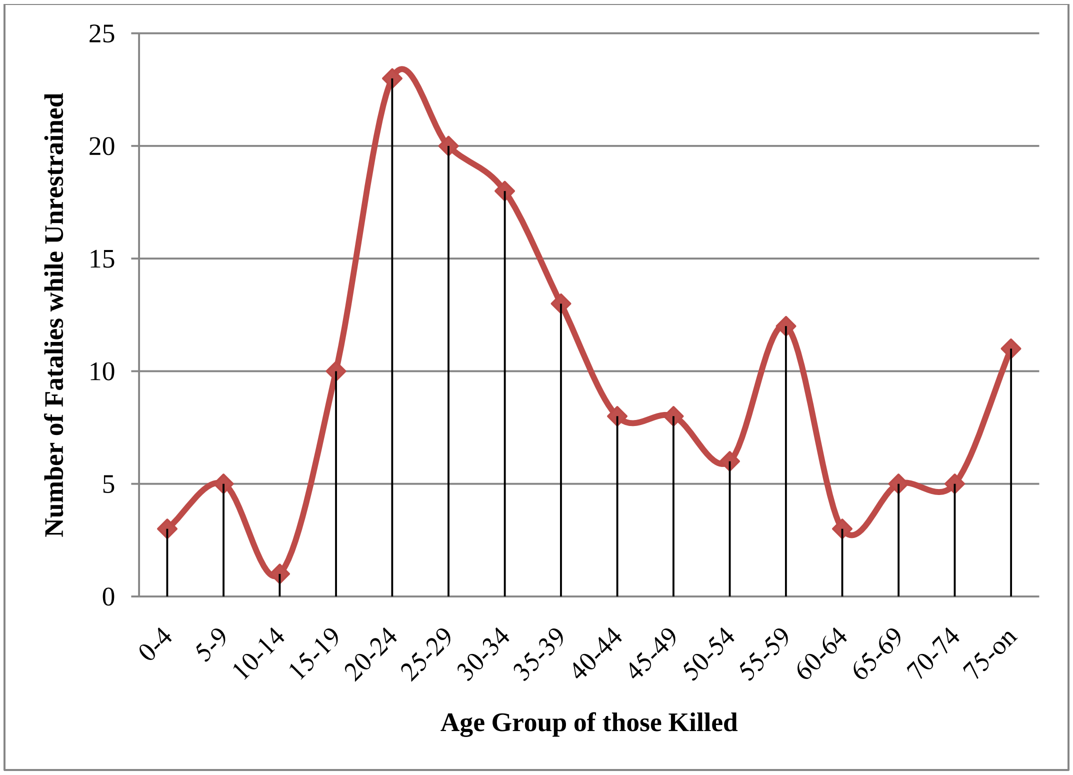


**Figure 6.3 Number of Minnesotans Not Using Restraints as per Age [25.]**

However, Evans has proved by regression analysis that the effectiveness of airbags does not depend on the age factor [26.]. The methodology applied by him was a regression analysis of the fatality rate with and without the use of airbags. Both regression analyses had age as independent variable.

These were the two equations obtained as a result of the regression analysis

$$Fatality\ Rate\ without\ using\ airbags = 30.87 - 0.339(Age)$$

$$Fatality\ Rate\ after\ using\ airbags = 54.27 - 0.339(Age)$$

In both of the regression equations, the coefficient of drivers' age is the same (0.339). Because age has the same influence on crash rate, Evans claims that effectiveness does not depend on the age factor.

Thus, the effectiveness and reduction in fatality rate of in-vehicle technologies is solely modeled as a property of the usage rate. The values used for fatality rate and seat belt usage have been given in Appendix G. The regression analysis of fatality rate as a factor of the seat belt usage in Minnesota gives the following equation:

Equation 6.1:

$$\begin{aligned} &Fatality\ rate\ per\ 100\ million\ vehicle\ miles\ traveled \\ &\qquad = 2.0965 - 0.0128 \times (Seat\ belt\ usage\ as\ percentage) \end{aligned}$$

The negative co-efficient of the seat belt usage indicates numerically that the fatality rate reduces and thus the effectiveness increases as the seat belt usage increases. This model can be used as an analogy to predict the effectiveness of the in-vehicle technologies.

Mandating seat belts by law has played a significant factor in their market penetration. It is hence valid to consider another example to evaluate the exposure. Anti-lock Braking System (ABS) has been implemented in cars as a safety measure since 1984.

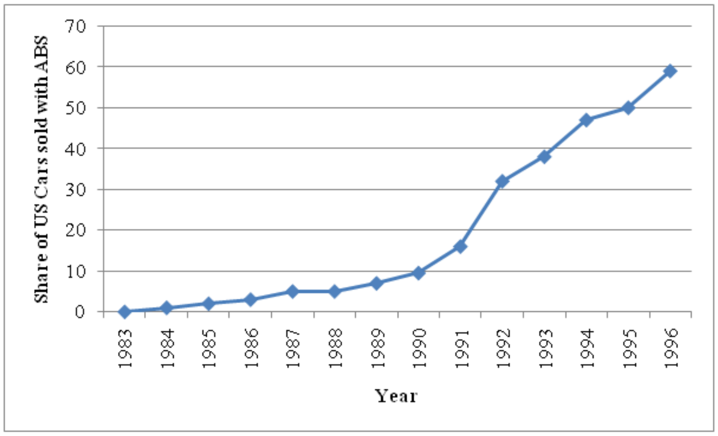


**Figure 6.4 Market Penetration of ABS [27.]**

Figure 6.4 tells us that by 1996, the market penetration of ABS in automobiles was about 59%. Values from this graph give us the technology diffusion for 13 years. For our analysis, market penetration rates are required for 20 years and hence for the next 7 years, we referred another article [28.].

Figure 6.5 is based on a study involving cost effectiveness of automate highway systems. ARV stands for automated ready vehicle. Four different alternatives are considered with increased number of electronics in the vehicle and decreasing electronics on the road. The base condition is implementing no electronics in the vehicle but only on the roads. The other three alternatives are integrating electronics in the vehicle which are shown in Figure 6.5 as ARV_low, ARV_medium and ARV_high. From ARV_low to ARV_high, the number of electronics in the vehicle is increased and that on the roads are decreased. To predict the market penetration of these vehicles, an analogy has been drawn to the market penetration of air bags, ABS and adaptive cruise control. The trend line of ARV_medium corresponds to the market penetration of ABS as in thousands of vehicles of the total vehicles sold. As per this graph, the market penetration of ABS in 14 years would be 75%. This is added to the previous penetration of 14 years and extrapolated to 20 years in order to follow an S curve. These values are then plotted to obtain the curve below for the entire 20 years.

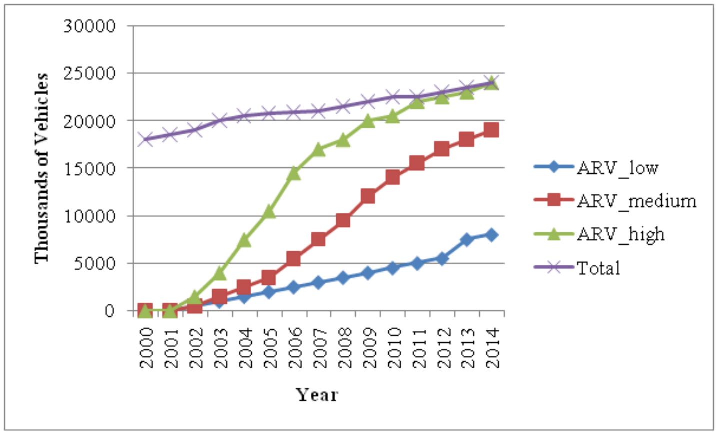


**Figure 6.5 Market Penetration of Automated Highway Systems, where ARV Stands for Automated Ready Vehicle [28.]**

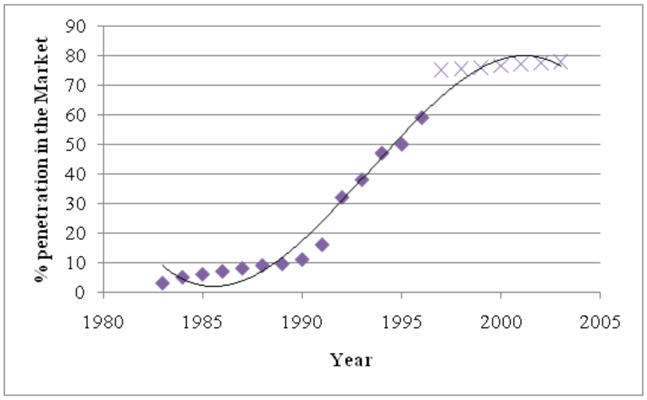


**Figure 6.6 Assumed ABS Market Penetration for 30 Years**

Based on these assumptions, the effectiveness would be modeled for the two in-vehicle technologies considered, vision-based lane departure warning systems and DGPS-based lane departure warning systems.

## 6.1 Effectiveness of Vision-Based Lane Departure Warning System (LDWS)

The following steps have been followed to predict the efficiency models for the in-vehicle technologies.

### 6.1.1 Step 1: Assuming Base Efficiencies

As mentioned before, field operation tests have been conducted to evaluate the efficiency of vision-based LDWS at UMTRI in the year 2006. According to the driver's response, the system was efficient by 68% in keeping the drivers within the lane markings after the alerts [29.]. It has been mentioned that the lane markings are visible only 75% of the times on the freeways. Thus, when using a LDWS on a freeway, the full 68% efficiency wouldn't be available. The efficiency of vision-based systems would be restricted to 75% of the 68% efficiency on the test track. The base efficiency of vision-based LDWS on roads would thus be about 50%.

Another FOT was conducted in February 2009 by the Federal Motor Carrier Safety Administration to analyze the cost effectiveness of a LDWS with respect to the motor carrier industry which are one of the stake holders when considering such in-vehicle systems. The efficiency rates for LDW to reduce single vehicle roadway crashes as per the FOT conducted by them were 23% on a lower scale and 53% on a higher scale [30.].

This gives us two different efficiency rates to consider, the efficiency by UMTRI which is 50% and the efficiency by FMCSA which is 23%. The higher efficiency is termed as the optimistic efficiency and the lower as pessimistic.

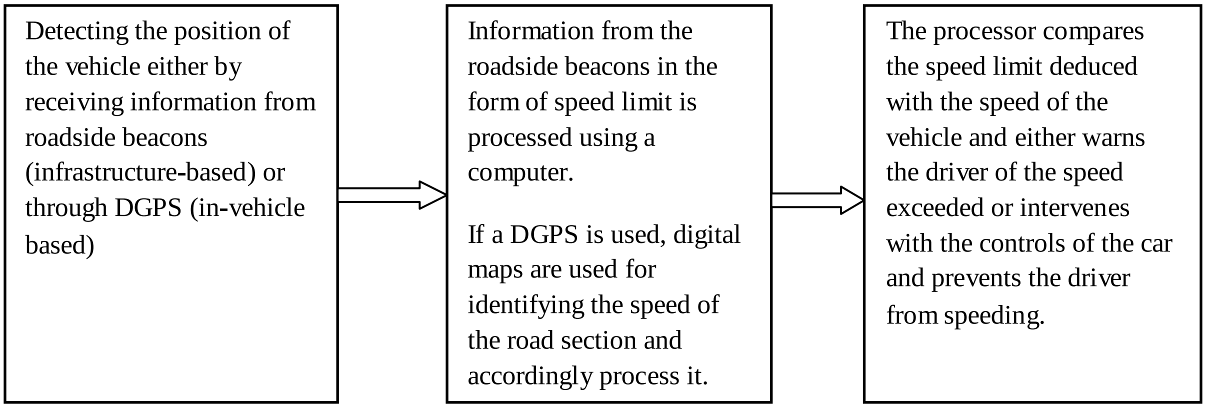
### 6.1.2 Step 2: Growth in Efficiency

The efficiency of technology usually follows growth curves. Due to the new technology arriving in the market, each new system is going to be built on the previous, resulting in more efficient systems [31.]. The efficiency of the vision-based LDWS systems can be broadly said to depend on the following three factors

- Change in the nature of the warning from advisory to interventional
- Improvement in the image processing software
- Improvement in maintenance of the lane markings

#### *6.1.2.1 Change in the nature of the system*

A study has been conducted in Leeds by Oliver Carsten for studying the deployment of Intelligent Speed Adaptation (ISA) in vehicle in London [32.]. This system integrates the infrastructure-based road sensors and in-vehicle technologies and warns the drivers based on the position of the vehicle and the speed limit on that road. The block diagram in Figure 6.7 shows the basic functioning of an ISA system.



Detecting the position of the vehicle either by receiving information from roadside beacons (infrastructure-based) or through DGPS (in-vehicle based)

Information from the roadside beacons in the form of speed limit is processed using a computer.

If a DGPS is used, digital maps are used for identifying the speed of the road section and accordingly process it.

The processor compares the speed limit deduced with the speed of the vehicle and either warns the driver of the speed exceeded or intervenes with the controls of the car and prevents the driver from speeding.

**Figure 6.7 Basic Functioning of an ISA System**

The system consists of three parts: identifying the position of the vehicle, identifying the prescribed speed limit the vehicle should be at, and warn the driver accordingly. The position of the vehicle is identified using either road side beacons or a DGPS. In case of using road side beacons, the posted speed limit is also transmitted to the vehicle. Else, the position through the DGPS is compared with digital maps to identify the speed limit at the location of the vehicle. A processor on the vehicle compares the posted speed limit with the speed limit of the vehicle. The driver is then warned either through audible signals or by intervening with the controls of the vehicle and reducing the speed.

The efficiency of the system increases as the nature of the warnings change from advisory to mandatory [32.]. In this case advisory means the driver is just warned about exceeding the speed limit, whereas in a mandatory system, the ISA is linked to the vehicle throttle control and the braking system. Thus the efficiency increases when the system intervenes with the driving controls.

When the lane departure warning systems were first seen in 2000, the system just provided audible and tactile warnings. These are now changing to interventional LDWS. The 2010 Lexus HS250h model offers a torque correction along with the LDWS. An electronic stability program (ESP) is integrated with the LDWS which provides a counter torque to the steering wheel if the driver accidently departs from the lane markings [19.]. According to the previous discussion [32.] if such a system is introduced in the future in all systems, it would change the efficiency of the LDWS.

#### *6.1.2.2 Improvement in the Image Processing Software*

Image processing software is used to analyze the position of the vehicle with respect to the lanes. The resolution and robustness of the system depends on the calculation capacity of the processor used [33.]. As cameras and imaging processing capabilities continue to improve, the expectation is that the availability of the vision-based lane departure warning system should continue to improve.

#### *6.1.2.3 Improvement in Maintenance of the Lane Markings*

Another issue faced by the vision-based image processing software is identifying the lane markings. The capacity of the LDWS to identify them depends on the retroreflectivity of the markings and the contrast between markings and pavement. A study was conducted in Florida to study the various factors affecting the performance of the LDWS [20.]. The performance of the system is evaluated in terms of a factor; efficacy rate (ER). ER is defined as the percent number of times the LDWS provides alarms to the total number of instances. The ER is low for yellow lane markings as compared to white lane markings. This is due to low contrast between the yellow color and the pavement concrete. The retroreflectivity of the markings and thus the performance of the LDWS also decrease as the age of the marking increases. The efficiency of the LDWS could thus be improved by better maintenance of the lane markings.

Due to the above three reasons, the efficiency of the lane departure warning systems can be assumed to increase in the next 20 years. The efficiency can be estimated to increase linearly. Thus assuming optimistic and pessimistic base efficiencies to be 50% and 23%respectively, the end efficiencies in 2030 would be around 65% and 28%.

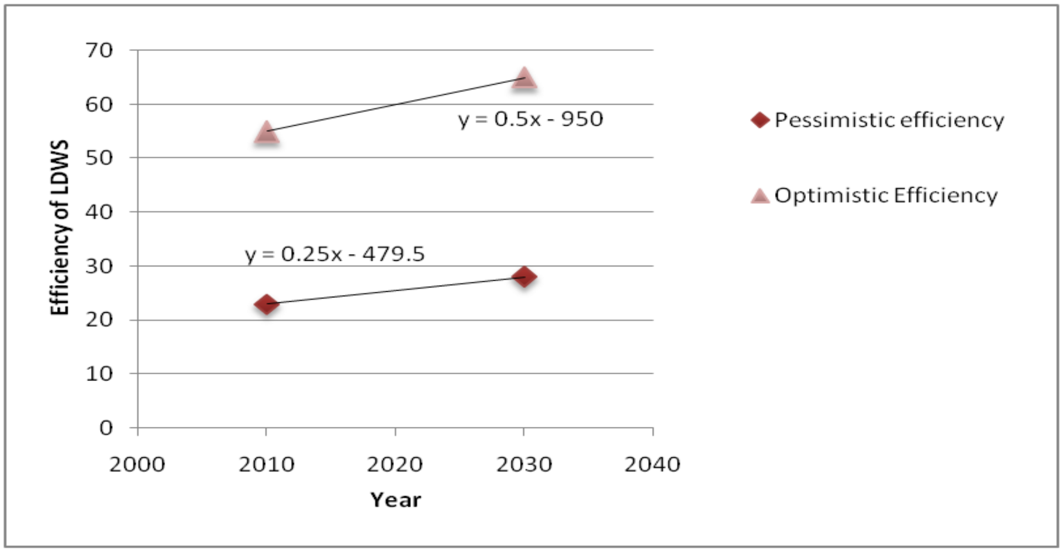


**Figure 6.7 Increasing Efficiencies of LDWS**

### 6.1.3 Absolute Efficiency

The above lines were obtained from a linear trend line using assumed start and end efficiency. Based on the linear equation obtained, individual efficiencies are obtained for the intermediate years and these are termed as absolute efficiency. For example in the equation for the optimistic efficiency,

Equation 6.2

$$Absolute\ Efficiency(2011) = 0.5 \times (2011) - 950 = 55.5\%$$

### 6.1.4 Effective Efficiency

These efficiency rates are further biased by the exposure in terms of the market penetration. Unlike the civil engineering based solutions, where the driver has a forced exposure, for in-vehicle technologies, the driver has an option whether to purchase the system or to overlook it. Such market penetration can be estimated based on existing systems such as seat belts (Figure 6.2) and ABS (Figure 6.6) as already discussed previously in this chapter. In Figure 6.2, seat belt usage values are plotted starting from the year 1985 to 2007. This period has been chosen to reflect the effect of making seat belts mandatory. The seat belt usage in 1985 in MN was 20%. It would be absurd to assume a start market penetration of 20% for the LDWS and hence a low market penetration is assumed at the start and after 10 years considering the LDWS to be made mandatory, the market penetration shows an increase.

Equation 6.3

$$Effective\ Efficiency(Year) = Absolute\ efficiency(Year) \times Marketpenetration(Year)$$

Individual values are available for the effective efficiency based on Equation 6.3. For example for the effective efficiency following the seat belt model, the following calculations have been done

$$Effective\ Efficiency\ (2011) = 55.5\% \times 0.1 = 5.55\%$$

where 0.10 represents the 10% seat belt usage of seat belts in the first year after introduction.

Two models are developed for the efficiency as an analogy to seat belts and ABS (Appendix H). Seat belts would reflect the efficiency if the in-vehicle technologies are mandated further in the next 20 years whereas the ABS model follows a trend of non-mandatory technologies.

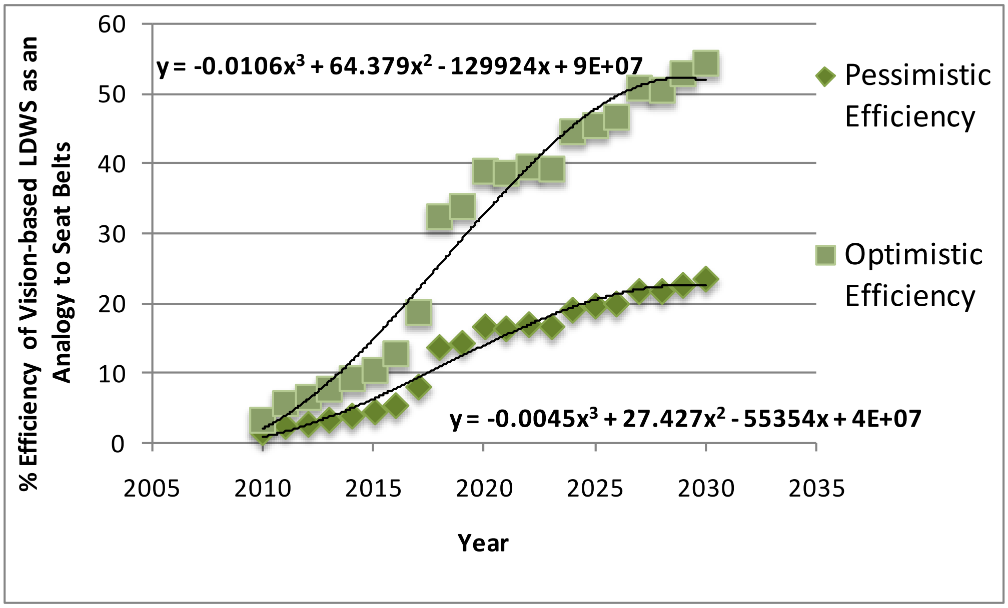


Figure 6.8 Effective Efficiency of Vision-Based LDWS as an Analogy to Seat Belts

Using the same absolute efficiency rates in equation 6.3 but different market penetration rates, the effective efficiency is calculated for ABS model. For example, for the optimal efficiency for year 2011 while using ABS exposure model,

$$EffectiveEfficiency\ (2011) = 55.5\% \times 0.05 = 2.78\%,$$

where 0.05 is the market penetration of ABS in the first year after its introduction.

The effective efficiencies are thus calculated from year 2010 to 2030 to obtain the following efficiency curves.

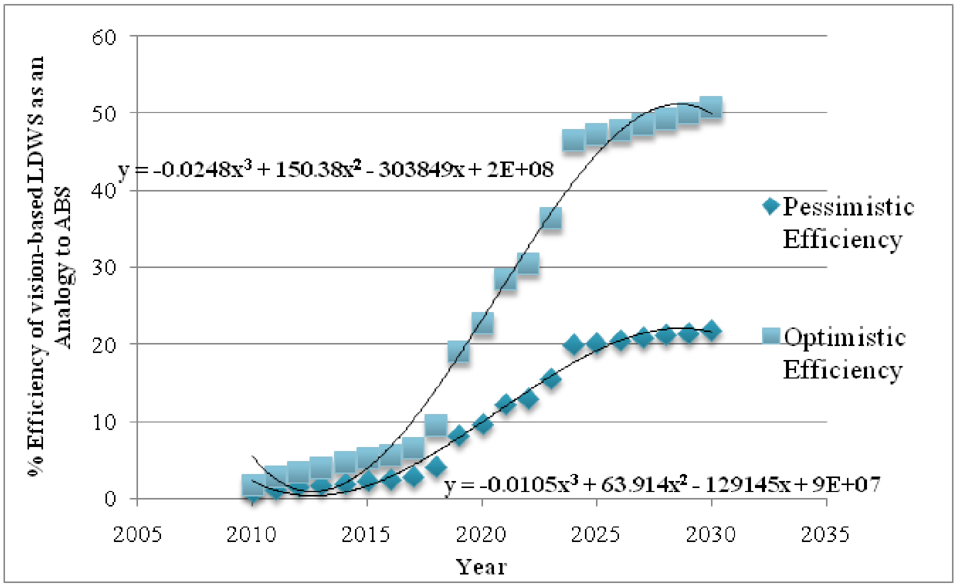


**Figure 6.9 Effective Efficiency of Vision-Based LDWS as an Analogy to ABS**

In Figure 6.3, a cubic polynomial is used to show the curve fitting equation. Hence the market penetration shows a reduced value as per the curve after the initial 2 years. This slightly contradicts the actual data which shows increasing market penetration. The raw data are the values that have been used in the analysis.

Summarizing, the above graphs based on equation:

**Table 6.1 Effective Efficiency of Vision-Based LDWS for 10 and 20 Year Analysis**

| | **Analogy to Seat Belts (Mandated by Law)** | | | **Analogy to ABS (Optional)** | | |
|---|---|---|---|---|---|---|
| | **Efficiency at the start** | **Efficiency at end of 10 years** | **Efficiency at end of 20 years** | **Efficiency at the start** | **Efficiency at end of 10 years** | **Efficiency at end of 20 years** |
| **Optimistic Efficiency** | 3.3% | 39% | 54.6% | 1.7% | 23% | 51% |
| **Pessimistic Efficiency** | 1.4% | 17% | 24% | 1.0 % | 10% | 22% |

## 6.2 Efficiency of DGPS-Based LDWS

The same process and steps suggested for the vision-based LDWS are followed for the DGPS-based LDWS.

### 6.2.1 Assuming Base Efficiencies

Using DGPS for lane departure warning is not an option that is available in the market currently. Hence the next section in this chapter is based on pure assumptions. With respect to using DGPS on freeways, the main advantage this system has over LDWS is that it can be available for a greater section of the freeway. LDWS is available only 75% of the time since the forward looking camera cannot capture the poor lane markings. Thus the reliability and efficiencies of DGPS can be assumed to be a 10 % greater than that of vision-based LDWS. The base efficiencies assumed are 65% for optimistic and 33% for pessimistic.

### 6.2.2 Growth in Efficiency

Due to similar hardware and software reasons as the vision-based LDWS, the efficiency of DGPS-based LDWS can similarly be assumed to increase by 20% in the next 20 years. Also, the increase in availability of digital maps which help in identifying the position of the vehicle and increased DGPS coverage would make the efficiencies as 78% optimistic and 38% pessimistic in 20 years.

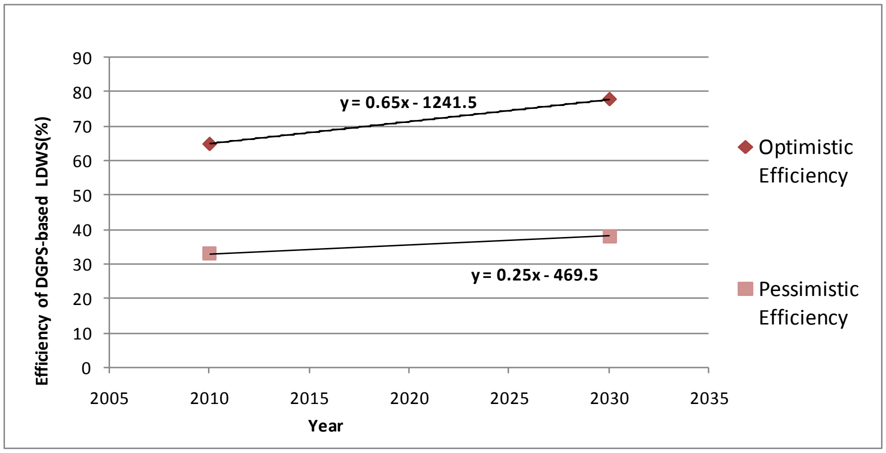


**Figure 6.10 Increasing Efficiencies of DGPS-Based LDWS**

### 6.2.3 Absolute Efficiency

The intermediate absolute efficiencies are obtained for individual years based on the equation 6.2.

### 6.2.4 Effective Efficiency

Using Equation 6.3, the effective efficiencies can be calculated for DGPS-based LDWS to give the following curves (Appendix I).

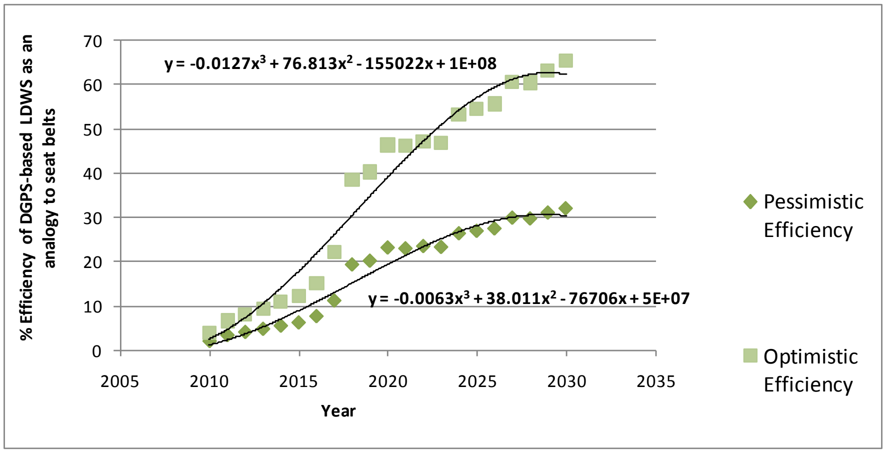


Figure 6.11 Effective Efficiency of DGPS-Based LDWS as an Analogy to Seat Belts

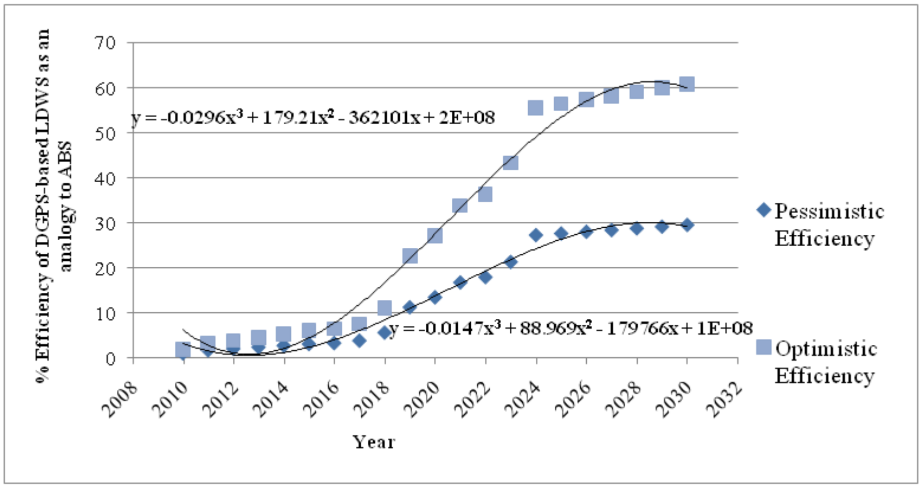


Figure 6.12 Effective Efficiency of DGPS-Based LDWS as an Analogy to ABS

Summarizing the efficiencies:

**Table 6.2 Effective Efficiency of DGPS-Based LDWS**

| | **Analogy to Seat Belts (Mandated by Law)** | | | **Analogy to ABS (Optional)** | | |
|---|---|---|---|---|---|---|
| | **Efficiency at the start** | **Efficiency at end of 10 years** | **Efficiency at end of 20 years** | **Efficiency at the start** | **Efficiency at end of 10 years** | **Efficiency at end of 20 years** |
| **Optimistic Efficiency** | 3.9% | 46.48% | 65.52% | 1.95% | 27.17% | 60.84% |
| **Pessimistic Efficiency** | 1.98% | 23.08% | 31.92% | 0.99% | 13.49% | 29.64% |

## 6.3 Summary

Two effectiveness values are obtained: an optimistic value and a pessimistic value. In comparison to infrastructure-based treatments for which the effectiveness remains constant once deployed, the effectiveness of in-vehicle technologies increases every year. Hence, added safety benefits are reaped every year.

# Chapter 7: Cost Models of In-Vehicle Technologies

Costs for technology are based mainly on the demand for it. As the demand increases, the production volume increases and thus the costs of manufacturing can be lowered, lowering the market price. The study of the market penetration of seat belts and ABS has shown us that the public have realized that safety technologies are required. Awareness about technology and safety has increased and this has increased the volume of products. This has reduced the costs and the market price which has further increased the sales volume and the cycle continues.

This has been shown with the help of a graph in a study related to estimating the cost of automotive technology. In Figure 7.1, the engine cost decreases as the volume increases [34.]. At the same time, it should be noted in the same Figure that beyond a certain value, as the volume further increases, per unit cost remains constant.

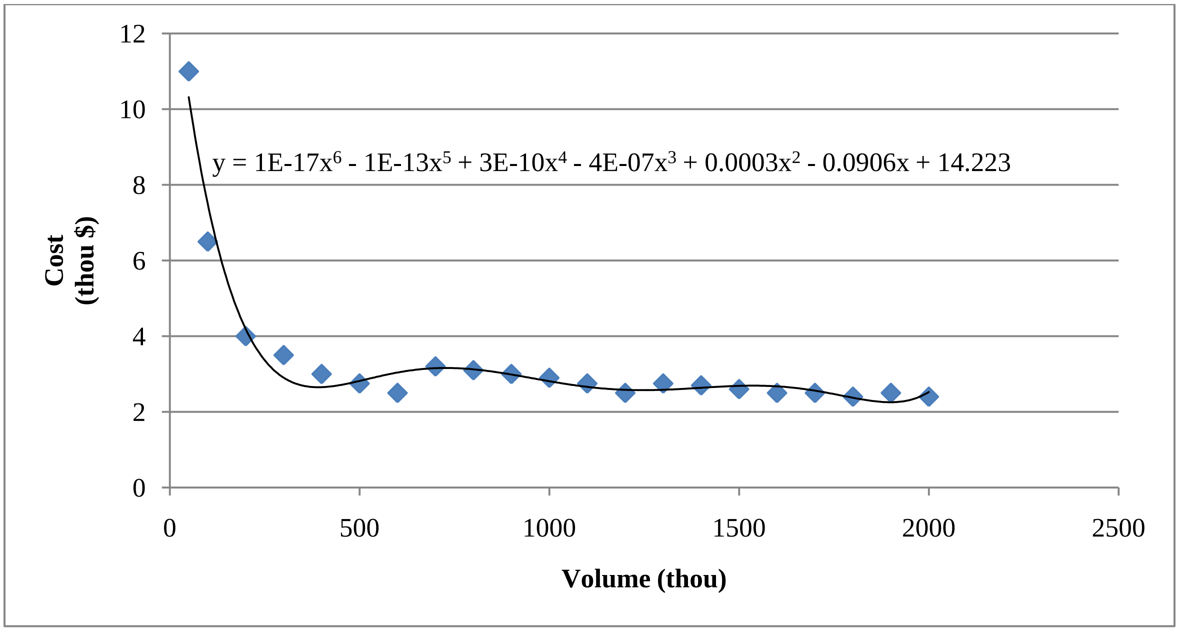


**Figure 7.1 Cost v/s Volume Relationship [34.]**

Based on this relation between the cost of the technology and the volume, cost models have been developed for the in-vehicle technologies.

## 7.1 Vision-Based Lane Departure Warning Systems

As per a study conducted by J.D. Power and Associates on the emerging automotive technologies in US in 2007, lane departure warning system shows a potential sales penetration of 42% when no cost information is provided. However, it drops to a very low 9% when a market price of $500 is revealed [35.]. This market price of $500 can be considered to be the base price in 2010. This is consistent with Table 4.3 which quotes the prices currently offered by car dealers for a lane departure warning system. In order for this technology to be competitive, its price is decreased. This increases the market penetration which further decreases the price. The cost of the system would hence decrease in the next 20 years.

The market penetration of LDWS has been assumed to increase as per analogies drawn to seat belts and ABS. The total volume of cars having LDWS would be a factor of market penetration and the number of vehicles in Minnesota.

$$Number\ of\ cars\ with\ LDWS\ in\ MN = Number\ of\ cars\ in\ MN \times Market\ penetration$$

The crash facts of Minnesota give the number of passenger cars registered in the years 2002 to 2007 [3.]. This can be extrapolated through 2030.

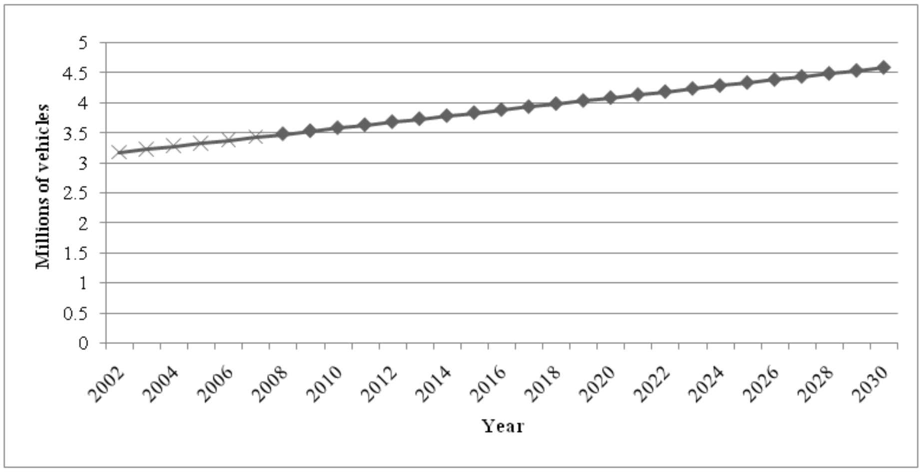


**Figure 7.2 Number of Registered Vehicles in Minnesota: Graph Created from Data in [3.]**

Based on the market penetration of seat belts and ABS, Figure 7.3 shows the number of vehicles that can be predicted to have LDWS in years 2010 to 2030 by equations 7.1 and 7.2:

Equation 7.1

$$\begin{aligned} &Number\ of\ cars\ with\ seat\ belts\ in\ millions(Year) \\ &\quad = Volume\ of\ cars\ in\ millions(Year) \\ &\quad \times Market\ penetration\ of\ seat\ belts(Year) \end{aligned}$$

Equation 7.2

$$\begin{aligned} &Number\ of\ cars\ with\ ABS\ in\ millions(Year) \\ &\quad = Volume\ of\ cars\ in\ millions(Year) \times Market\ penetration\ of\ ABS(Year) \end{aligned}$$

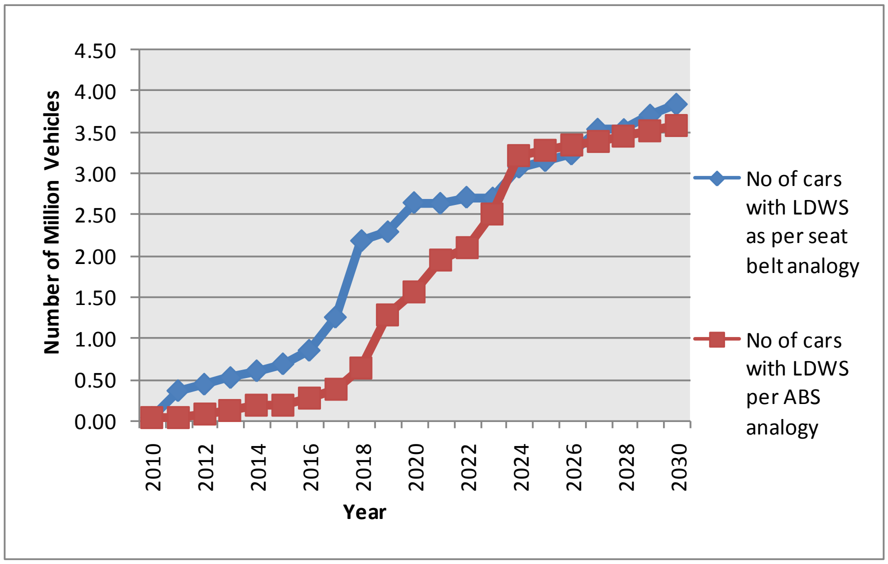


Figure 7.3 Number of Vehicles with Vision-Based LDWS (Appendix J)

Using Figure 7.3, the number of vehicles with LDWS as per seat belt and ABS models increases by a factor of 100 in 20 years. The cost of LDWS thus can be estimated to be $200 at end of 20 years if the LDWS system follows the ABS model. If it follows the seat belt model that would mean it is mandatory and hence the demand for it would be more and thus lower price per unit. Per unit cost while following seat belt model can be estimated to be $150 at end of 20 years.

For the ABS model, assuming two end points as $500 and $200, a logarithmic relationship between the year of deployment and volume of cars equipped with LDWS has been developed. The equations for the curve have been used to obtain the cost at the intermediate volumes (Appendix J).

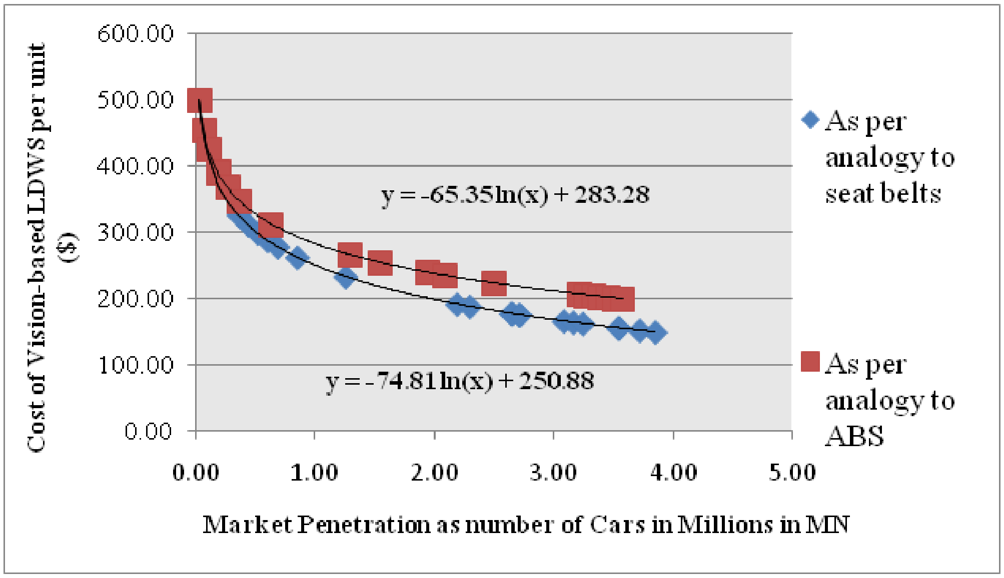


Figure 7.4 Cost Modeling for Vision-Based Lane Departure Warning Systems

The cost is calculated for deploying the entire fleet at that year by using the following equation:

Equation 7.3:

$$CostOfDeploying(Year) = CostPerUnit(Year) \times MarketPenetration(Year)$$

Summarizing the cost models, the following would be the costs at end of 10 and 20 years:

**Table 7.1 Cost Models for Vision-Based LDWS**

| | **Cost per unit of LDWS At End of 10 Years** | **Cost per unit of LDWS At End of 20 Years** | **Cost for deploying LDWS for total volume of cars at end of 10 years** | **Cost for deploying LDWS for total volume of cars at end of 20 years** |
|---|---|---|---|---|
| **As per Analogy to Seat Belts** | $178 | $150 | $471,969,247.22 | $577,710,000.00 |
| **As per Analogy to ABS** | $255 | $200 | $394,911,610.50 | $715,260,000 |

### 7.2 DGPS-Based Lane Departure Warning Systems

The DGPS-based LDWS is not yet implemented in the automobiles in the market. Hence assumptions are going to be made for its high volume cost. For the DGPS with cell phone modem, a base price of $8,000 can be assumed with it falling to $500 at end of 20 years while following the market penetration trends for seat belts.

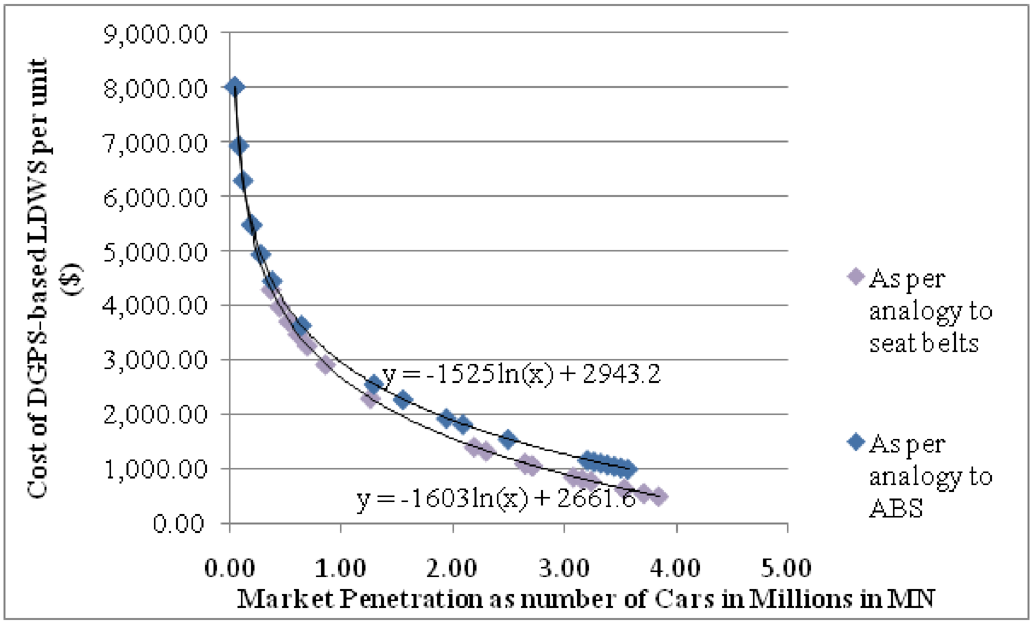


**Figure 7.5 Cost Model of DGPS-Based LDWS**

The logarithmic curves are plotted with two end points. The curve equations generated by Excel are used to find the costs at the intermediate years. (Appendix J). Equation 7.1 is used to give the following values for deploying the entire fleet with DGPS-based LDWS.

**Table 7.2 Cost Model of DGPS-Based LDWS**

| | **Cost per unit at end of 10 Years** | **Cost per unit at End of 20 Years** | **Cost for deploying for total volume of cars at end of 10 years** | **Cost for deploying for total volume of cars at end of 20 years** |
|---|---|---|---|---|
| **As per Analogy to Seat Belts** | $1,097 | $ 500 | $2,911,694,142 | $1,925,700,000 |
| **As per Analogy to ABS** | $2,274 | $1,000 | $3,526,904,084 | $3,576,300,000 |

## 7.3 Summary

This chapter has laid out the cost models of in-vehicle technologies. Thus the effectiveness and the costs of the various countermeasures for avoiding crashes along curves and tangential sections have been listed. These would be used to calculate the benefit:cost ratios. The next chapter is a primer on the benefit:cost analysis and the approach taken to evaluate the infrastructure and technology-based treatments listed in the previous chapters.

# Chapter 8: Methods of Quantifying Costs and Benefits

In the previous chapters we have introduced various infrastructure-based and technology-based solutions to reduce the road departure crashes. Two parameters, effectiveness and costs of each have been studied; however for treatments such as curve flattening, though it has high efficiency, it is very expensive. On the other hand, rumble strips, though low in efficiency are very economical. Hence, a common quantifiable parameter is needed to relate these two quantities and hence a benefit:cost analysis is required. The benefit:cost analysis measures exactly how beneficial it is to expend a dollar amount for a particular treatment. From this, the most optimum solution can be determined to avoid crashes along curves and tangential sections.

Different methodologies have been defined for this purpose and they are presented in this chapter.

## 8.1 Cost Effectiveness Analysis

Cost effectiveness analysis considers benefits in terms of a number, for e.g. number of lives saved, number of crashes prevented. It then calculates the cost effectiveness ratio (CE) which is the cost per the number of benefits, for e.g. dollars per number of lives saved or dollars per number of crashes prevented.

$$CE = \frac{Total\ Costs}{Total\ Benefits}$$

**Table 8.1 Cost Effectiveness Analysis**

| ADVANTAGES | DISADVANTAGES |
|---|---|
| • Simpler evaluation methods<br>• Useful in calculating cost effectiveness for benefits for which it is difficult to associate a monetary value | • It does not take into account the life of the project<br>• At a time, you cannot take into account multiple benefits, only 1 benefit can be evaluated |

In 1996, University of Southern California conducted a research on evaluating the cost effectiveness of Automated Highway Systems (AHS). The entire cost of the system was evaluated against the increased capacity per lane [28.]. To calculate the increased capacity of lanes, the number of vehicles entering the AHS per unit time was calculated. This divided by the proportion of days that AHS vehicles traverse, give the total number of vehicles equipped for AHS for which the cost of the system was calculated by considering the total mechanical and electrical components used. Growth curves were used to extrapolate these costs to a future value. The total cost was converted into an annual cost assuming a 30 year lifetime and 5% after inflation discount rate, which resulted in a cost estimate per year.

### 8.2 Cost Utility Analysis

Cost utility analysis is an extension of cost effectiveness analysis. It is mainly used in the health analysis programs. While cost effectiveness measures only in terms of quantity, cost utility analysis attaches a parameter of quality also to the benefit accounted which is called quality adjusted life years (QALY). For e.g. while considering the crashes avoided, it would also take into consideration the fatality measure and severity of the crash.

**Table 8.2 Cost Utility Analysis**

| ADVANTAGES | DISADVANTAGES |
|---|---|
| • Useful in calculating cost effectiveness for benefits for which it is difficult to associate a monetary value<br>• Measured in terms of quality adjusted life years which gives a relation between quality and length of human life. | • It is difficult to attach any numerical value to additional life years in compensation for costs.<br>• Mainly based on surveys, hence biased by demographic differences.<br>• No consistency between different QALY evaluation techniques |

Cost utility analysis was used in a study while deciding between an alternative to replace conventional diesel (CD) engines to reduce emissions in urban transit buses. The two fuels considered were compressed natural gas (CNG) and emission controlled diesel (ECD). The total costs were calculated against quality of life years lost due to exposure to ozone and particulate matter [36.]. A quality adjusted life year (QALY) is a very common term in healthcare. To give a simple example, if after treatment A, the patient lives for 3 years in the best of his health, the number 1 is associated for each year and the total QALY is 3. However, after treatment B if the patient lives for 3 years but with a handicap, the number associated with each year would be less than a year probably 0.5. The total QALY for treatment B would thus be 4.5.

After calculating the QALY for ECD and CNG engines, the QALY for CNG is 9 annually per 1000 buses and for ECD it is 6 annually per 1000 buses. Cost effectiveness ratio is calculated given by the following equation:

$$CE_{\mathrm{alt}} = \frac{Cost_{\mathrm{alt}} - Cost_{\mathrm{CD}}}{QALY_{\mathrm{CD}} - QALY_{\mathrm{alt}}},$$

where Cost"alt" is the cost of the two alternatives considered (either ECD or CNG).

QALYalt is the QALY of the two alternatives considered. The CE of ECD is $ 270,000 per QALY as compared to $1,700,000 per QALY for CNG. Thus, ECD is more cost effective [36.].

### 8.3 Distributional Weighted Benefit:Cost Analysis

Costs and benefits may be of different value to different groups of people based on their income. Thus the benefits are weighted as per a numerical parameter attributed to every such group. This is mainly useful for policy making decisions. If a town is divided into people of 3 income groups, the importance of a policy to all would be different. For e.g. a policy related to distribution of free books is more beneficial to the poor than to the rich. Thus if the three groups are given relative weighting; 3 for poor people; 2 for the middle class and 1 for the rich, the total benefit reaped out of the book distribution would be

$$Benefit = 3 \times Number\ of\ poor\ people + 2 \times Number\ of middle\ class\ people + 1 \times Number\ of\ rich\ people$$

**Table 8.3 Distributed Weighted CBA**

| ADVANTAGES | DISADVANTAGES |
|---|---|
| • Different income groups considered | • No standard procedure available for weighing costs and benefits |

### 8.4 Benefit:Cost Analysis

Kaldor Hicks efficiency is the base of benefit:cost analysis. According to this principle, all the people who are benefited by a particular project should at least be compensated by the people who are worsened by the same project. In other words, the benefits should outnumber the costs.

**Table 8.4 Benefit:Cost Analysis**

| ADVANTAGES | DISADVANTAGES |
|---|---|
| • Based on willingness to pay and social welfare theory<br>• Used in majority of traditional transportation economic evaluation projects<br>• Takes into account the life of the project<br>• Convenient for comparing alternatives with status quo<br>• Can take into consideration multiple benefits | • Costs have to be inflated to future value or benefits have to be discounted to present value. Deciding the exact value of this social discount rate can be tedious.<br>• All benefits have to be monetized using shadow pricing. |

### 8.5 Internal Rate of Return

The formula for net present value is

$$NPV = \frac{\sum C}{(1+r)^t},$$

where NPV is Net present value, C is total cost, r is the rate of interest, and t is the time period.

If this above equation is equated to 0, the r value obtained is called the Internal Rate of Return or IRR.

Theoretically, if you have certain amount of money and are taking a decision whether to invest it in project A or project B, the project with the higher IRR is the one money should be invested in.

**Table 8.5 Internal Rate of Return**

| ADVANTAGES | DISADVANTAGES |
|---|---|
| • Quick technique to decide whether to invest in a project or not | • Cannot be used for comparing different projects<br>• Does not take into account the analysis period and the cash flow pattern<br>• Not unique, there can be multiple IRR for a particular NPV.<br>• They are percentages, not dollar values and hence not reliable for comparison. |

This method is mainly used by the corporate world to evaluate the returns on an investment.

These were the various methods that can be used for quantifying out cost and benefits. The cost benefit analysis approach was selected. The reason the cost effectiveness analysis was rejected was because it does not take into account the life of the treatment. In our application it is necessary to consider how long the treatment would be beneficial because that would determine the total cost for a length of analysis period. Estimating the QALY would have been tedious and Mn/DOT already has monetary values assigned to the crashes as per severity. Using the relative weighting method too would have been cumbersome. Hence the benefit:cost analysis approach has been selected which is explained in detail in the next chapter.

# Chapter 9: Benefit:Cost Analysis

Benefit:cost analysis has been the most popular and efficient technique for economic evaluation in ITS projects due to the clarity in the procedure. It is based on the Kaldor Hicks efficiency principle which states that the net benefits should be more than the total costs. The costs and benefits are measured in terms of opportunity costs and willingness to pay respectively. Opportunity cost is the lost opportunity to invest that amount in some other venture other than the current project that would have reaped certain benefits. Willingness to pay is the sum that the consumer is willing to pay or expects to be paid in order to accept the project. These are the following basic steps followed in any benefit:cost analysis:

1. List down the various alternative solutions for the given problem. It is always advisable to first start with a counterfactual approach which is a situation where no solution is applied. That is the original condition from which you started. This is the status quo and all other alternatives are compared with it. Costs that are common to all can be discounted. The status quo in our case would be without any treatments on the curves and tangential sections and the infrastructure and technology-based would be the different alternatives.

2. Evaluate the capital costs in terms of opportunity costs. Also note the depreciating value of the asset according to the analysis period. Technology costs keep on changing. Technology diffusion usually follows an S-curve [37.]. (See Figure 9.1).

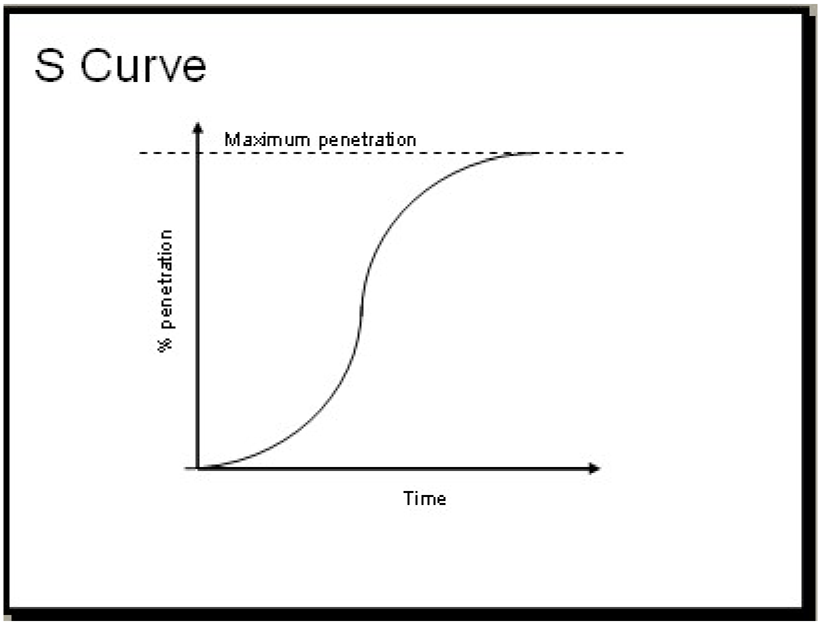


Figure 9.1 Technology Diffusion S-Curve [37.]

People show hesitation when technology is just introduced, so diffusion starts slowly, it then grows exponentially, peaks and then remains saturates. Accordingly the costs keep on changing. The costs are high initially to cover the R&D costs and the costs to introduce the product. As competitors in the market selling the same product increase, the costs reduce. This has already been introduced in the chapter on cost modeling, that as volume of product increases, cost decreases to a point.

3. Evaluate the operational costs in terms of annual costs. For example, the flashing beacons need some kind of maintenance in form of adequate electric power so that they operate at all times.

4. Predict and monetize the benefits. For example, in our case the benefits are in the form of reduced crashes. A dollar amount is associated with each crash as per its type. Each crash saved is equivalent to a benefit.

5. The costs and benefits have to be discounted using a discount rate. The discount rate used in US for projects is usually 7% [38.]. There are two types of discount rates- nominal and real. Nominal discount rates are the ones considered without taking into account the inflation rates. For real discount rates, the inflation rate is taken into account.

The real discount rate or also called as the rate of interest

$$r = \frac{(1+n)}{(1+i)} - 1$$

where n is the nominal discount rate, and i is the inflation rate.

Thus, as the inflation rate increases, the real discount rate would increase. This would change the net present value of the technology. The real discount rate is also called as social discount rate (SDR).

6. Each benefit:cost analysis has an analysis period. However the systems continue to impact even after this analysis period if their life exceeds this period. Terminal values are added to account for the impact of the project after the analysis period. Terminal values can be computed by extrapolating the benefits or as per the residual value of the components in the project. The remaining capital value or terminal value is calculated as the percentage of useful life remaining beyond the analysis period and that is multiplied by the construction cost [39.].

7. The uncertainties in the project are recognized and a sensitivity analysis is done to find the variability. This is done in case of data when we are not sure about the exact value. Different confidence bounds are considered, and this tells us if there is any significant difference in the end results due to these different variations [38.]. If yes, then the data needs to be looked into for errors. For example there are three different efficiencies for the lane departure warning systems. This is because these are based on the responses of drivers participating in the field operational test. But once the system is developed, there are no means of estimating the efficiencies. Hence different efficiency values are considered and the change in the benefit:cost ratio is noted as the efficiencies change.

8. Either a benefit:cost or a cost:benefit ratio is calculated for all the different alternatives. In the following chapters, a benefit:cost ratio is calculated for all the

different alternatives. Since the costs are in present time and the benefits are in future, the net present value (NPV) of benefits is computed for different alternatives [39.].

Two components of cost are considered, capital costs and operational costs. Capital costs are already in present value. The operational costs are incurred every year as per the required maintenance. For example, for the dynamic curve warning sign the battery needs to be replaced after every 4 years. The battery costs $160. This is the cost of the battery in the 5th year when it would be replaced. However, for calculating the benefit:cost ratio, the present value of the cost is required so that the benefit, capital costs and operational cost are all in one time frame.

The benefit:cost ratio is given by

$$Benefit{:}\,Cost\ Ratio = \frac{NPV\ of\ Benefits}{Capital\ costs + NPV\ of\ operational\ costs}$$

The alternative with the highest benefit:cost ratio is considered. The benefit:cost ratio if considered is simply the inverse of the benefit:cost ratio and thus a low cost:benefit ratio is desired.

The method described above is implemented in the next chapter to evaluate the benefit:cost ratios for the various countermeasures described to reduce crashes along curves and tangential sections.

# Chapter 10: Benefit:Cost Analysis of Different Alternatives

The benefit:cost ratios are presented in the following chapter.

Initially a 5 year analysis was considered. However, for certain treatments where the efficiency has been as low as 15%, there are no expected fatalities occurring in the first 5 years. Hence, a 10 and 20 year analysis is done. The efficiency is based on before:after analysis for the infrastructure-based treatments. For technology- based and in-vehicle solutions, it is based on field operational tests and studies done in the past. In Minnesota in 2007, 510 fatal crashes occurred [3.]. Each fatal costs $6,800,000. The total economic loss due to fatalities is thus about 3.5 billion dollars. The number of severe injuries was 1,736 [3.]. According to Figure 1, each severe injury crash costs $390,000, thus the total economic losses due to severe injury crashes are about 680 million dollars. The loss incurred due to severity crashes is just one-fifth that due to fatal crashes. This makes fatalities the most crucial and thus the efficiency is converted in to the number of years required to prevent at least one fatal. Since each fatal costs $6,800,000 the benefit after preventing each fatal is equal to this amount. The total benefit is calculated on basis of the number of fatalities prevented in 10 years for a 10 year analysis and 20 years for a 20 year analysis. This benefit is at the end of the analysis period and has to be converted into current dollar amount. This is done by calculating the NPV of benefits. The rate of interest for this calculation is taken as 3.6 % since this is the standard rate of interest mentioned by Mn/DOT in its benefit:cost analysis primer [39.].

## 10.1 Safety Systems for Curves

204 curves are considered in our data set which account total of 35 miles. The number of fatal crashes per year for all these curves is 0.918. In other words, one fatal is expected every 13 months.

Various curve crash mitigation treatments have been studied to be implemented at curves which have been explained in detail in the earlier chapters. To just mention them again, these are the solutions which have been proposed

- Infrastructure-based
  1. Rumble strips
  2. Curve flattening
  3. Chevrons
  4. Static curve warning sign – Only the curve warning sign
  5. Static curve speed warning sign – Curve warning sign along with the advisory speed sign

Recall, however, that 80% of the curves studied in the cross-sectional analysis and the before:after analysis already had Curve Warning Signs or Curve warning signs with a speed advisory, and that these curves still had high crash rates. In practice, these two conditions represent a baseline condition.

- Technology-based Road Solutions
  1. Dynamic curve speed warning sign

### 10.1.1 Curve Flattening

As per the before:after analysis, the efficiency of curve flattening is 66%. In other words, the flattened curve prevents two of the three crashes which would have occurred had the curve not been flattened.

Since the number of fatal crashes per year saved in the sample set is 0.918, it would take four years to save at least 2 lives.

Hence there are two possibilities; either 4 or 3 fatalities could be prevented in the first 10 years. As per Mn/DOT's benefit:cost analysis primer, the service life for all infrastructure-based treatments is considered to be 20 years [39.]. Thus, for a 20 year analysis either 7 or 6 fatal crashes could be prevented. This is shown by the line diagram below:

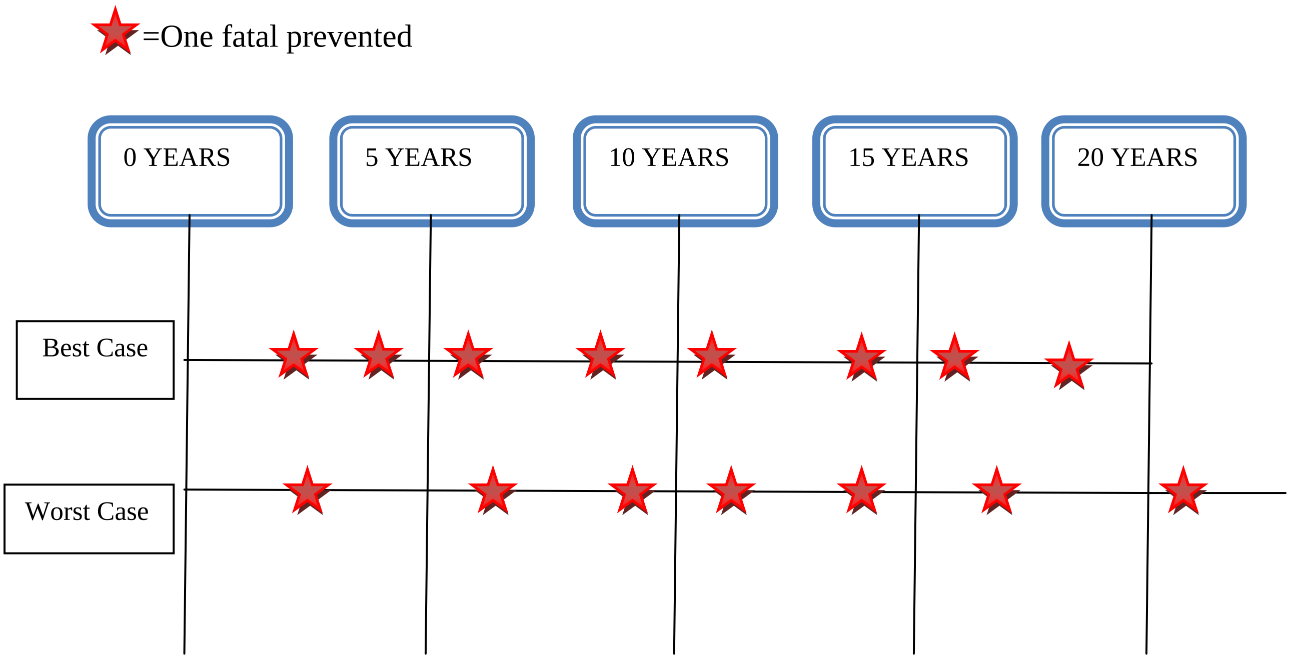


**Figure 10.1 Example of Best Case and Worst Case**

#### *10.1.1.1 Condition 1*

For a 10 year analysis, if 4 fatalities are prevented, the benefit would be \$27,200,000. This benefit occurs at the end of 10 years and thus has to be converted into the present value by the formula

$$NPV\ Benefit = \frac{\$27{,}200{,}000}{(1+0.036)^{10}} = \$19{,}097{,}272.91$$

- The cost for reconstructing the curve and flattening it is \$300,000. Since there are 204 curves in the sample set, the total cost is \$61,200,000.

- We are doing an analysis for 10 years. However, the service life is 20 years and hence the curve flattening will continue functioning for 10 more years after the analysis period. Since we have considered 4 fatalities, its benefits for 12 years are consumed considering that 1 fatal is prevented in every 3 years. Hence 8 years of service life is left. Thus the remaining capital value (RCV) which is given by the percentage of useful life left after the analysis period multiplied by the initial cost [39.] is

$$RCV = \frac{1}{3} \times \frac{(20 - 12)}{20} \times 61{,}200{,}000 = \$8{,}160{,}000$$

- This RCV value is at the end of the analysis period and is hence converted to present value

$$Present\ Value\ RCV = \frac{8{,}160{,}000}{(1 + 0.036)^{10}} = \$5{,}729{,}181.81$$

- This is discounted from the total costs and thus the costs after discounting RCV are

$$Discounted\ Costs = \$61{,}200{,}000 - \$5{,}729{,}181.81 = \$55{,}470{,}818.19$$

- The benefit:cost ratio is thus calculated as

$$Benefit{:}\ Cost\ Ratio = \frac{\$19{,}097{,}272.71}{\$55{,}470{,}818.19} = 0.34$$

Thus, the curve flattening gives a low benefit:cost ratio for a 10 year analysis considering 4 fatalities are prevented in the first 10 years.

#### *10.1.1.2 Condition 2*

- 3 fatalities prevented in the first 10 years.

$$NPV\ Benefit = \frac{\$20{,}400{,}000}{(1 + 0.036)^{10}} = \$14{,}322{,}954.53$$

- While considering 3 fatalities in 10 years, its benefits are just consumed for 10 years.

$$RCV = \frac{1}{3} \times \frac{(20 - 10)}{20} \times \$61{,}200{,}000 = \$10{,}200{,}000$$

$$Present\ Value\ RCV = \frac{\$10{,}200{,}000}{(1 + 0.036)^{10}} = \$7{,}161{,}477.27$$

- This is discounted from the total costs and thus the costs after discounting RCV are

$$Discounted\ Costs = \$61{,}200{,}000 - \$7{,}161{,}477.27 = \$54{,}038{,}522.73$$

- The benefit:cost ratio is thus calculated as

$$Benefit\colon Cost\ Ratio = \frac{\$14{,}322{,}954.53}{\$54{,}038{,}522.73} = 0.27$$

Thus two different benefit:cost ratios are obtained for a 20 year analysis too giving four benefit:cost ratios for each safety system.

Similarly, detailed analysis is done for rumble strips, chevrons, dynamic curve speed warning signs. The calculations are included in Appendix K and the benefit:cost ratio is provided in the Table 10.1 below.

**Table 10.1 Benefit:Cost Ratios of Safety Systems for Curves**

| | | PERCENT EFFECTIVENESS | COST PER CURVE | BENEFIT:COST RATIO FOR 10 YR ANALYSIS | | BENEFIT:COST RATIO FOR 20 YR ANALYSIS | |
|---|---|---|---|---|---|---|---|
| | | | | **Best Case** | **Worst Case** | **Best Case** | **Worst Case** |
| **Infrastructure** | **Rumble Strips** | 15 | $3,000 per mile | 90.94 | 45.47 | 56.27 | 37.51 |
| | **Curve Flattening** | 66 | $300,000 | 0.35 | 0.27 | 0.42 | 0.37 |
| | **Chevrons** | 20 | $1,000 | 47.93 | 24.35 | 42.37 | 32 |
| **Technology** | **Dynamic Curve Speed Warning Sign** | 30 | $12,000 for installation + $160 after every four years for battery | 6.15 | 4.18 | 6.60 | |

As per the benefit cost ratio, both for 10 and 20 year analysis period, rumble strips are most cost effective. Curve flattening shows a very low benefit:cost ratio and hence not advisable. Instead, for a very hazardous curve, rather than curve flattening it is economical to have a dynamic curve speed warning sign with radars which has a comparable effectiveness value.

### 10.1.2 Incremental Benefit:Cost Ratio for Technology Compared to Traditional Solutions

To compare on a broad scale the infrastructure-based solutions and technology-based solutions, the benefit:cost ratios of static curve warning signs with advisory speed signs and dynamic curve speed warning signs are compared.

Incremental benefit:cost ratios are calculated using

Equation 10.1:

$$Incremental\ Benefit{:}\ Cost\ Ratio_{\mathrm{AB}} = \frac{Benefit_{\mathrm{A}} - Benefit_{\mathrm{B}}}{Cost_{\mathrm{A}} - Cost_{\mathrm{B}}} [40.]$$

This gives the incremental benefit:cost ratio between alternative A and B

Such incremental benefit:cost ratios are calculated for different curve signs. Alternative A is an infrastructure-based curve speed warning sign. Alternative B is dynamic curve speed warning sign.

**Table 10.2 Comparison of Alternatives for Curves**

| | | CURVE SPEED WARNING SIGN (BASELINE) | DYNAMIC CURVE SPEED WARNING SIGN |
|---|---|---|---|
| **10 YEAR COST** | BEST CASE | $73,806.64 | $2,327,215.90 |
| | WORST CASE | $73,022.29 | $2,284,247.04 |
| **10 YEAR BENEFIT** | BEST CASE | 2 fatalities prevented | 3 fatalities prevented |
| | WORST CASE | 1 fatality prevented | 2 fatalities prevented |
| **10 YEAR INCREMENTAL BENEFIT:COST RATIO** | BEST CASE | - | **3.02** |
| | WORST CASE | - | **3.08** |
| **20 YEAR COST** | BEST CASE | $96,193.60 | $2,537,592.12 |
| | WORST CASE | $95,642.90 | |
| **20 YEAR BENEFIT** | BEST CASE | 4 fatalities prevented | 5 fatalities prevented |
| | WORST CASE | 3 fatalities prevented | |
| **20 YEAR INCREMENTAL BENEFIT:COST RATIO** | BEST CASE | - | **2.79** |
| | WORST CASE | - | **5.57** |

This comparison shows that it is beneficial for the solutions to be changed from infrastructure-based to road sign technology-based such as dynamic curve warning signs with flashing beacons and a radar.

## 10.2 Safety Systems for Tangential Sections

### 10.2.1 Infrastructure-Based

For tangential sections, the following infrastructure-based alternatives are evaluated for their benefit:cost ratios.

- Infrastructure-based
  1. Enhancing aggregate shoulders (presented below)
  2. Enhancing paved shoulders (presented in Appendix K)

- In-vehicle Technologies
  1. Vision-based LDWS (presented below)
  2. DGPS-based LDWS (presented in Appendix K)

#### *10.2.1.1 Aggregate to Enhanced: 0 to 2 ft*

- As discussed in Chapter 5, the average sectional efficiency is used.

$$Average\ sectional\ efficiency\ for\ aggregate\ to\ enhanced = 0.44$$

- As per the before:after analysis for aggregate to enhanced tangential sections,

$$Vehicle\ Miles\ Travelled\ (VMT) = 187{,}000{,}000$$
$$Total\ Miles\ of\ aggregate\ sections\ that\ were\ enhanced = 31.74$$
$$Total\ years = 37$$
$$Annual\ VMT\ per\ mile\ of\ road = \frac{187{,}000{,}000}{31.744 \times 37} = 159{,}212.89$$

- Calculating exposure,

$Fatal\ crash\ rate = 0.03\ per\ million\ vehicle\ miles\ travelled\ per\ year$(Based on cross-sectional analysis)

$$Total\ miles\ of\ aggregate\ sections\ in\ the\ sample\ set = 115.8$$

$$Number\ of\ fatal\ crashes\ exposed\ to = \frac{(Fatal\ crash\ rate) \times (No.\ of\ miles\ in\ this\ section) \times (Annual\ VMT\ per\ mile)}{1{,}000{,}000}$$

$$= \frac{0.03 \times 115.8 \times 159{,}212.89}{1{,}000{,}000} = 0.55\ fatals\ per\ year$$

- Considering the average sectional efficiency, the number of fatalities prevented due to this treatment on this section of the road is calculated.

$$Number\ of\ fatals\ prevented = 0.44 \times 0.55 = 0.24\ fatals\ per\ year$$

$$Number\ of\ fatals\ prevented\ in\ 10\ years = 2.4\ fatals\ per\ year$$

- Cost of adding rumble strips is $3,000 per mile

$$Total\ cost = \$3{,}000 \times 115.8 = \$347{,}400.00$$

- Monetizing the benefits in terms of fatalities prevented

$$Benefit = 2.4 \times \$6{,}800{,}000 = \$16{,}548{,}919.19$$

$$NPV\ of\ benefits = \frac{\$16{,}548{,}919.19}{(1 + 0.036)^{10}} = \$11{,}619{,}089.08$$

- Calculating benefit:cost ratio

$$Benefit{:}\ cost\ ratio = \frac{\$11{,}619{,}089.08}{\$347{,}400} = 33.45$$

Similar procedure is followed to calculate the benefit:cost ratios for enhancing aggregate and paved tangential sections of different widths (Appendix K).

### 10.2.2 In-Vehicle Technologies

Vision-based and DGPS-based lane departure warning systems have been described in the previous chapter along with their efficiencies and cost models. Since the benefits of in-vehicle technologies are reaped throughout the road section miles they are exposed to, a statewide analysis is studied for these three technologies.

#### *10.2.2.1 Vision-Based LDWS*

- As per the optimistic efficiency and cost models for a mandatory model,

$$Optimistic\ Efficiency\ in\ the\ first\ year = 0.03$$

- As per crash facts, the total number of road departure fatalities occurring in the state of Minnesota in 2007 was 253.

$$Number\ of\ fatals\ prevented\ in\ first\ year = Efficiency \times 253 = 0.03 \times 253 \sim 8$$

- For the second year,

$$Optimistic\ efficiency = 0.06$$

- Assuming the same number of road departure fatal crashes occurring every year

$$\begin{aligned} Number\ of\ fatals\ prevented\ in\ second\ year &= Efficiency \times 253 \\ &= 0.06 \times 253 \sim 14 \end{aligned}$$

The total number of fatalities prevented in two years is thus the cumulative sum of fatalities prevented in the first and second year

$$Total\ number\ of\ fatals\ prevented\ in\ 2\ years = 8 + 14 = 22$$

- Such cumulative fatalities prevented are calculated for 10 years

$$Total\ number\ of\ fatals\ prevented\ in\ 10\ years \sim 455$$

- Monetizing the benefits as per fatalities saved,

$$Benefits = 455 \times \$6{,}800{,}000 = \$3{,}093{,}193{,}180$$

$$Costs\ for\ deploying\ for\ entire\ fleet = \$471{,}969{,}247$$

$$Benefit{:}\,cost\ ratio = \frac{\$3{,}093{,}193{,}180}{\$471{,}969{,}247} = 6.55$$

Following exactly the same procedure, different benefit:cost ratios are obtained for vision-based and DGPS-based LDWS depending on the different conditions assumed (Appendix K).

**Table 10.3 Benefit:Cost Ratios for Tangential Sections**

| | | 10 YEAR ANALYSIS | | 20 YEAR ANALYSIS | |
|---|---|---|---|---|---|
| **ENHANCING AGGREGATE SHOULDERS** | 0-2 ft | 33.45 | | 27.99 | |
| | 2-4 ft | 11.15 | | 9.33 | |
| | 4-6 ft | 22.30 | | 18.66 | |
| | 6-8 ft | 11.15 | | 9.33 | |
| | 8-10 ft | 22.30 | | 18.66 | |
| **ENHANCING PAVED SHOULDERS** | 0-2 ft | 83.69 | | 70.05 | |
| | 2-4 ft | 83.69 | | 70.05 | |
| | 6-8 ft | 41.84 | | 35.02 | |
| | 8-10 ft | 20.92 | | 17.51 | |
| | | **OPTIMISTIC EFFICIENCY** | **PESSIMISTIC EFFICIENCY** | **OPTIMISTIC EFFICIENCY** | **PESSIMISTIC EFFICIENCY** |
| **VISION-BASED LDWS** | Mandatory Model | 6.55 | 2.77 | 19.16 | 8.18 |
| | Non-Mandatory Model | 3.69 | 1.56 | 12.51 | 5.35 |
| **DGPS-BASED LDWS** | Mandatory Model | 1.26 | 0.63 | 6.86 | 3.38 |
| | Non-Mandatory Model | 1.04 | 0.52 | 3.69 | 1.82 |

### 10.3 Summary

For curves, the benefit:cost ratios as computed are very high for static signs and the incremental benefit:cost ratio is high for dynamic curve warning signs. However, most of the curves analyzed in the cross-sectional analysis had static warning signs and still had high crash rates. The assumption used herein is that the crash rate would have been even higher had no signs been present. In practice, though, the baseline condition is really the condition where static curve warning signs are in place. Thus according to the benefit:cost ratio, infrastructure –based and technology-based curve warning signs are cost-effective.

For tangential sections, enhancing shoulders by adding rumble strips is the most cost beneficial with the vision-based LDWS being comparable for certain shoulder widths for a 20 year analysis while assuming optimistic efficiency. However these results are pertaining to the sample set used in the cross-sectional and before:after analysis and hence a statewide deployment model is studied in Chapter 11 to decide the optimal solution.

# Chapter 11: Deployment Factor

In 2007, 510 people died in the state of Minnesota due to road accidents, of which 253 were fatalities due to road departure crashes [3.]. It has already been introduced that it costs the state billions of dollars. Various treatments have been suggested along with the benefit:cost ratios to provide the cost effective solution to reduce this monetary loss. However, along with money it is the human lives that are being lost. There is a lot of pain and suffering, loss of productive work associated with each fatality and injury; and it is the state's duty to prevent this and provide their people with safe roads. Mn/DOT's Toward Zero Deaths (TZD) is a goal which moves in this direction and thus the solution that is proposed, should not just be cost-effective, but also one that reduces the number of fatalities considerably and helps Mn/DOT move towards its goal of TZD.

## 11.1 Safety Systems for Curves

Rumble strips are one of the most low cost treatments suggested for avoiding crashes along curves. However, their efficiency is low just about 15 % as against 66% of curve flattening.

In the sequel, a general estimate of the number of at-risk curves per county is 50. There are 87 counties in MN, so that makes it a reasonable volume of 4,350 at-risk curves in the entire state. This is the estimate that has been assumed. 80% of the curves already have static signs, and an additional 12% of the curves have chevrons. This is the baseline assumed. Hence to find the incremental benefits of safety systems, static signs can be implemented to the remaining 20% of the curves, or 870 curves. Chevrons are already implemented on 12% of curves, or 520 curves. Hence, chevrons can be implemented on an additional 3,830 curves. Rumble strips, curve flattening, and dynamic curve warning signs could be implemented to all the 4,350 curves

### 11.1.1 Towards TZD

#### *11.1.1.1 For 100% of Statewide At-risk Curves: Rumble Strips*

The fatality rate per curve per year is 0.0045. The exposure to fatalities in MN for rumble strips is

$$0.0045 \times 4{,}350 \sim 20$$

Since efficiency of rumble strips at curves is 15%, the number of fatalities prevented due to adding rumble strips on curves is

$$0.15 \times 20 \sim 3$$

Thus the percentage of achievement towards TZD that is the percentage of fatalities prevented of the total 253 road departure fatalities is

$$\frac{3}{253} \times 100 = 1.19\%$$

Rumble strips are thus 1.19% successful towards TZD.

***11.1.1.2 For 20% of Curves: Static Warning Signs***

The total number of fatalities exposed to per year at curves in MN without static signs is

$$0.0045 \times 870 \sim 4$$

Since efficiency of static curve warning signs is 18% [16.], the number of fatalities prevented due to implementing static curve signs on 20% of the curves is

$$0.18 \times 4 = 0.72$$

Thus the percentage of achievement towards TZD is

$$\frac{0.72}{253} \times 100 = 0.28\%$$

Static signs are thus 0.28% successful towards TZD.

Similar procedure is used for other treatments to get the following values (Appendix L Table 1):

**Table 11.1 Contribution Towards TZD by Solutions Suggested at Curves**

| Treatment | Number of Curves in State Treatment/Sign/Safety System could be Implemented to | Contribution to TZD | Benefit:Cost Ratio (Assuming the best case for a 20 year analysis) |
|---|---|---|---|
| Rumble Strips | 4,350 | 1.19% | 56.72 |
| Curve Flattening | 4,350 | 5.22% | 0.42 |
| Chevrons | 3,830 | 1.34% | 111.72 |
| Dynamic Curve Speed Warning Sign | 4,350 | 2.37% | 3.36 |

The third and the second columns in the table, the TZD percentage and the benefit:cost ratio, are the two parameters which have to be compared to decide upon an optimum solution. The benefit:cost ratio is highest for chevrons but it just contributes by 1.34% to TZD. Curve flattening contributes by 5.22% but it is a highly expensive treatment and shows a very poor benefit:cost ratio of 0.42 which is less than 1. Dynamic curve warning signs show a benefit:cost ratio higher than 1. Thus, benefits are reaped for the amount of financial resources invested in it. It also contributes to the TZD goal by a fairly high percentage of 3.48% as compared to the other treatments. This method of inspection is very crude and a more specific method is required.

### 11.1.2 Towards TZD for Fixed Amount of Financial Resources (Deployment Factor)

The previous method of calculating the safety benefits with respect to TZD was without any budget constraints. However, in reality a fixed safety amount is reserved each year. Given a fixed budget to spend while implementing countermeasures, the safety system which would reduce the most number of fatalities is the optimal solution. A budget of $2,000,000 is assumed. Since the rumble strips, curve flattening and dynamic curve speed warning signs could be implemented on 100% of curves, the entire $2,000,000 can be used. Static signs have to be implemented only on 20% of curves, hence assigning a budget of 20% of the entire $2,000,000 that is $4,000,000 for static signs. Chevrons could be implemented on 90% of the curves and hence a budget of $1,800,000 (90% of $2,000,000) can be assumed for chevrons.

#### *11.1.2.1 For 100% Curves*

Rumble strips cost $3,000 per mile. For $2,000,000 the number of miles to which rumble strips can be milled on is

$$\frac{\$2{,}000{,}000}{\$3{,}000} \sim 667$$

Since 204 curves in our data set equal a total of 35 miles, 667 miles would be approximately 3887 curves. Assuming 0.0045 fatalities per curve per year, the number of fatalities it is exposed to is

$$0.0045 \times 3887 \sim 17\ fatals\ per\ year$$

Since the efficiency of rumble strips is 15%, the number of fatalities prevented is

$$0.15 \times 17 \sim 3$$

Thus, its TZD contribution is

$$\frac{3}{253} = 1.04\%$$

This number is called the deployment factor.

#### *11.1.2.2 For 20% Curves*

Static curve warning signs cost $170 per curve. For $400,000 (20% of 2 million dollars) the number of curves to which these signs could be installed is

$$\frac{\$400{,}000}{\$170} \sim 2353$$

Assuming 0.0045 fatalities per curve per year, the number of fatalities it is exposed to is

$$0.0045 \times 2353 \sim 11\ fatals\ per\ year$$

Since the efficiency of static signs is 18%, the number of fatalities prevented is

$$0.18 \times 11 \sim 2$$

Thus, its TZD contribution is

$$\frac{2}{253} = 0.75\%$$

Thus the deployment factor for static curve warning signs is 0.75%.

Table 11.2 gives the deployment factor for all the safety treatments for curves (Appendix L Table 2).

**Table 11.2 Deployment Factor for Safety Systems for Curves**

| Treatment | Deployment factor |
|---|---|
| Rumble strips | 1.04 |
| Curve flattening | 0.008 |
| Chevrons | 0.64 |
| Dynamic curve speed warning signs | 0.09 |

The deployment factor can be used as a deciding factor to implement treatments. As per Table 10.3, for a given budget rumble strips have the highest deployment factor, that is they prevent the most number of fatalities per year.

It is important to note that for curves, only a one-year analysis period is considered. This is because the $2M assumed available can address all at-risk intersections with the lower cost countermeasures.

### 11.2 Safety Systems for Tangential Sections

Tangential sections cover a larger area. In the state of MN, there are estimated 53,000 tangential sections. Given the number of road departure fatalities in MN was 253 in the year 2007, the fatal crash rate for the tangential sections would be 0.005.

### 11.2.1 Enhancing Tangential Sections

Assuming a budget of $2,000,000 every year, the cost of adding rumble strips is $3,000 per mile. Hence the number of miles enhanced every year is

$$\frac{\$2{,}000{,}000}{\$3{,}000} \sim 667$$

The number of fatalities exposed to thus every year is

$$0.005 \times 667 \sim 3$$

Assuming an efficiency of 0.36 for enhancing tangential sections, the number of fatalities prevented is

$$0.36 \times 3 \sim 1$$

If 667 miles are enhanced every year, totally 1,334 miles are enhanced by end of the second year.

$$0.005 \times 1{,}334 \sim 7\ fatals$$

The number of fatalities prevented after enhancing tangential sections is

$$0.36 \times 7 \sim 2$$

Adding the cumulative fatalities prevented in 10 years, the total number of fatalities prevented in 10 years after enhancing 667 miles of tangential sections each year is 66. Assuming the number of road departure fatalities to be constant at 253 each year, the total fatalities occurring in 10 year due to road departure accidents is 2,530. Thus the TZD contribution after 10 years of enhancing tangential sections is

$$\frac{66}{2530} \times 100 = 2.61\%$$

A 10 year deployment factor hence for enhancing tangential sections is 2.61%.

### 11.2.2 In-Vehicle Technologies

The vision-based lane departure warning system has a starting unit price of $500 in 2010. Hence if the budget is $2,000,000; the number of vehicles that could be equipped with the system is

$$\frac{\$2{,}000{,}000}{\$500} = 4{,}000$$

The total number of cars assumed in the state in 2010 in Chapter 6 is 3.58 million. These cars are exposed to the total 253 road departure crashes in the state. Thus, 4,000 cars would be exposed to

$$\frac{253 \times 4{,}000}{3.58 \times 10^6} = 0.28$$

Assuming the optimistic efficiency of 55% at the start, the number of fatalities prevented is

$$\frac{55}{100} \times 0.28 = 0.15$$

As per the cost model, the unit price decreases to $326 following the mandatory model. Hence the number of cars that could be equipped in the same 2 million dollar budget is 6,122. The total number of vehicles equipped with the vision-based LDWS would be total sum of those in the two years and hence the exposure to fatal crashes would be more. Also, the efficiency increases every year linearly. The fatal crashes prevented are calculated every year for 10 years. The total fatalities thus prevented in 10 years is 42. Assuming the number of road departure fatalities to be constant each year, the total number of road departure crashes is 2530.

The contribution to TZD is

$$\frac{42}{2530} \times 100 = 1.65\%$$

Similarly deployment factor is calculated for vision-based and DGPS-based systems assuming both mandatory and non-mandatory options. The 10 year deployment factor for vision-based LDWS assuming a mandatory deployment model is 1.65%.

**Table 11.3 Deployment Factor for Safety Systems for Tangential Sections**

| Treatment/Safety System | | Deployment Factor |
|---|---|---|
| Enhancing Tangential Sections | | 2.61% |
| Vision-based LDWS | Mandatory | 1.65% |
| | Non-Mandatory | 1.37% |
| DGPS-based LDWS | Mandatory | 0.1% |
| | Non-Mandatory | 0.1% |

The vision-based lane departure warning systems are thus comparable to enhancing tangential sections in their deployment factor.

# Chapter 12: Policy Implications and Recommendations

The results of this research effort suggest two policy issue areas for Mn/DOT's consideration – the first dealing with horizontal curves and the second with paved shoulders.

## 12.1 Horizontal Curves

### 12.1.1 Design of Horizontal Curves

A typical practice in the design of a horizontal curve radius is to first identify a design speed and then determine the recommended minimum radius based on the guidelines in the *Road Design Manual*. For a 60 MPH design speed the recommended minimum curve radius is 1,350 feet (4.25 degrees) and at 65 MPH the recommended minimum is 1,640 feet (3.5 degrees). However, based on a review of a sample of 278 curves on the state system (57 curves from the data set developed for this project and 221 from a safety study currently underway in Mn/DOT District 7) the average curve radius was found to be approximately 1,820 feet (3.25 degrees) and the longest was found to be 5,600 feet (1 degree). This indicates designers have regularly chosen to provide longer curve radii than the suggested minimums in the *Road Design Manual*, conceivably to provide a greater margin of safety for the vehicles negotiating the curve. This notion of a greater margin of safety associated with larger curve radii is clearly supported by the documented results of this research, but only up to a point. Both the earlier work done in Texas and these results suggest that starting at around a 2,000 foot radius (3 degrees), the expected crash rate in curves approximates the average system crash rate for all two-lane state highways (it should be noted that curves account for about 5% of the system mileage). Potential policy implications include discouraging designers from selecting curve radii greater than 2,000 feet, solely based on the safety of vehicles traversing the curve and encouraging designers to give greater consideration to providing a more consistent design among curves along a particular segment of road as part of a context sensitive solution.

**Recommendation:** It is recommended that Mn/DOT revise the section of the *Road Design Manual* dealing with the design of horizontal curves to include this information relating safety and curve radii and to encourage an approach to design that provides a greater consistency among curves along a segment of highway.

### 12.1.2 Traffic Control Devices

A typical practice in the application of traffic control devices on the approaches to and through horizontal curves is to defer to the guidance in the *Minnesota Manual on Uniform Traffic Control Devices* (MMUTCD). These guidelines indicate that the use of a horizontal alignment warning signs (Curve sign, Turn sign, Speed Advisory, Chevron, etc) is optional – they may be used based on the exercise of judgment. However, it appears that a lack of any guidance about how to identify specific curves that are candidates for the application of traffic control devices has resulted in a level of inconsistency – 20% of the curves in the data set had no advanced warning signs and this included some curves in every radius category. This inconsistent application of traffic signs can increase an agency's exposure to liability – two similar curves on the same system that are signed differently – if there is no written record of the thought process that resulted in the inconsistent application. Potential policy implications involve preparing new guidelines for the MMUTCD that would require agencies to provide a higher level of consistency by calling for proactively placing signs based on curve radius and the relative degree of risk. For example:

- Curves > 2,000 feet – Low risk (Crash Rate = System average): No Advance Warning signs.
- Curves > 1,500 feet & < 2,000 feet – Moderate risk (Crash rate = 2xSystem average): Advance Warning Sign
- Curves < 1,500 feet – High risk (Crash rate > 5xSystem average & 90% of fatal crashes): Advanced Warning + Chevrons

**Recommendation:** It is recommended that Mn/DOT revise part 2C of the Minnesota Manual on Uniform Traffic Control Devices dealing with horizontal alignment warning signs to include more specific suggestions about consistently applying a specific package of warning signs at all locations in a specific set of horizontal curves based on their radius.

## 12.2 Shoulders

### 12.2.1 Programmatic Issue

The issue of paving shoulders along two-lane rural roads (and how to pay for the improvement) is a topic being discussed across Mn/DOT and by a number of county engineers. One of the key points is whether or not paved shoulders are in fact a safety feature, and if so, should they be considered eligible for Highway Safety Improvement Program (HSIP) funding. The results of this research generally indicate that paved shoulders are in fact a safety feature – the Cross-Sectional study found an overall 23% reduction in crashes associated with shoulder paving, the before:after study found a 16% reduction and these crash reductions are consistent with 15% reduction reported in FHWA's *Desk Top Reference for Crash Reduction Factors*. It should be noted that the overall 23% crash reduction for shoulder paving was not consistent among the various shoulder width categories, but that is likely due to the relatively small sample size. The results of both the Cross-Sectional and before:after studies also found similar crash reductions associated with adding shoulder enhancements – edge line rumble strips/stripEs – approximately 15%, which appears to be conservative compared to the 31% reduction reported in the *Desk Top Reference*. The bottom line is that both treatments appear to have similar crash reductions, but when construction costs are considered, a possible policy direction emerges. The cost of adding paved shoulders ($60,000 - $100,000/mile) is 20 to 30 times the cost of adding edge line rumble stripEs ($3,000/mile). The policy would encourage designers to build as much safety into their projects as possible by adding paved shoulders plus edge line rumble stripEs on all construction/reconstruction projects but to focus limited HSIP funds on the edge line rumble stripEs due to their high cost-effectiveness and lower installation costs (which allows for a wider, proactive deployment across the system, consistent with the objectives in the SHSP).

**Recommendation:** It is recommended that Mn/DOT adopt a policy of funding the addition of full-width paved shoulders as part of the construction/reconstruction program and focusing the limited HSIP funds on lower cost edgeline rumble stripEs (plus up to two feet of shoulder paving if necessary to optimize the safety benefits).

### 12.2.2 Design Issue

An additional policy change appears worthy of consideration based on these newly documented crash statistics. A review of Mn/DOT's *Road Design Manual* indicates that paved shoulders are only a required design feature on two-lane roads with daily traffic volumes greater than 3,000 vehicles per day and it appears that this guidance is based on the issue of exposure. However, a recent review of crash statistics along almost 1,700 miles of the two-lane Trunk Highways in Districts 3 and 7 found that roads with less than 3,000 ADT were more at risk – these lower volume roads had a higher fatal crash rate and twice as many severe road departure crashes. In fact, in each District the volume range between 1,000 and 2,500 ADT was the most at-risk from a safety perspective – with the highest fatal crash rate and the highest fraction, rate and density of severe road departure crashes. These statistics combined with the results of this study (which prove that paved shoulders are a safety benefit – a reduced crash rate and a reduction fraction of road departure crashes) certainly suggests re-evaluating the current approach of basing shoulder paving decisions solely on exposure.

**Recommendation:** It is recommended that Mn/DOT revise the *Road Design Manual* to require paved shoulders as part of all construction/reconstruction projects along two-lane highways at all traffic volume levels because of the proven safety benefits.

# Chapter 13: Summary

Minnesota's Strategic Highway Safety Plan identified addressing single vehicle road departure crashes as one the State's Safety Emphasis Areas based on the fact that these types of crashes account for 32% of State wide fatal crashes, 36% of fatal crashes in Greater Minnesota and 47% of fatal crashes on local systems in Greater Minnesota. This data clearly indicates that the large number of fatal crashes on State and local systems in rural areas associated with road departure crashes represents a pool of crashes susceptible to correction. However, this new focus on road departure crashes along rural highways also results in the need for better information about the factors that contribute to these types of crashes (in order to support the efforts to identify at-risk locations) and the relative effectiveness of various mitigation strategies.

The objective of this research project is to add to the understanding in Minnesota of the effects that two particular design features – horizontal curves and shoulders – have on highway safety, particularly on two-lane facilities in rural areas and provide an optimum solution either infrastructure-based or technology-based to reduce the road departure crashes. There is a basic understanding that horizontal curves are more at-risk than tangent sections of highway and that shoulders are considered to be safety features, but questions remain about details for which there are currently no good answers. These questions include:

- Are all curves equally at-risk?
    - ➢ The cross-sectional analysis of the 204 curves in the data set found that all curves are NOT equally at-risk. Crash rates were found to increase as the curve radius decreases – curves with radii greater than 2,000 feet have crash rates that are approximately equal to the state wide average for all two-lane highways, curves with a 1,500 foot radius have a crash rate approximately two times the state wide average, curves with a 1,000 foot radius have a crash rate five times the state wide average and curves with a 500 foot radius have a crash rate eleven times the state wide average.
    - ➢ The cross-sectional analysis also found a relationship between curve radii and crash severity. Approximately 90% of the fatal crashes and 75% of the injuries occurred in curves with radii less than 1,500 feet.

- Does the use of static warning signs lower the risk in horizontal curves?
    - ➢ The use of warning signs was determined from the responses to the survey of practice and the data indicate a level of inconsistency in their use – almost 20% of the curves had no warning signs and in long radius curves (over 2,000 feet) the fraction without signs rose to approximately 50%. This inconsistent use is potentially a concern because, even though both curve warning signs and chevrons are considered to be optional, the inconsistent application across a system of highways can increase the agencies exposure to liability.
    - ➢ The cross-sectional analysis indicated that the use of curve warning signs has a small noticeable effect on crash rates – the advanced warning signs reduced the crash rate on curves with radii greater than 1,000 feet and chevrons reduced the crash rate on curves with radii less than 500 feet.

    - The deployment factor that is the percentage of the total road departure fatalities reduced for static signs is not as high as that of rumble strips along curves.

- Do all widths and types of shoulders equally contribute to safety?

    - The results of the cross-sectional analysis of 137 segments of rural highway (almost 930 miles) supports the theories documented in the safety literature – the segments with wider shoulders (4 feet and greater) had 30% lower Crash and Severity rates than segments with narrower shoulders (less than 4 feet) and segments with improved shoulders (paved, composite and enhanced) had 15% lower Crash and Severity rates than segments with aggregate shoulders.
    - Identifying trends relative to fatal crashes is more challenging – the data indicates that only the widest category of shoulders (8 feet and greater) have lower fatal crash rates and there is no difference in fatal crash rates between aggregate and improved shoulders.
    - The results of the cross-sectional analysis also indicate that segments with wider shoulders (4 feet and greater) had a 33% lower fraction of road departure crashes than segments with narrower shoulders (less than 4 feet) and that segments with improved shoulders had a 20% lower fraction of road departure crashes than segments with aggregate shoulders.
    - As per the benefit:cost ratio, enhancing paved shoulders which are 0-2 ft and 2-4 ft wide is the most beneficial.

- What are the effects of low-cost shoulder edge treatments (shoulder paving & edge line rumble strips/stripEs)?

    - The results of the before:after analysis indicates that indicates that paving aggregate shoulders and adding enhancements (rumble strips/stripEs) to paved shoulders both reduced crash rates by approximately 15% and going from aggregate shoulders to paved shoulders with enhancements reduced crashes by more than 35%.
    - When individual sectional efficiencies were calculated for paving shoulders, most of the efficiencies are negative stating that paving shoulders is not a very beneficent treatment. However, the maintenance costs associated with paved shoulders is low and hence would be economical for a long-term cost effectiveness analysis. However, given to the results in our data set, paving shoulders was not considered as an alternative in the benefit:cost ratio calculations.
    - Rumble Strips both along curves and tangential sections have a high benefit:cost ratio. Also, their contribution towards reduction in fatalities is also high.

- Do new technologies aimed at improving driver’s ability to navigate along rural highways represent an opportunity to reduce road departure crashes?

    - Two in-vehicle technologies; vision-based lane departure warning systems and DGPS_based lane departure warning systems have been analyzed. The benefit:cost ratios of vision-based lane departure warning systems are comparable to enhancing tangential sections.
    - The deployment factor; that is the percentage of fatalities reduced though at the beginning is low, and in 10 years after deploying, as the cost decreases and the number of cars equipped with the system increases; the deployment factor also increases. In 10

years, the vision-based LDWS would be comparable to enhancing shoulders for the same amount of budget.

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# Appendix A

# Information Request for Cross Sectional Analyses

December 20, 2007

Dear Minnesota County Engineers:

The Minnesota Department of Transportation's Office of Research Services recently approved the study *Analysis of Highway Design and Geometric Effects on Crashes*. This is to be completed by CH2M HILL in partnership with the University of Minnesota.

The study's focus is on the prevention of lane departure crashes [single vehicle run-off the road + head-on + opposite direction sideswipe] on rural two-lane roads through shoulder widening or paving and horizontal curve treatments. The importance of lane departure crashes is made apparent in the 2007 Minnesota Strategic Highway Safety Plan, which identified a total of 1,576 lane departure fatalities during a five-year period [2001 – 2005], a majority of which occurred in rural areas and on local roads.

This study will research the safety effects that Shoulder Design and Horizontal Curves may have on crashes, especially lane departure crashes. This will be done in two ways:

> **Before-After Study:** This compares the crash history on the SAME section that had a shoulder or horizontal curve change. Example candidates for this study would be where, within the past 10 years, a project that: a) ONLY changed shoulders, b) reconstructed a section with a change to a horizontal curve, or c) a signing/marking/etc. change at a curve. The purpose of the before-after study is to evaluate traditional improvements (i.e., widening shoulder to full-width, reconstructing curve with greater radius, etc.) and evaluate any new, unique, or innovative designs or treatments.
>
> **Cross-Sectional Study:** This compares the crash history of DIFFERENT sections against each other. Candidates for this would be those who have NOT had a change in shoulder design or horizontal curvature in the past 5 years.

In order to complete the research, we are creating an inventory of corridors and curves nominated for either the shoulder study or the curve study and also for either the cross-sectional study or the before-after study. *(Yes, this project includes a total of four studies!)* ***Roadways for this study must be paved, rural, two-lane highways with a posted speed limit of 55 mph.***

> Nominations for the before-after study may be either **corridors** (for the shoulder study) or **locations** (for the curve study). For the before-after study, please also consider nearby locations that could be used as a control group (i.e., unimproved).
>
> For the shoulder cross-sectional study, corridors will also ideally have a length of at least 5 miles with a consistent shoulder design throughout.
>
> For the curve cross-sectional study, curves may have advanced warning and in-curve delineation (i.e., curve warning signs and chevrons), but should have shoulders and markings similar to the rest of the corridor.

Please complete the attached nomination forms by **February 1, 2008** and return it to Howard Preston by email (hpreston@ch2m.com). Nominations can be made for all four studies or any combination of studies.

Thank you in advance for your assistance with this survey. Your participation should be considered entirely voluntary. Your name and contact information will be removed from any information that appears in the project report or other public documents. If you have any questions or would like to discuss the research further, please contact Howard Preston at 651-365-8514 [hpreston@ch2m.com] or Richard Storm at 651-365-8515 [rstorm@ch2m.com].

Sincerely,

| | |
|---|---|
| Glen Ellis, PE | Howard Preston, PE |
| Minnesota DOT | CH2M HILL |
| Technical Liaison | Principal Investigator |

Enclosure

## General Contact Information:

Name: ______________________________ Date: ______________________________

County: ______________________________ Position: ______________________________

Address: ______________________________ Phone: ______________________________

______________________________ Email: ______________________________

______________________________

Space has been provided to nominate up to six locations. More than six locations can be nominated. Simply copy the tables to a new page.

Nominated corridors must be on roadways that are ***paved, rural, two-lane highways with a posted speed limit of 55 mph.*** Furthermore, segments will ideally have a length of at least 5 miles with a consistent shoulder design throughout.

For the following nominations, please attach any supporting documentation (i.e., photos, design details, etc.) that you feel may be useful in the selection of candidate locations.

Please complete the attached nomination forms by February 1, 2008 and return it to Howard Preston by email (hpreston@ch2m.com).

## Segment 1:

Route: ______________________________

Starting Point: ______________________________

Ending Point: ______________________________

Segment Length: ______________________________

ADT (please include source and year): ______________________________

If needed, are as-built or design plans available? ______________________________

Date Improvement Made: ______________________________

Improvement Description: ______________________________

Reason for Improvement: ______________________________

Possible Control Location: ______________________________

* Improvements can be traditional shoulder paving and/or widening projects or may include innovative shoulder safety improvements.

## Segment 2:

Route: ______________________________

Starting Point: ______________________________

Ending Point: ______________________________

Segment Length: ______________________________

ADT (please include source and year): ______________________________

If needed, are as-built or design plans available? ______________________________

Date Improvement Made: ______________________________

Improvement Description: ______________________________

Reason for Improvement: ______________________________

Possible Control Location: ______________________________

* Improvements can be traditional shoulder paving and/or widening projects or may include innovative shoulder safety improvements.

## General Contact Information:

|  |  |  |  |
|---|---|---|---|
| Name: | ______________________ | Date: | ______________________ |
| County: | ______________________ | Position: | ______________________ |
| Address: | ______________________ | Phone: | ______________________ |
|  | ______________________ | Email: | ______________________ |
|  | ______________________ |  |  |

Space has been provided to nominate up to six locations. More than six locations can be nominated. Simply copy the tables to a new page.

Nominated corridors must be on roadways that are ***paved, rural, two-lane highways with a posted speed limit of 55 mph.*** Furthermore, segments will ideally have a length of at least 5 miles with a consistent shoulder design throughout.

Please note that a "composite" shoulder is where a portion of the shoulder is paved and the outside portion of the shoulder is gravel.

For the following nominations, please attach any supporting documentation (i.e., photos, design details, etc.) that you feel may be useful in the selection of candidate locations.

Please complete the attached nomination forms by February 1, 2008 and return it to Howard Preston by email (hpreston@ch2m.com).

**Segment 1:**

Route: ______________________________

Starting Point: ______________________________

Ending Point: ______________________________

Segment Length: ______________________________

ADT (please include source and year): ______________________________

If needed, are as-built or design plans available? ______________________________

Shoulder Surface Type: ☐ Gravel ☐ Paved ☐ Composite

Total Shoulder Width: ______________

If a composite shoulder, please describe: Paved Width: __________
Gravel Width: __________

**Segment 2:**

Route: ______________________________

Starting Point: ______________________________

Ending Point: ______________________________

Segment Length: ______________________________

ADT (please include source and year): ______________________________

If needed, are as-built or design plans available? ______________________________

Shoulder Surface Type: ☐ Gravel ☐ Paved ☐ Composite

Total Shoulder Width: ______________

If a composite shoulder, please describe: Paved Width: __________
Gravel Width: __________

## General Contact Information:

Name: ______________________ Date: ______________________

County: ______________________ Position: ______________________

Address: ______________________ Phone: ______________________

______________________ Email: ______________________

______________________

Space has been provided to nominate up to six locations. More than six locations can be nominated. . Simply copy the fields to a new page.

Nominated locations must be on roadways that are ***paved, rural, two-lane highways with a posted speed limit of 55 mph.***

For the following nominations, please attach any supporting documentation (i.e., photos, design details, etc.) that you feel may be useful in the selection of candidate locations.

Please complete the attached nomination forms by February 1, 2008 and return it to Howard Preston by email (hpreston@ch2m.com).

## Curve 1:

Route: ______________________

Starting Point: ______________________

Ending Point: ______________________

Radius: ______________________

ADT (please include source and year): ______________________

If needed, are as-built or design plans available? ______________________

Date Improvement Made: ______________________

Improvement Description: ______________________

Reason for Improvement: ______________________

Possible Control Location: ______________________

* Improvements can be traditional signing or shoulder paving projects or may include innovative horizontal curve safety improvements.

## Curve 2:

Route: ______________________

Starting Point: ______________________

Ending Point: ______________________

Radius: ______________________

ADT (please include source and year): ______________________

If needed, are as-built or design plans available? ______________________

Date Improvement Made: ______________________

Improvement Description: ______________________

Reason for Improvement: ______________________

Possible Control Location: ______________________

* Improvements can be traditional signing or shoulder paving projects or may include innovative horizontal curve safety improvements.

## General Contact Information:

Name: ______________________ Date: ______________________

County: ______________________ Position: ______________________

Address: ______________________ Phone: ______________________

______________________ Email: ______________________

______________________

Please consider nominating up to three locations in each range of Degree of Curvature. However, please make at least one nomination in each range. Locations do not have to be high crash locations, but simply horizontal curves that represent the average design used by your agency. Please consider nominating a mix of horizontal curves that are with and without advance warning signs or in-curve delineation (i.e., chevrons).

Nominated locations must be on roadways that are ***paved, rural, two-lane highways with a posted speed limit of 55 mph.***

For the following nominations, please attach any supporting documentation (i.e., photos, design details, etc.) that you feel may be useful in the selection of candidate locations.

Please complete the attached nomination forms by February 1, 2008 and return it to Howard Preston by email (hpreston@ch2m.com).

## 0º < Degree of Curve < 3.5º:

Route: ______________________________

Starting Point: ______________________________

Ending Point: ______________________________

Radius: ______________________________

Are Advance Warning Signs or In-Curve Delineation Present (if yes, please describe)? ______________________________

ADT (please include source and year): ______________________________

If needed, are as-built or design plans available? ______________________________

Route: ______________________________

Starting Point: ______________________________

Ending Point: ______________________________

Radius: ______________________________

Are Advance Warning Signs or In-Curve Delineation Present (if yes, please describe)? ______________________________

ADT (please include source and year): ______________________________

If needed, are as-built or design plans available? ______________________________

Route: ______________________________

Starting Point: ______________________________

Ending Point: ______________________________

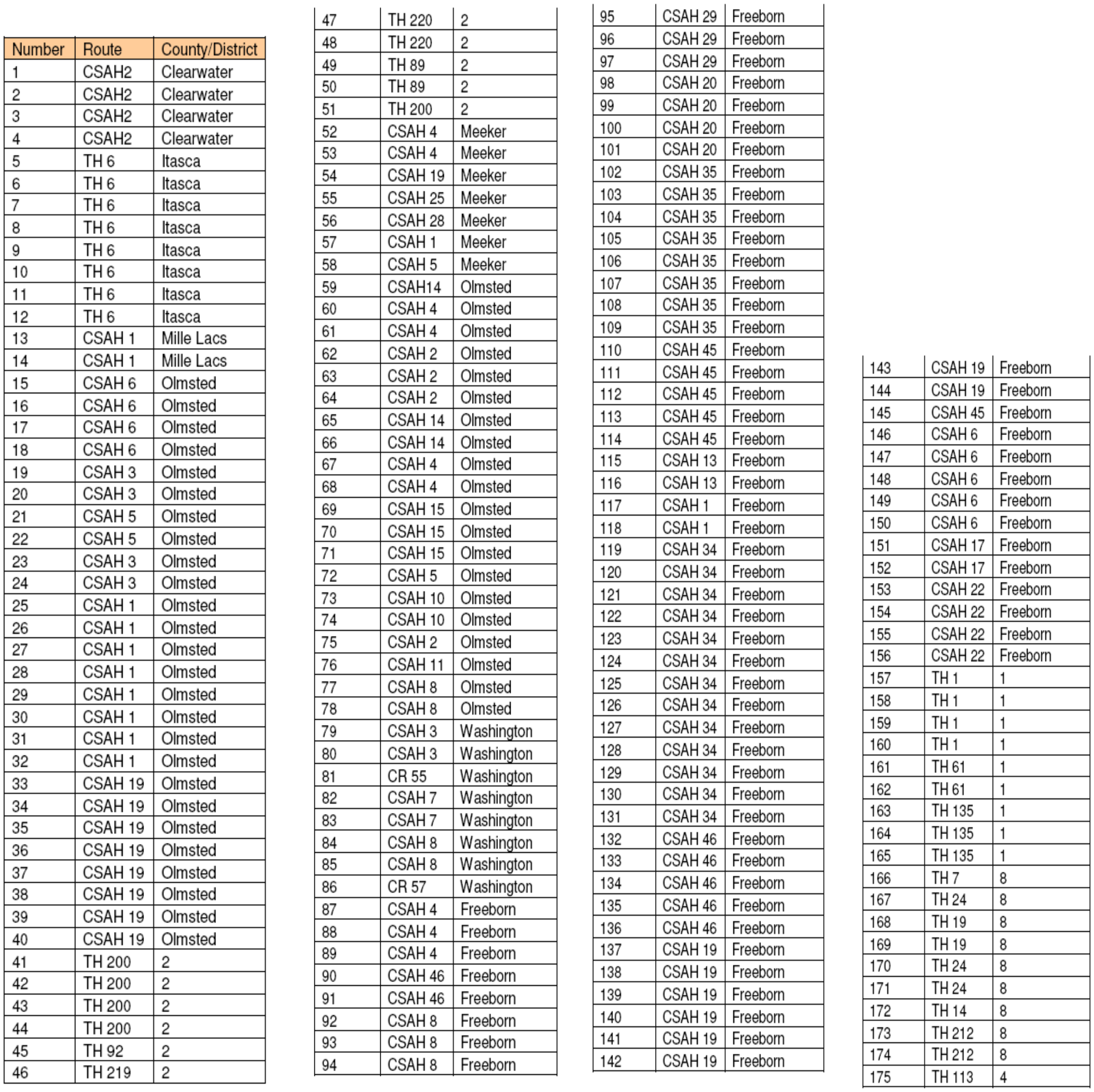
Radius: ______________________________

Are Advance Warning Signs or In-Curve Delineation Present (if yes, please describe)? ______________________________

ADT (please include source and year): ______________________________

If needed, are as-built or design plans available? ______________________________

# Appendix B
# Curve Cross-Sectional Candidate



| Number | Route | County/District |
|---|---|---|
| 1 | CSAH2 | Clearwater |
| 2 | CSAH2 | Clearwater |
| 3 | CSAH2 | Clearwater |
| 4 | CSAH2 | Clearwater |
| 5 | TH 6 | Itasca |
| 6 | TH 6 | Itasca |
| 7 | TH 6 | Itasca |
| 8 | TH 6 | Itasca |
| 9 | TH 6 | Itasca |
| 10 | TH 6 | Itasca |
| 11 | TH 6 | Itasca |
| 12 | TH 6 | Itasca |
| 13 | CSAH 1 | Mille Lacs |
| 14 | CSAH 1 | Mille Lacs |
| 15 | CSAH 6 | Olmsted |
| 16 | CSAH 6 | Olmsted |
| 17 | CSAH 6 | Olmsted |
| 18 | CSAH 6 | Olmsted |
| 19 | CSAH 3 | Olmsted |
| 20 | CSAH 3 | Olmsted |
| 21 | CSAH 5 | Olmsted |
| 22 | CSAH 5 | Olmsted |
| 23 | CSAH 3 | Olmsted |
| 24 | CSAH 3 | Olmsted |
| 25 | CSAH 1 | Olmsted |
| 26 | CSAH 1 | Olmsted |
| 27 | CSAH 1 | Olmsted |
| 28 | CSAH 1 | Olmsted |
| 29 | CSAH 1 | Olmsted |
| 30 | CSAH 1 | Olmsted |
| 31 | CSAH 1 | Olmsted |
| 32 | CSAH 1 | Olmsted |
| 33 | CSAH 19 | Olmsted |
| 34 | CSAH 19 | Olmsted |
| 35 | CSAH 19 | Olmsted |
| 36 | CSAH 19 | Olmsted |
| 37 | CSAH 19 | Olmsted |
| 38 | CSAH 19 | Olmsted |
| 39 | CSAH 19 | Olmsted |
| 40 | CSAH 19 | Olmsted |
| 41 | TH 200 | 2 |
| 42 | TH 200 | 2 |
| 43 | TH 200 | 2 |
| 44 | TH 200 | 2 |
| 45 | TH 92 | 2 |
| 46 | TH 219 | 2 |
| 47 | TH 220 | 2 |
| 48 | TH 220 | 2 |
| 49 | TH 89 | 2 |
| 50 | TH 89 | 2 |
| 51 | TH 200 | 2 |
| 52 | CSAH 4 | Meeker |
| 53 | CSAH 4 | Meeker |
| 54 | CSAH 19 | Meeker |
| 55 | CSAH 25 | Meeker |
| 56 | CSAH 28 | Meeker |
| 57 | CSAH 1 | Meeker |
| 58 | CSAH 5 | Meeker |
| 59 | CSAH14 | Olmsted |
| 60 | CSAH 4 | Olmsted |
| 61 | CSAH 4 | Olmsted |
| 62 | CSAH 2 | Olmsted |
| 63 | CSAH 2 | Olmsted |
| 64 | CSAH 2 | Olmsted |
| 65 | CSAH 14 | Olmsted |
| 66 | CSAH 14 | Olmsted |
| 67 | CSAH 4 | Olmsted |
| 68 | CSAH 4 | Olmsted |
| 69 | CSAH 15 | Olmsted |
| 70 | CSAH 15 | Olmsted |
| 71 | CSAH 15 | Olmsted |
| 72 | CSAH 5 | Olmsted |
| 73 | CSAH 10 | Olmsted |
| 74 | CSAH 10 | Olmsted |
| 75 | CSAH 2 | Olmsted |
| 76 | CSAH 11 | Olmsted |
| 77 | CSAH 8 | Olmsted |
| 78 | CSAH 8 | Olmsted |
| 79 | CSAH 3 | Washington |
| 80 | CSAH 3 | Washington |
| 81 | CR 55 | Washington |
| 82 | CSAH 7 | Washington |
| 83 | CSAH 7 | Washington |
| 84 | CSAH 8 | Washington |
| 85 | CSAH 8 | Washington |
| 86 | CR 57 | Washington |
| 87 | CSAH 4 | Freeborn |
| 88 | CSAH 4 | Freeborn |
| 89 | CSAH 4 | Freeborn |
| 90 | CSAH 46 | Freeborn |
| 91 | CSAH 46 | Freeborn |
| 92 | CSAH 8 | Freeborn |
| 93 | CSAH 8 | Freeborn |
| 94 | CSAH 8 | Freeborn |
| 95 | CSAH 29 | Freeborn |
| 96 | CSAH 29 | Freeborn |
| 97 | CSAH 29 | Freeborn |
| 98 | CSAH 20 | Freeborn |
| 99 | CSAH 20 | Freeborn |
| 100 | CSAH 20 | Freeborn |
| 101 | CSAH 20 | Freeborn |
| 102 | CSAH 35 | Freeborn |
| 103 | CSAH 35 | Freeborn |
| 104 | CSAH 35 | Freeborn |
| 105 | CSAH 35 | Freeborn |
| 106 | CSAH 35 | Freeborn |
| 107 | CSAH 35 | Freeborn |
| 108 | CSAH 35 | Freeborn |
| 109 | CSAH 35 | Freeborn |
| 110 | CSAH 45 | Freeborn |
| 111 | CSAH 45 | Freeborn |
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| 113 | CSAH 45 | Freeborn |
| 114 | CSAH 45 | Freeborn |
| 115 | CSAH 13 | Freeborn |
| 116 | CSAH 13 | Freeborn |
| 117 | CSAH 1 | Freeborn |
| 118 | CSAH 1 | Freeborn |
| 119 | CSAH 34 | Freeborn |
| 120 | CSAH 34 | Freeborn |
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| 128 | CSAH 34 | Freeborn |
| 129 | CSAH 34 | Freeborn |
| 130 | CSAH 34 | Freeborn |
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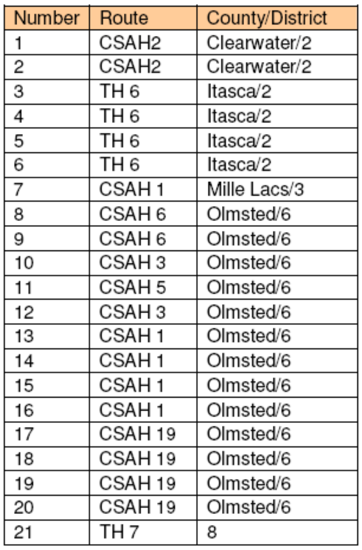
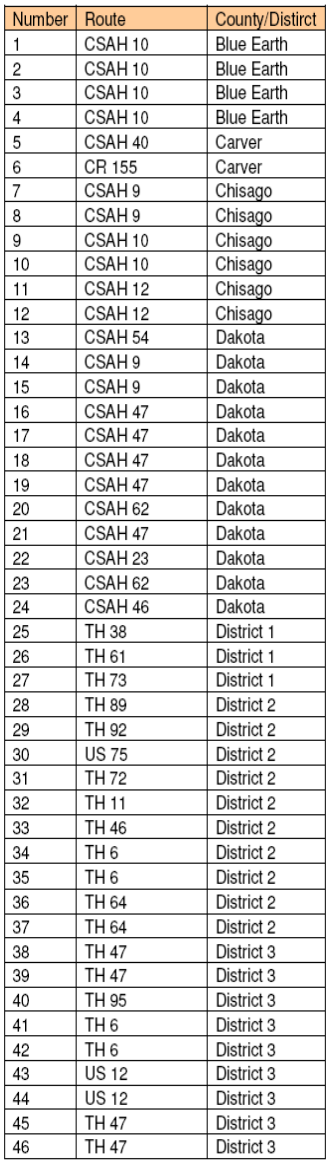
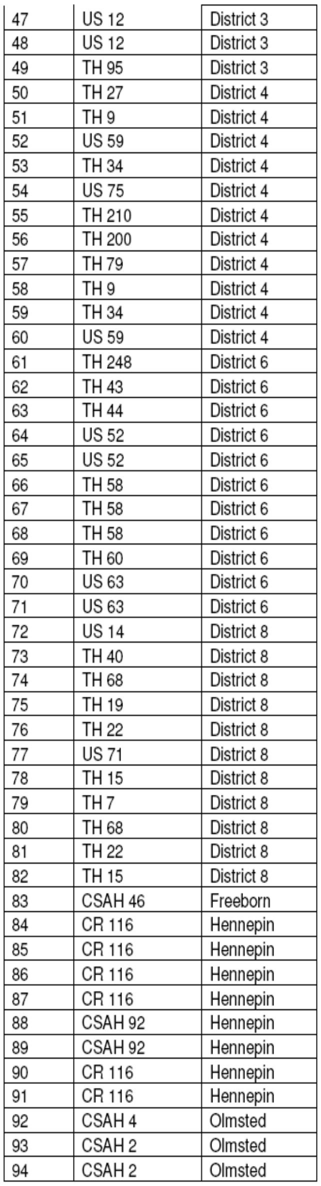
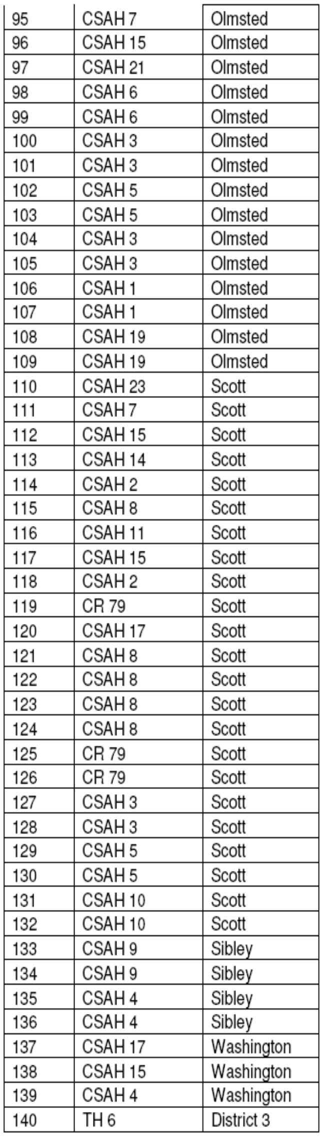
| 132 | CSAH 46 | Freeborn |
| 133 | CSAH 46 | Freeborn |
| 134 | CSAH 46 | Freeborn |
| 135 | CSAH 46 | Freeborn |
| 136 | CSAH 46 | Freeborn |
| 137 | CSAH 19 | Freeborn |
| 138 | CSAH 19 | Freeborn |
| 139 | CSAH 19 | Freeborn |
| 140 | CSAH 19 | Freeborn |
| 141 | CSAH 19 | Freeborn |
| 142 | CSAH 19 | Freeborn |
| 143 | CSAH 19 | Freeborn |
| 144 | CSAH 19 | Freeborn |
| 145 | CSAH 45 | Freeborn |
| 146 | CSAH 6 | Freeborn |
| 147 | CSAH 6 | Freeborn |
| 148 | CSAH 6 | Freeborn |
| 149 | CSAH 6 | Freeborn |
| 150 | CSAH 6 | Freeborn |
| 151 | CSAH 17 | Freeborn |
| 152 | CSAH 17 | Freeborn |
| 153 | CSAH 22 | Freeborn |
| 154 | CSAH 22 | Freeborn |
| 155 | CSAH 22 | Freeborn |
| 156 | CSAH 22 | Freeborn |
| 157 | TH 1 | 1 |
| 158 | TH 1 | 1 |
| 159 | TH 1 | 1 |
| 160 | TH 1 | 1 |
| 161 | TH 61 | 1 |
| 162 | TH 61 | 1 |
| 163 | TH 135 | 1 |
| 164 | TH 135 | 1 |
| 165 | TH 135 | 1 |
| 166 | TH 7 | 8 |
| 167 | TH 24 | 8 |
| 168 | TH 19 | 8 |
| 169 | TH 19 | 8 |
| 170 | TH 24 | 8 |
| 171 | TH 24 | 8 |
| 172 | TH 14 | 8 |
| 173 | TH 212 | 8 |
| 174 | TH 212 | 8 |
| 175 | TH 113 | 4 |

# Appendix C
# Curve Before:After Locations



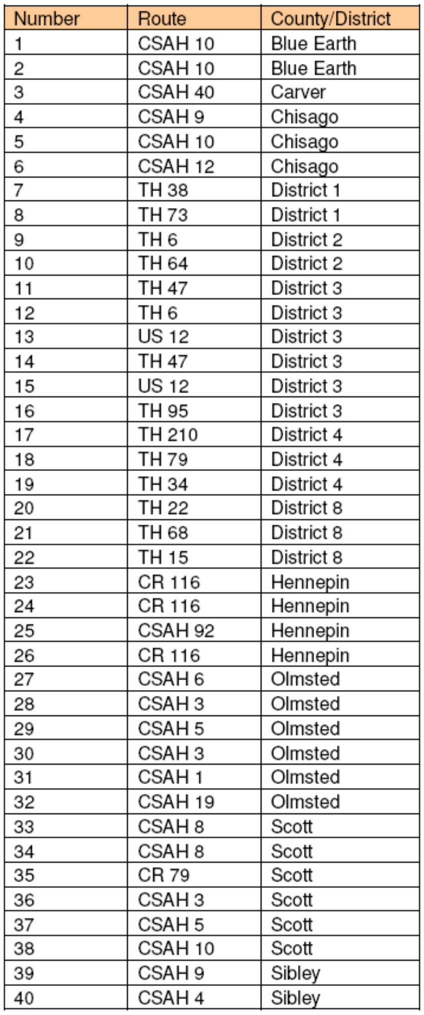
| Number | Route | County/District |
|---|---|---|
| 1 | CSAH2 | Clearwater/2 |
| 2 | CSAH2 | Clearwater/2 |
| 3 | TH 6 | Itasca/2 |
| 4 | TH 6 | Itasca/2 |
| 5 | TH 6 | Itasca/2 |
| 6 | TH 6 | Itasca/2 |
| 7 | CSAH 1 | Mille Lacs/3 |
| 8 | CSAH 6 | Olmsted/6 |
| 9 | CSAH 6 | Olmsted/6 |
| 10 | CSAH 3 | Olmsted/6 |
| 11 | CSAH 5 | Olmsted/6 |
| 12 | CSAH 3 | Olmsted/6 |
| 13 | CSAH 1 | Olmsted/6 |
| 14 | CSAH 1 | Olmsted/6 |
| 15 | CSAH 1 | Olmsted/6 |
| 16 | CSAH 1 | Olmsted/6 |
| 17 | CSAH 19 | Olmsted/6 |
| 18 | CSAH 19 | Olmsted/6 |
| 19 | CSAH 19 | Olmsted/6 |
| 20 | CSAH 19 | Olmsted/6 |
| 21 | TH 7 | 8 |

# Appendix D
## Shoulder Cross-Sectional Candidates

| Number | Route | County/Distirct |
|---|---|---|
| 1 | CSAH 10 | Blue Earth |
| 2 | CSAH 10 | Blue Earth |
| 3 | CSAH 10 | Blue Earth |
| 4 | CSAH 10 | Blue Earth |
| 5 | CSAH 40 | Carver |
| 6 | CR 155 | Carver |
| 7 | CSAH 9 | Chisago |
| 8 | CSAH 9 | Chisago |
| 9 | CSAH 10 | Chisago |
| 10 | CSAH 10 | Chisago |
| 11 | CSAH 12 | Chisago |
| 12 | CSAH 12 | Chisago |
| 13 | CSAH 54 | Dakota |
| 14 | CSAH 9 | Dakota |
| 15 | CSAH 9 | Dakota |
| 16 | CSAH 47 | Dakota |
| 17 | CSAH 47 | Dakota |
| 18 | CSAH 47 | Dakota |
| 19 | CSAH 47 | Dakota |
| 20 | CSAH 62 | Dakota |
| 21 | CSAH 47 | Dakota |
| 22 | CSAH 23 | Dakota |
| 23 | CSAH 62 | Dakota |
| 24 | CSAH 46 | Dakota |
| 25 | TH 38 | District 1 |
| 26 | TH 61 | District 1 |
| 27 | TH 73 | District 1 |
| 28 | TH 89 | District 2 |
| 29 | TH 92 | District 2 |
| 30 | US 75 | District 2 |
| 31 | TH 72 | District 2 |
| 32 | TH 11 | District 2 |
| 33 | TH 46 | District 2 |
| 34 | TH 6 | District 2 |
| 35 | TH 6 | District 2 |
| 36 | TH 64 | District 2 |
| 37 | TH 64 | District 2 |
| 38 | TH 47 | District 3 |
| 39 | TH 47 | District 3 |
| 40 | TH 95 | District 3 |
| 41 | TH 6 | District 3 |
| 42 | TH 6 | District 3 |
| 43 | US 12 | District 3 |
| 44 | US 12 | District 3 |
| 45 | TH 47 | District 3 |
| 46 | TH 47 | District 3 |
| 47 | US 12 | District 3 |
| 48 | US 12 | District 3 |
| 49 | TH 95 | District 3 |
| 50 | TH 27 | District 4 |
| 51 | TH 9 | District 4 |
| 52 | US 59 | District 4 |
| 53 | TH 34 | District 4 |
| 54 | US 75 | District 4 |
| 55 | TH 210 | District 4 |
| 56 | TH 200 | District 4 |
| 57 | TH 79 | District 4 |
| 58 | TH 9 | District 4 |
| 59 | TH 34 | District 4 |
| 60 | US 59 | District 4 |
| 61 | TH 248 | District 6 |
| 62 | TH 43 | District 6 |
| 63 | TH 44 | District 6 |
| 64 | US 52 | District 6 |
| 65 | US 52 | District 6 |
| 66 | TH 58 | District 6 |
| 67 | TH 58 | District 6 |
| 68 | TH 58 | District 6 |
| 69 | TH 60 | District 6 |
| 70 | US 63 | District 6 |
| 71 | US 63 | District 6 |
| 72 | US 14 | District 8 |
| 73 | TH 40 | District 8 |
| 74 | TH 68 | District 8 |
| 75 | TH 19 | District 8 |
| 76 | TH 22 | District 8 |
| 77 | US 71 | District 8 |
| 78 | TH 15 | District 8 |
| 79 | TH 7 | District 8 |
| 80 | TH 68 | District 8 |
| 81 | TH 22 | District 8 |
| 82 | TH 15 | District 8 |
| 83 | CSAH 46 | Freeborn |
| 84 | CR 116 | Hennepin |
| 85 | CR 116 | Hennepin |
| 86 | CR 116 | Hennepin |
| 87 | CR 116 | Hennepin |
| 88 | CSAH 92 | Hennepin |
| 89 | CSAH 92 | Hennepin |
| 90 | CR 116 | Hennepin |
| 91 | CR 116 | Hennepin |
| 92 | CSAH 4 | Olmsted |
| 93 | CSAH 2 | Olmsted |
| 94 | CSAH 2 | Olmsted |
| 95 | CSAH 7 | Olmsted |
| 96 | CSAH 15 | Olmsted |
| 97 | CSAH 21 | Olmsted |
| 98 | CSAH 6 | Olmsted |
| 99 | CSAH 6 | Olmsted |
| 100 | CSAH 3 | Olmsted |
| 101 | CSAH 3 | Olmsted |
| 102 | CSAH 5 | Olmsted |
| 103 | CSAH 5 | Olmsted |
| 104 | CSAH 3 | Olmsted |
| 105 | CSAH 3 | Olmsted |
| 106 | CSAH 1 | Olmsted |
| 107 | CSAH 1 | Olmsted |
| 108 | CSAH 19 | Olmsted |
| 109 | CSAH 19 | Olmsted |
| 110 | CSAH 23 | Scott |
| 111 | CSAH 7 | Scott |
| 112 | CSAH 15 | Scott |
| 113 | CSAH 14 | Scott |
| 114 | CSAH 2 | Scott |
| 115 | CSAH 8 | Scott |
| 116 | CSAH 11 | Scott |
| 117 | CSAH 15 | Scott |
| 118 | CSAH 2 | Scott |
| 119 | CR 79 | Scott |
| 120 | CSAH 17 | Scott |
| 121 | CSAH 8 | Scott |
| 122 | CSAH 8 | Scott |
| 123 | CSAH 8 | Scott |
| 124 | CSAH 8 | Scott |
| 125 | CR 79 | Scott |
| 126 | CR 79 | Scott |
| 127 | CSAH 3 | Scott |
| 128 | CSAH 3 | Scott |
| 129 | CSAH 5 | Scott |
| 130 | CSAH 5 | Scott |
| 131 | CSAH 10 | Scott |
| 132 | CSAH 10 | Scott |
| 133 | CSAH 9 | Sibley |
| 134 | CSAH 9 | Sibley |
| 135 | CSAH 4 | Sibley |
| 136 | CSAH 4 | Sibley |
| 137 | CSAH 17 | Washington |
| 138 | CSAH 15 | Washington |
| 139 | CSAH 4 | Washington |
| 140 | TH 6 | District 3 |

# Appendix E
# Shoulder Before:After Candidates



| Number | Route | County/District |
|---|---|---|
| 1 | CSAH 10 | Blue Earth |
| 2 | CSAH 10 | Blue Earth |
| 3 | CSAH 40 | Carver |
| 4 | CSAH 9 | Chisago |
| 5 | CSAH 10 | Chisago |
| 6 | CSAH 12 | Chisago |
| 7 | TH 38 | District 1 |
| 8 | TH 73 | District 1 |
| 9 | TH 6 | District 2 |
| 10 | TH 64 | District 2 |
| 11 | TH 47 | District 3 |
| 12 | TH 6 | District 3 |
| 13 | US 12 | District 3 |
| 14 | TH 47 | District 3 |
| 15 | US 12 | District 3 |
| 16 | TH 95 | District 3 |
| 17 | TH 210 | District 4 |
| 18 | TH 79 | District 4 |
| 19 | TH 34 | District 4 |
| 20 | TH 22 | District 8 |
| 21 | TH 68 | District 8 |
| 22 | TH 15 | District 8 |
| 23 | CR 116 | Hennepin |
| 24 | CR 116 | Hennepin |
| 25 | CSAH 92 | Hennepin |
| 26 | CR 116 | Hennepin |
| 27 | CSAH 6 | Olmsted |
| 28 | CSAH 3 | Olmsted |
| 29 | CSAH 5 | Olmsted |
| 30 | CSAH 3 | Olmsted |
| 31 | CSAH 1 | Olmsted |
| 32 | CSAH 19 | Olmsted |
| 33 | CSAH 8 | Scott |
| 34 | CSAH 8 | Scott |
| 35 | CR 79 | Scott |
| 36 | CSAH 3 | Scott |
| 37 | CSAH 5 | Scott |
| 38 | CSAH 10 | Scott |
| 39 | CSAH 9 | Sibley |
| 40 | CSAH 4 | Sibley |

# Appendix F
# Group and Sectional Efficiency for Tangential Sections

**Table 1 AP tangential sections**
**(Crash rates are in units: crashes per million vehicle miles per year)**

| Section | Number of crashes before | Number of crashes after | VMT before | VMT after | Actual crash rate before | Actual crash rate after | Sectional Efficiency |
|---|---|---|---|---|---|---|---|
| 1 | 7 | 5 | 2,088,968 | 3,037,530 | 3.4 | 1.6 | 0.53 |
| 2 | 5 | 10 | 4,223,415 | 5,552,334 | 1.2 | 1.8 | -0.50 |
| 3 | 6 | 7 | 2,779,110 | 6,504,300 | 2.2 | 1.1 | 0.50 |
| 4 | 23 | 36 | 5,584,500 | 8,303,750 | 4.1 | 4.3 | -0.05 |
| 5 | 0 | 3 | 773,800 | 1,131,500 | 0 | 2.7 | |
| 6 | 26 | 63 | 12,922,460 | 18,896,050 | 2 | 3.3 | -0.65 |
| 7 | 10 | 17 | 7,108,001 | 16,319,508 | 1.4 | 1 | 0.29 |
| 8 | 20 | 53 | 12,403,038 | 29,728,089 | 1.6 | 1.8 | -0.13 |
| 9 | 1 | 4 | 773,800 | 1,131,500 | 1.3 | 3.5 | -1.69 |
| 10 | 21 | 18 | 5,574,426 | 10,720,050 | 3.8 | 1.7 | 0.55 |
| 11 | 8 | 15 | 8,186,220 | 13,643,700 | 1 | 1.1 | -0.10 |
| 12 | 19 | 40 | 16,303,948 | 46,674,047 | 1.2 | 0.9 | 0.25 |
| 13 | 67 | 6 | 11,647,360 | 2,024,412 | 5.8 | 3 | 0.48 |
| 14 | 26 | 79 | 12,986,328 | 32,940,929 | 2 | 2.4 | -0.20 |
| 15 | 11 | 23 | 15,937,725 | 34,120,200 | 0.7 | 0.7 | 0.00 |
| 16 | 12 | 1 | 4,245,972 | 4,360,728 | 2.8 | 0.2 | 0.93 |
| 17 | 83 | 41 | 102,623,400 | 131,892,750 | 0.8 | 0.3 | 0.63 |
| 18 | 53 | 73 | 54,679,646 | 48,739,627 | 1 | 1.5 | -0.50 |
| 19 | 14 | 33 | 19,852,496 | 24,748,186 | 0.7 | 1.3 | -0.86 |
| 20 | 56 | 9 | 25,228,800 | 3,350,700 | 2.2 | 2.7 | -0.23 |
| 21 | 9 | 1 | 8,030,000 | 6,132,000 | 1.1 | 0.2 | 0.82 |
| Average | | | | | | | 0.0036 |

**Table 2 AE Tangential Sections**
**(Crash rates are in units: crashes per million vehicle miles per year)**

| Section | Number of crashes before | Number of crashes after | VMT before | VMT after | Actual crash rate before | Actual crash rate after | Sectional Efficiency |
|---|---|---|---|---|---|---|---|
| 1 | 16 | 19 | 13,933,875 | 31,583,450 | 1.1 | 0.6 | 0.45 |
| 2 | 140 | 33 | 81,784,236 | 26,767,640 | 1.7 | 1.2 | 0.29 |
| 3 | 10 | 8 | 19,003,725 | 6,263,400 | 0.5 | 1.3 | -1.6 |
| 4 | 34 | 32 | 16,197,240 | 20,434,890 | 2.1 | 1.6 | 0.24 |
| 5 | 25 | 5 | 8,598,093 | 4,430,315 | 2.9 | 1.1 | 0.6 |
| 6 | 14 | 4 | 6,648,840 | 3,830,310 | 2.1 | 1 | 0.52 |
| 7 | 68 | 18 | 40,996,800 | 21,637,200 | 1.7 | 0.8 | 0.53 |

**Table 3 PE Tangential Sections**
**(Crash rates are in units: crashes per million vehicle miles per year)**

| Section | Number of crashes before | Number of crashes after | VMT before | VMT after | Actual crash rate before | Actual crash rate after | Sectional Efficiency |
|---|---|---|---|---|---|---|---|
| 1 | 18 | 18 | 35,248,050 | 60,772,500 | 0.5 | 0.3 | 0.57 |
| 2 | 3 | 12 | 9,672,135 | 24,290,750 | 0.3 | 0.5 | 0.4 |
| 3 | 19 | 2 | 9,154,200 | 2,280,520 | 2.1 | 0.9 | -0.67 |
| 4 | 166 | 193 | 65,413,840 | 67,831,600 | 2.5 | 2.8 | -0.12 |
| 5 | 92 | 91 | 107,047,200 | 126,947,000 | 0.9 | 0.7 | 0.22 |

# Appendix G
# Fatality Rates and Seat Belt Usage in MN

| YEAR | FATALITY RATE (PER 100 MILLION VEHICLE MILES TRAVELLED) | SEAT BELT USAGE (%) |
|---:|---:|---:|
| 1975 | 3.04 | 20 |
| 1976 | 3 | 20 |
| 1977 | 3.05 | 20 |
| 1978 | 3.4 | 20 |
| 1979 | 3.04 | 20 |
| 1980 | 3.03 | 20 |
| 1981 | 2.67 | 20 |
| 1982 | 1.98 | 20 |
| 1983 | 1.83 | 20 |
| 1984 | 1.81 | 20 |
| 1985 | 1.84 | 20 |
| 1986 | 1.67 | 33 |
| 1987 | 1.51 | 32 |
| 1988 | 1.69 | 47 |
| 1989 | 1.61 | 44 |
| 1990 | 1.47 | 47 |
| 1991 | 1.35 | 53 |
| 1992 | 1.41 | 51 |
| 1993 | 1.27 | 55 |
| 1994 | 1.48 | 57 |
| 1995 | 1.35 | 65 |
| 1996 | 1.26 | 64 |
| 1997 | 1.28 | 65 |
| 1998 | 1.34 | 64 |
| 1999 | 1.24 | 72 |
| 2000 | 1.19 | 73 |
| 2001 | 1.07 | 74 |
| 2002 | 1.21 | 80 |
| 2003 | 1.18 | 79 |
| 2004 | 1 | 82 |
| 2005 | 0.99 | 84 |
| 2006 | 0.87 | 83 |
| 2007 | 0.89 | 88 |

# Appendix H
# Effective Efficiency of Vision-Based LDWS

**Table 1: As an Analogy to Seat Belts**

| YEAR | MARKET PENETRATION (%) | PESSIMISTIC BASE EFFICIENCY (%) | OPTIMISTIC BASE EFFICIENCY (%) | PESSIMISTIC EFFICIENCY (%) | OPTIMISTIC EFFICIENCY (%) |
|---|---|---|---|---|---|
| 2010 | 6 | 23 | 55 | 1.38 | 3.3 |
| 2011 | 10 | 23.25 | 55.5 | 2.325 | 5.55 |
| 2012 | 12 | 23.5 | 56 | 2.82 | 6.72 |
| 2013 | 14 | 23.75 | 56.5 | 3.325 | 7.91 |
| 2014 | 16 | 24 | 57 | 3.84 | 9.12 |
| 2015 | 18 | 24.25 | 57.5 | 4.365 | 10.35 |
| 2016 | 22 | 24.5 | 58 | 5.39 | 12.76 |
| 2017 | 32 | 24.75 | 58.5 | 7.92 | 18.72 |
| 2018 | 55 | 25 | 59 | 13.75 | 32.45 |
| 2019 | 57 | 25.25 | 59.5 | 14.3925 | 33.915 |
| 2020 | 65 | 25.5 | 60 | 16.575 | 39 |
| 2021 | 64 | 25.75 | 60.5 | 16.48 | 38.72 |
| 2022 | 65 | 26 | 61 | 16.9 | 39.65 |
| 2023 | 64 | 26.25 | 61.5 | 16.8 | 39.36 |
| 2024 | 72 | 26.5 | 62 | 19.08 | 44.64 |
| 2025 | 73 | 26.75 | 62.5 | 19.5275 | 45.625 |
| 2026 | 74 | 27 | 63 | 19.98 | 46.62 |
| 2027 | 80 | 27.25 | 63.5 | 21.8 | 50.8 |
| 2028 | 79 | 27.5 | 64 | 21.725 | 50.56 |
| 2029 | 82 | 27.75 | 64.5 | 22.755 | 52.89 |
| 2030 | 84 | 28 | 65 | 23.52 | 54.6 |

## Table 2: As an Analogy to ABS

| YEAR | MARKET PENETRATION (%) | PESSIMISTIC BASE EFFICIENCY (%) | OPTIMISTIC BASE EFFICIENCY (%) | PESSIMISTIC EFFICIENCY (%) | OPTIMISTIC EFFICIENCY (%) |
|---|---|---|---|---|---|
| 2010 | 3 | 23 | 55 | 0.69 | 1.65 |
| 2011 | 5 | 23.25 | 55.5 | 1.1625 | 2.775 |
| 2012 | 6 | 23.5 | 56 | 1.41 | 3.36 |
| 2013 | 7 | 23.75 | 56.5 | 1.6625 | 3.955 |
| 2014 | 8 | 24 | 57 | 1.92 | 4.56 |
| 2015 | 9 | 24.25 | 57.5 | 2.1825 | 5.175 |
| 2016 | 9.5 | 24.5 | 58 | 2.3275 | 5.51 |
| 2017 | 11 | 24.75 | 58.5 | 2.7225 | 6.435 |
| 2018 | 16 | 25 | 59 | 4 | 9.44 |
| 2019 | 32 | 25.25 | 59.5 | 8.08 | 19.04 |
| 2020 | 38 | 25.5 | 60 | 9.69 | 22.8 |
| 2021 | 47 | 25.75 | 60.5 | 12.1025 | 28.435 |
| 2022 | 50 | 26 | 61 | 13 | 30.5 |
| 2023 | 59 | 26.25 | 61.5 | 15.4875 | 36.285 |
| 2024 | 75 | 26.5 | 62 | 19.875 | 46.5 |
| 2025 | 75.5 | 26.75 | 62.5 | 20.19625 | 47.1875 |
| 2026 | 76 | 27 | 63 | 20.52 | 47.88 |
| 2027 | 76.5 | 27.25 | 63.5 | 20.84625 | 48.5775 |
| 2028 | 77 | 27.5 | 64 | 21.175 | 49.28 |
| 2029 | 77.5 | 27.75 | 64.5 | 21.50625 | 49.9875 |
| 2030 | 78 | 28 | 65 | 21.84 | 50.7 |

# Appendix I
# Effective Efficiency of DGPS-Based LDWS

**Table 1: As Analogy to Seat Belts**

| YEAR | MARKET PENETRATION (%) | PESSIMISTIC BASE EFFICIENCY (%) | OPTIMISTIC BASE EFFICIENCY (%) | PESSIMISTIC EFFICIENCY (%) | OPTIMISTIC EFFICIENCY (%) |
|---|---|---|---|---|---|
| 2010 | 6 | 33 | 65 | 1.98 | 3.9 |
| 2011 | 10 | 33.25 | 65.65 | 3.325 | 6.565 |
| 2012 | 12 | 33.5 | 66.3 | 4.02 | 7.956 |
| 2013 | 14 | 33.75 | 66.95 | 4.725 | 9.373 |
| 2014 | 16 | 34 | 67.6 | 5.44 | 10.816 |
| 2015 | 18 | 34.25 | 68.25 | 6.165 | 12.285 |
| 2016 | 22 | 34.5 | 68.9 | 7.59 | 15.158 |
| 2017 | 32 | 34.75 | 69.55 | 11.12 | 22.256 |
| 2018 | 55 | 35 | 70.2 | 19.25 | 38.61 |
| 2019 | 57 | 35.25 | 70.85 | 20.0925 | 40.3845 |
| 2020 | 65 | 35.5 | 71.5 | 23.075 | 46.475 |
| 2021 | 64 | 35.75 | 72.15 | 22.88 | 46.176 |
| 2022 | 65 | 36 | 72.8 | 23.4 | 47.32 |
| 2023 | 64 | 36.25 | 73.45 | 23.2 | 47.008 |
| 2024 | 72 | 36.5 | 74.1 | 26.28 | 53.352 |
| 2025 | 73 | 36.75 | 74.75 | 26.8275 | 54.5675 |
| 2026 | 74 | 37 | 75.4 | 27.38 | 55.796 |
| 2027 | 80 | 37.25 | 76.05 | 29.8 | 60.84 |
| 2028 | 79 | 37.5 | 76.7 | 29.625 | 60.593 |
| 2029 | 82 | 37.75 | 77.35 | 30.955 | 63.427 |
| 2030 | 84 | 38 | 78 | 31.92 | 65.52 |

**Table 2: As an Analogy to ABS**

| YEAR | MARKET PENETRATION (%) | PESSIMISTIC BASE EFFICIENCY (%) | OPTIMISTIC BASE EFFICIENCY (%) | PESSIMISTIC EFFICIENCY (%) | OPTIMISTIC EFFICIENCY (%) |
|---|---|---|---|---|---|
| 2010 | 3 | 33 | 65 | 0.99 | 1.95 |
| 2011 | 5 | 33.25 | 65.65 | 1.6625 | 3.2825 |
| 2012 | 6 | 33.5 | 66.3 | 2.01 | 3.978 |
| 2013 | 7 | 33.75 | 66.95 | 2.3625 | 4.6865 |
| 2014 | 8 | 34 | 67.6 | 2.72 | 5.408 |
| 2015 | 9 | 34.25 | 68.25 | 3.0825 | 6.1425 |
| 2016 | 9.5 | 34.5 | 68.9 | 3.2775 | 6.5455 |
| 2017 | 11 | 34.75 | 69.55 | 3.8225 | 7.6505 |
| 2018 | 16 | 35 | 70.2 | 5.6 | 11.232 |
| 2019 | 32 | 35.25 | 70.85 | 11.28 | 22.672 |
| 2020 | 38 | 35.5 | 71.5 | 13.49 | 27.17 |
| 2021 | 47 | 35.75 | 72.15 | 16.8025 | 33.9105 |
| 2022 | 50 | 36 | 72.8 | 18 | 36.4 |
| 2023 | 59 | 36.25 | 73.45 | 21.3875 | 43.3355 |
| 2024 | 75 | 36.5 | 74.1 | 27.375 | 55.575 |
| 2025 | 75.5 | 36.75 | 74.75 | 27.74625 | 56.43625 |
| 2026 | 76 | 37 | 75.4 | 28.12 | 57.304 |
| 2027 | 76.5 | 37.25 | 76.05 | 28.49625 | 58.17825 |
| 2028 | 77 | 37.5 | 76.7 | 28.875 | 59.059 |
| 2029 | 77.5 | 37.75 | 77.35 | 29.25625 | 59.94625 |
| 2030 | 78 | 38 | 78 | 29.64 | 60.84 |

# Appendix J
# Cost Modeling

## Table 1: Vision-Based LDWS

| YEAR | VOLUME OF CARS IN MILLIONS | MP OF SEAT BELTS (%) | MP OF ABS (%) | NO OF CARS WITH SEAT BELTS IN MILLIONS | NO OF CARS WITH ABS IN MILLIONS | COST OF VISION BASED LDWS PER SEAT BELTS | COST OF VISION BASED LDWS AS PER ABS | COST OF ENTIRE FLEET WITH VISION BASED LDWS AS PER SEAT BELTS | COST OF ENTIRE FLEET VISION BASED LDWS AS PER ABS |
|---|---|---|---|---|---|---|---|---|---|
| 2010.00 | 3.58 | 1.00 | 0.00 | 0.04 | 0.04 | 500.00 | 500.00 | 17895000.00 | 18146500.00 |
| 2011.00 | 3.63 | 10.00 | 1.00 | 0.36 | 0.04 | 326.70 | 499.99 | 118570437.36 | 18146105.18 |
| 2012.00 | 3.68 | 12.00 | 2.00 | 0.44 | 0.07 | 312.03 | 453.79 | 137779300.40 | 33395494.62 |
| 2013.00 | 3.73 | 14.00 | 3.00 | 0.52 | 0.11 | 299.49 | 426.41 | 156387609.70 | 47713779.62 |
| 2014.00 | 3.78 | 16.00 | 5.00 | 0.60 | 0.19 | 288.49 | 392.15 | 174490891.74 | 74120305.99 |
| 2015.00 | 3.83 | 18.00 | 5.00 | 0.69 | 0.19 | 278.69 | 391.29 | 192157132.03 | 74941119.80 |
| 2016.00 | 3.88 | 22.00 | 7.00 | 0.85 | 0.27 | 262.71 | 368.45 | 224292457.52 | 100090388.18 |
| 2017.00 | 3.93 | 32.00 | 9.50 | 1.26 | 0.37 | 233.71 | 347.65 | 293998763.40 | 129830365.45 |
| 2018.00 | 3.98 | 55.00 | 16.00 | 2.19 | 0.64 | 192.24 | 312.75 | 420970543.90 | 199228904.60 |
| 2019.00 | 4.03 | 57.00 | 32.00 | 2.30 | 1.29 | 188.63 | 266.63 | 433491426.23 | 343993464.14 |
| 2020.00 | 4.08 | 65.00 | 38.00 | 2.65 | 1.55 | 177.88 | 254.59 | 471969247.22 | 394911610.50 |
| 2021.00 | 4.13 | 64.00 | 47.00 | 2.64 | 1.94 | 178.12 | 239.90 | 471078907.87 | 465929054.88 |
| 2022.00 | 4.18 | 65.00 | 50.00 | 2.72 | 2.09 | 176.06 | 235.07 | 478649210.69 | 491592882.93 |
| 2023.00 | 4.23 | 64.00 | 59.00 | 2.71 | 2.50 | 176.32 | 223.47 | 477672501.58 | 558091721.56 |
| 2024.00 | 4.28 | 72.00 | 75.00 | 3.08 | 3.21 | 166.63 | 207.02 | 513868619.20 | 665016119.02 |
| 2025.00 | 4.33 | 73.00 | 75.50 | 3.16 | 3.27 | 164.72 | 205.82 | 521096826.82 | 673394317.84 |
| 2026.00 | 4.38 | 74.00 | 76.00 | 3.24 | 3.33 | 162.84 | 204.63 | 528263936.99 | 681772117.63 |
| 2027.00 | 4.43 | 80.00 | 76.50 | 3.55 | 3.39 | 156.16 | 203.46 | 553932570.91 | 690149017.56 |
| 2028.00 | 4.48 | 79.00 | 77.00 | 3.54 | 3.45 | 156.25 | 202.30 | 553557825.75 | 698524519.98 |
| 2029.00 | 4.53 | 82.00 | 77.50 | 3.72 | 3.51 | 152.63 | 201.14 | 567552948.55 | 706898130.31 |
| 2030.00 | 4.58 | 84.00 | 78.00 | 3.85 | 3.58 | 150.00 | 200.00 | 577710000.00 | 715260000.00 |

## Table 2: DGPS-Based LDWS

| YEAR | VOLUME OF CARS IN MILLIONS | MP OF SEAT BELTS (%) | MP OF ABS (%) | NO OF CARS WITH SEAT BELTS IN MILLIONS | NO OF CARS WITH ABS IN MILLIONS | COST OF DGPS AS PER SEAT BELTS | COST OF DGPS AS PER ABS | COST OF ENTIRE FLEET WITH DGPS BASED LDWS AS PER SEAT BELTS | COST OF ENTIRE FLEET WITH DGPS BASED LDWS AS PER ABS |
|---|---|---|---|---|---|---|---|---|---|
| 2010 | 3.58 | 1.00 | 0.00 | 0.04 | 0.04 | 8000.00 | 8000.00 | 286320000.00 | 290344000.00 |
| 2011 | 3.63 | 10.00 | 1.00 | 0.36 | 0.04 | 4286.31 | 8000.30 | 1555631619.61 | 290354846.18 |
| 2012 | 3.68 | 12.00 | 2.00 | 0.44 | 0.07 | 3971.99 | 6922.26 | 1753839049.05 | 509422877.42 |
| 2013 | 3.73 | 14.00 | 3.00 | 0.52 | 0.11 | 3703.12 | 6283.22 | 1933717152.26 | 703073370.13 |
| 2014 | 3.78 | 16.00 | 5.00 | 0.60 | 0.19 | 3467.60 | 5483.78 | 2097312834.18 | 1036489620.09 |
| 2015 | 3.83 | 18.00 | 5.00 | 0.69 | 0.19 | 3257.60 | 5463.62 | 2246082862.18 | 1046420551.96 |
| 2016 | 3.88 | 22.00 | 7.00 | 0.85 | 0.27 | 2915.01 | 4930.61 | 2488767731.61 | 1339429395.29 |
| 2017 | 3.93 | 32.00 | 9.50 | 1.26 | 0.37 | 2293.74 | 4445.26 | 2885409212.78 | 1660103333.31 |
| 2018 | 3.98 | 55.00 | 16.00 | 2.19 | 0.64 | 1405.17 | 3630.90 | 3077008276.58 | 2312967651.41 |
| 2019 | 4.03 | 57.00 | 32.00 | 2.30 | 1.29 | 1327.79 | 2554.70 | 3051360079.36 | 3295931385.02 |
| 2020 | 4.08 | 65.00 | 38.00 | 2.65 | 1.55 | 1097.39 | 2273.72 | 2911694141.89 | 3526904084.26 |
| 2021 | 4.13 | 64.00 | 47.00 | 2.64 | 1.94 | 1102.61 | 1930.89 | 2916034068.19 | 3750132740.19 |
| 2022 | 4.18 | 65.00 | 50.00 | 2.72 | 2.09 | 1058.36 | 1818.08 | 2877350885.90 | 3802143446.52 |
| 2023 | 4.23 | 64.00 | 59.00 | 2.71 | 2.50 | 1064.05 | 1547.44 | 2882570559.30 | 3864585541.81 |
| 2024 | 4.28 | 72.00 | 75.00 | 3.08 | 3.21 | 856.31 | 1163.50 | 2640769471.06 | 3737617955.44 |
| 2025 | 4.33 | 73.00 | 75.50 | 3.16 | 3.27 | 815.48 | 1135.56 | 2579738554.20 | 3715315219.70 |
| 2026 | 4.38 | 74.00 | 76.00 | 3.24 | 3.33 | 775.17 | 1107.89 | 2514668019.04 | 3691158475.22 |
| 2027 | 4.43 | 80.00 | 76.50 | 3.55 | 3.39 | 631.91 | 1080.50 | 2241567651.68 | 3665136035.18 |
| 2028 | 4.48 | 79.00 | 77.00 | 3.54 | 3.45 | 633.99 | 1053.36 | 2246033750.87 | 3637236285.99 |
| 2029 | 4.53 | 82.00 | 77.50 | 3.72 | 3.51 | 556.37 | 1026.48 | 2068826179.51 | 3607447686.76 |
| 2030 | 4.58 | 84.00 | 78.00 | 3.85 | 3.58 | 500.00 | 1000.00 | 1925700000.00 | 3576300000.00 |

# Appendix K
# Benefit:Cost Ratio

# Table 1: 10 Year Analysis for Safety Systems for Curves

| Solution | Efficiency | Preventing 1 crash out of 'y' | Saving 1 life in 'x' years | Service Life | No of fatals prevented in 10 years | Costs | Additional costs | Total costs for 204 curves | Benefit at end of 10 years | NPV of benefit |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | |
| **Rumble Strips** | 0.15 | 7 | 8 | 10 | 2.00 | $3,000 per mile | 0.00 | $105,000.00 | $13,600,000.00 | $9,548,636.36 |
| | | | | | 1.00 | | 0.00 | $105,000.00 | $6,800,000.00 | $4,774,318.18 |
| | | | | | | | | | | |
| **Curve Flattening** | 0.66 | 2 | 3 | 20 | 4.00 | $300,000.00 | 0.00 | $61,200,000.00 | $27,200,000.00 | $19,097,272.71 |
| | | | | | 3.00 | $300,000.00 | | $61,200,000.00 | $20,400,000.00 | $14,322,954.53 |
| | | | | | | | | | | |
| **Chevrons** | 0.20 | 5 | 6 | 15 | 2.00 | $1,000.00 | 0.00 | $204,000.00 | $13,600,000.00 | $9,548,636.36 |
| | | | | | 1.00 | | | $204,000.00 | $6,800,000.00 | $4,774,318.18 |
| | | | | | | | | | | |
| **Static Curve Warning Sign** | 0.18 | 6 | 7 | 7 | 2.00 | $170.00 | Replacement after 7 years=120/(1.036^8) | $53,127.32 | $13,600,000.00 | $9,548,636.36 |
| | | | | | 1.00 | | | $53,127.32 | $6,800,000.00 | $4,774,318.18 |
| | | | | | | | | | | |
| **Static Curve Speed Warning Sign** | 0.22 | 5 | 6 | 7 | 2.00 | $230.00 | Replacement after 7 years=230/(1.036^8) | $74,590.99 | $13,600,000.00 | $9,548,636.36 |
| | | | | | 1.00 | | | $74,590.99 | $6,800,000.00 | $4,774,318.18 |
| | | | | | | | | | | |
| **Dynamic Curve Speed Warning Signs** | 0.30 | 3 | 4 | 20 | 3.00 | $12,000.00 | 160 for battery replacement after very 4 years= 160/1.036^5 + 160/1.036^9+160/1.036^13+160/1.036^17 | $2,499,091.35 | $20,400,000.00 | $14,322,954.53 |
| | | | | | 2.00 | | | $2,499,091.35 | $13,600,000.00 | $9,548,636.36 |

# Table 2: 20 Year Analysis for Safety Systems for Curves

| Solution | Efficiency | Preventing 1 crash out of 'y' | Saving 1 life in 'x' years | Service Life | No of fatals prevented in 20 years | Costs | Additional costs | Total costs for 204 curves | Benefit at end of 20 years | NPV of benefit |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | |
| Rumble Strips | 0.15 | 7.00 | 8 | 10 | 3 | $3,000 per mile | (3000*35)/(1.036^10) | $178,721.09 | $20,400,000.00 | $10,056,226.79 |
| | | | | | 2 | | (3000*35)/(1.036^10) | $178,721.09 | $13,600,000.00 | $6,704,151.20 |
| | | | | | | | | | | |
| Curve Flattening | 0.66 | 2.00 | 3 | 20 | 7 | $300,000.00 | 0.00 | $61,200,000.00 | $47,600,000.00 | $23,464,529.19 |
| | | | | | 6 | $300,000.00 | | $61,200,000.00 | $40,800,000.00 | $20,112,453.59 |
| | | | | | | | | | | |
| Chevrons | 0.20 | 5.00 | 6 | 14 | 4 | $1,000.00 | replacement after 15 years = 1000/1.036^16= 567.86 | $319,843.44 | $27,200,000.00 | $13,408,302.39 |
| | | | | | 3 | | | $319,843.44 | $20,400,000.00 | $10,056,226.79 |
| | | | | | | | | | | |
| Static Curve Warning Sign | 0.18 | 5.56 | 7 | 7 | 3 | $170.00 | 120/1.036^8 +120/1.036^15 | $67,529.07 | $20,400,000.00 | $10,056,226.79 |
| | | | | | 2 | | | $67,529.07 | $13,600,000.00 | $6,704,151.20 |
| | | | | | | | | | | |
| Static Curve Speed Warning Sign | 0.22 | 5.00 | 6 | 7 | 4 | $230.00 | Replacement after 7 years=230/(1.036^8)+230/(1.036^15) | $96,193.60 | $27,200,000.00 | $13,408,302.39 |
| | | | | | 3 | | | $96,193.60 | $20,400,000.00 | $10,056,226.79 |
| | | | | | | | | | | |
| Dynamic Curve Warning Signs | 0.30 | 3.00 | 4 | 20 | 5 | $12,000.00 | 160 for battery replacement after very 4 years= 160/1.036^5 + 160/1.036^9 | $2,537,592.12 | $34,000,000.00 | $16,760,377.99 |

## Table 3: 10 Year Analysis for Infrastructure-Based Treatments for Tangential Sections

| **WIDTH** | **MILES** | **FATAL CRASH RATE** | **NO. OF FATAL CRASHES EXPOSED TO** | **NO OF FATAL CRASHES PREVENTED** | **NO OF FATAL CRASHES PREVENTED TO IN 10 YEARS** | **COST** | **BENEFIT AT END OF 10 YEARS** | **NPV OF BENEFITS** | **BENEFIT:COST RATIO** |
|---|---|---|---|---|---|---|---|---|---|
| **AGGREGATE TO ENHANCED** | | | | | | | | | |
| 0 TO 2 ft | 115.80 | 0.03 | 0.55 | 0.24 | 2.43 | 347,400.00 | 16,548,919.19 | 11,619,089.08 | 33.45 |
| 2 TO 4 ft | 86.90 | 0.01 | 0.14 | 0.06 | 0.61 | 260,700.00 | 4,139,611.62 | 2,906,444.56 | 11.15 |
| 4 TO 6 ft | 39.90 | 0.02 | 0.13 | 0.06 | 0.56 | 119,700.00 | 3,801,392.49 | 2,668,979.01 | 22.30 |
| 6 TO 8 ft | 60.80 | 0.01 | 0.10 | 0.04 | 0.43 | 182,400.00 | 2,896,299.04 | 2,033,507.82 | 11.15 |
| 8 TO 10 ft | 12.00 | 0.02 | 0.04 | 0.02 | 0.17 | 36,000.00 | 1,143,275.94 | 802,700.45 | 22.30 |
| **PAVED TO ENHANCED** | | | | | | | | | |
| 0 TO 2 ft | 13.10 | 0.04 | 0.26 | 0.07 | 0.69 | 39,300.00 | 4,684,438.61 | 3,288,970.65 | 83.69 |
| 2 TO 4 ft | 23.40 | 0.04 | 0.46 | 0.12 | 1.23 | 70,200.00 | 8,367,623.17 | 5,874,955.20 | 83.69 |
| 6 TO 8 ft | 63.60 | 0.02 | 0.62 | 0.17 | 1.67 | 190,800.00 | 11,371,385.33 | 7,983,913.48 | 41.84 |
| 8 TO 10 ft | 55.90 | 0.01 | 0.27 | 0.07 | 0.73 | 167,700.00 | 4,997,330.50 | 3,508,653.80 | 20.92 |

## Table 4: 20 Year Analysis for Infrastructure-Based Treatments for Tangential Sections

| WIDTH | MILES | FATAL CRASH RATE | NO. OF FATAL CRASHES EXPOSED TO | NO OF FATAL CRASHES PREVENTED | NO OF FATAL CRASHES PREVENTED TO IN 20 YEARS | INITIAL COST | COST OF RE-ENHANCING AFTER 10 YEARS | TOTAL COST | BENEFIT AT END OF 20 YEARS | NPV OF BENEFITS | BENEFIT: COST RATIO |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **AGGREGATE TO ENHANCED** | | | | | | | | | | | |
| 0 TO 2 ft | 115.80 | 0.03 | 0.55 | 0.24 | 4.87 | 347,400.00 | 235,435.80 | 582,835.80 | 33,097,838.38 | 16,315,655.35 | 27.99 |
| 2 TO 4 ft | 86.90 | 0.01 | 0.14 | 0.06 | 1.22 | 260,700.00 | 176,678.51 | 437,378.51 | 8,279,223.25 | 4,081,262.09 | 9.33 |
| 4 TO 6 ft | 39.90 | 0.02 | 0.13 | 0.06 | 1.12 | 119,700.00 | 81,121.66 | 200,821.66 | 7,602,784.98 | 3,747,810.30 | 18.66 |
| 6 TO 8 ft | 60.80 | 0.01 | 0.10 | 0.04 | 0.85 | 182,400.00 | 123,613.96 | 306,013.96 | 5,792,598.08 | 2,855,474.51 | 9.33 |
| 8 TO 10 ft | 12.00 | 0.02 | 0.04 | 0.02 | 0.34 | 36,000.00 | 24,397.49 | 60,397.49 | 2,286,551.87 | 1,127,160.99 | 18.66 |
| **PAVED TO ENHANCED** | | | | | | | | | | | |
| 0 TO 2 ft | 13.10 | 0.04 | 0.26 | 0.07 | 1.38 | 39,300.00 | 26,633.93 | 65,933.93 | 9,368,877.22 | 4,618,409.52 | 70.05 |
| 2 TO 4 ft | 23.40 | 0.04 | 0.46 | 0.12 | 2.46 | 70,200.00 | 47,575.11 | 117,775.11 | 16,735,246.33 | 8,249,678.07 | 70.05 |
| 6 TO 8 ft | 63.60 | 0.02 | 0.62 | 0.17 | 3.34 | 190,800.00 | 129,306.71 | 320,106.71 | 22,742,770.66 | 11,211,100.96 | 35.02 |
| 8 TO 10 ft | 55.90 | 0.01 | 0.27 | 0.07 | 1.47 | 167,700.00 | 113,651.65 | 281,351.65 | 9,994,661.00 | 4,926,891.07 | 17.51 |

## Table 5: Vision-Based Lane Departure Warning Systems

| MANDATORY | | | | | |
|---|---|---|---|---|---|
| **Optimistic efficiency** | **NO OF FATALITIES PREVENTED EACH YEAR (optimistic)** | **No of fatalities prevented cumulative** | **BENEFITS (Optimistic)** | **COSTS FOR ENTIRE FLEET (Seat Belt)** | **BENEFIT:COST RATIO (optimistic)** |
| 3.3 | 8.349 | 8.349 | 56,773,200 | 17,895,000 | 3.17257334 |
| 5.55 | 14.0415 | 22.3905 | 152,255,400 | 118,570,437 | 1.28409242 |
| 6.72 | 17.0016 | 39.3921 | 267,866,280 | 137,779,300 | 1.94416926 |
| 7.91 | 20.0123 | 59.4044 | 403,949,920 | 156,387,610 | 2.58300463 |
| 9.12 | 23.0736 | 82.478 | 560,850,400 | 174,490,892 | 3.21421018 |
| 10.35 | 26.1855 | 108.6635 | 738,911,800 | 192,157,132 | 3.84535194 |
| 12.76 | 32.2828 | 140.9463 | 958,434,840 | 224,292,458 | 4.27314788 |
| 18.72 | 47.3616 | 188.3079 | 1,280,493,720 | 293,998,763 | 4.35543914 |
| 32.45 | 82.0985 | 270.4064 | 1,838,763,520 | 420,970,544 | 4.36791492 |
| 33.915 | 85.80495 | 356.21135 | 2,422,237,180 | 433,491,426 | 5.58773953 |
| 39 | 98.67 | 454.88135 | 3,093,193,180 | 471,969,247 | 6.55380239 |
| 38.72 | 97.9616 | 552.84295 | 3,759,332,060 | 471,078,908 | 7.98025978 |
| 39.65 | 100.3145 | 653.15745 | 4,441,470,660 | 478,649,211 | 9.27917682 |
| 39.36 | 99.5808 | 752.73825 | 5,118,620,100 | 477,672,502 | 10.7157521 |
| 44.64 | 112.9392 | 865.67745 | 5,886,606,660 | 513,868,619 | 11.4554702 |
| 45.625 | 115.43125 | 981.1087 | 6,671,539,160 | 521,096,827 | 12.8028781 |
| 46.62 | 117.9486 | 1099.0573 | 7,473,589,640 | 528,263,937 | 14.1474538 |
| 50.8 | 128.524 | 1227.5813 | 8,347,552,840 | 553,932,571 | 15.0696191 |
| 50.56 | 127.9168 | 1355.4981 | 9,217,387,080 | 553,557,826 | 16.6511729 |
| 52.89 | 133.8117 | 1489.3098 | 10,127,306,640 | 567,552,949 | 17.8438094 |
| 54.6 | 138.138 | 1627.4478 | 11,066,645,040 | 577,710,000 | 19.1560559 |
| | | | | | |
| Pessimistic efficiency | NO OF FATALITIES PREVENTED EACH YEAR (pessimistic) | No of fatalities prevented cumulative (pessimistic) | BENEFITS (pessimistic) | COSTS FOR ENTIRE FLEET (Seat Belt) | BENEFIT:COST RATIO (Seat Belt pessimistic) |
| 1.38 | 3.4914 | 3.4914 | 23,741,520 | 17,895,000 | 1.32671249 |
| 2.325 | 5.88225 | 9.37365 | 63,740,820 | 118,570,437 | 0.53757767 |
| 2.82 | 7.1346 | 16.50825 | 112,256,100 | 137,779,300 | 0.81475301 |
| 3.325 | 8.41225 | 24.9205 | 169,459,400 | 156,387,610 | 1.08358584 |
| 3.84 | 9.7152 | 34.6357 | 235,522,760 | 174,490,892 | 1.34977108 |
| 4.365 | 11.04345 | 45.67915 | 310,618,220 | 192,157,132 | 1.61648031 |
| 5.39 | 13.6367 | 59.31585 | 403,347,780 | 224,292,458 | 1.79831183 |
| 7.92 | 20.0376 | 79.35345 | 539,603,460 | 293,998,763 | 1.83539364 |
| 13.75 | 34.7875 | 114.14095 | 776,158,460 | 420,970,544 | 1.84373579 |
| 14.3925 | 36.413025 | 150.553975 | 1,023,767,030 | 433,491,426 | 2.36167769 |
| 16.575 | 41.93475 | 192.488725 | 1,308,923,330 | 471,969,247 | 2.77332334 |
| 16.48 | 41.6944 | 234.183125 | 1,592,445,250 | 471,078,908 | 3.38042146 |
| 16.9 | 42.757 | 276.940125 | 1,883,192,850 | 478,649,211 | 3.93439038 |
| 16.8 | 42.504 | 319.444125 | 2,172,220,050 | 477,672,502 | 4.5475091 |

| | | | | | |
|---|---|---|---|---|---|
| 19.08 | 48.2724 | 367.716525 | 2,500,472,370 | 513,868,619 | 4.865976 |
| 19.5275 | 49.404575 | 417.1211 | 2,836,423,480 | 521,096,827 | 5.44317934 |
| 19.98 | 50.5494 | 467.6705 | 3,180,159,400 | 528,263,937 | 6.02001988 |
| 21.8 | 55.154 | 522.8245 | 3,555,206,600 | 553,932,571 | 6.4181216 |
| 21.725 | 54.96425 | 577.78875 | 3,928,963,500 | 553,557,826 | 7.09765686 |
| 22.755 | 57.57015 | 635.3589 | 4,320,440,520 | 567,552,949 | 7.6124008 |
| 23.52 | 59.5056 | 694.8645 | 4,725,078,600 | 577,710,000 | 8.17898011 |
| | | | | | |
| Non-Mandatory | | | | | |
| Optimistic efficiency | NO OF FATALITIES PREVENTED EACH YEAR (optimistic) | No of fatalities prevented cumulative | BENEFITS (Optimistic) | COSTS FOR ENTIRE FLEET (ABS) | BENEFIT:COST RATIO (ABS optimistic) |
| 1.65 | 4.1745 | 4.1745 | 28,386,600 | 18,146,500 | 1.56430166 |
| 2.775 | 7.02075 | 11.19525 | 76,127,700 | 18,146,105 | 4.1952639 |
| 3.36 | 8.5008 | 19.69605 | 133,933,140 | 33,395,495 | 4.01051524 |
| 3.955 | 10.00615 | 29.7022 | 201,974,960 | 47,713,780 | 4.23305304 |
| 4.56 | 11.5368 | 41.239 | 280,425,200 | 74,120,306 | 3.78337888 |
| 5.175 | 13.09275 | 54.33175 | 369,455,900 | 74,941,120 | 4.92994902 |
| 5.51 | 13.9403 | 68.27205 | 464,249,940 | 100,090,388 | 4.63830692 |
| 6.435 | 16.28055 | 84.5526 | 574,957,680 | 129,830,365 | 4.42853009 |
| 9.44 | 23.8832 | 108.4358 | 737,363,440 | 199,228,905 | 3.70108665 |
| 19.04 | 48.1712 | 156.607 | 1,064,927,600 | 343,993,464 | 3.09577859 |
| 22.8 | 57.684 | 214.291 | 1,457,178,800 | 394,911,610 | 3.68988594 |
| 28.435 | 71.94055 | 286.23155 | 1,946,374,540 | 465,929,055 | 4.17740538 |
| 30.5 | 77.165 | 363.39655 | 2,471,096,540 | 491,592,883 | 5.02671342 |
| 36.285 | 91.80105 | 455.1976 | 3,095,343,680 | 558,091,722 | 5.54629922 |
| 46.5 | 117.645 | 572.8426 | 3,895,329,680 | 665,016,119 | 5.85749664 |
| 47.1875 | 119.384375 | 692.226975 | 4,707,143,430 | 673,394,318 | 6.99017397 |
| 47.88 | 121.1364 | 813.363375 | 5,530,870,950 | 681,772,118 | 8.11249215 |
| 48.5775 | 122.901075 | 936.26445 | 6,366,598,260 | 690,149,018 | 9.22496171 |
| 49.28 | 124.6784 | 1060.94285 | 7,214,411,380 | 698,524,520 | 10.3280718 |
| 49.9875 | 126.468375 | 1187.41123 | 8,074,396,330 | 706,898,130 | 11.4222913 |
| 50.7 | 128.271 | 1315.68223 | 8,946,639,130 | 715,260,000 | 12.5082336 |
| | | | | | |
| Pessimistic efficiency | NO OF FATALITIES PREVENTED EACH YEAR (pessimistic) | No of fatalities prevented cumulative (pessimistic) | BENEFITS (pessimistic) | COSTS FOR ENTIRE FLEET (ABS) | BENEFIT:COST RATIO (ABS pessimistic) |
| 0.69 | 1.7457 | 1.7457 | 11,870,760 | 18,146,500 | 0.65416251 |
| 1.1625 | 2.941125 | 4.686825 | 31,870,410 | 18,146,105 | 1.75632235 |
| 1.41 | 3.5673 | 8.254125 | 56,128,050 | 33,395,495 | 1.68070725 |
| 1.6625 | 4.206125 | 12.46025 | 84,729,700 | 47,713,780 | 1.77579099 |
| 1.92 | 4.8576 | 17.31785 | 117,761,380 | 74,120,306 | 1.58878702 |
| 2.1825 | 5.521725 | 22.839575 | 155,309,110 | 74,941,120 | 2.07241512 |
| 2.3275 | 5.888575 | 28.72815 | 195,351,420 | 100,090,388 | 1.95175005 |
| 2.7225 | 6.887925 | 35.616075 | 242,189,310 | 129,830,365 | 1.86542886 |

|  |  |  |  |  |  |
|---|---|---|---|---|---|
| 4 | 10.12 | 45.736075 | 311,005,310 | 199,228,905 | 1.56104512 |
| 8.08 | 20.4424 | 66.178475 | 450,013,630 | 343,993,464 | 1.30820401 |
| 9.69 | 24.5157 | 90.694175 | 616,720,390 | 394,911,610 | 1.5616669 |
| 12.1025 | 30.619325 | 121.3135 | 824,931,800 | 465,929,055 | 1.77050946 |
| 13 | 32.89 | 154.2035 | 1,048,583,800 | 491,592,883 | 2.13303291 |
| 15.4875 | 39.183375 | 193.386875 | 1,315,030,750 | 558,091,722 | 2.35629861 |
| 19.875 | 50.28375 | 243.670625 | 1,656,960,250 | 665,016,119 | 2.49160915 |
| 20.19625 | 51.0965125 | 294.767138 | 2,004,416,535 | 673,394,318 | 2.97658665 |
| 20.52 | 51.9156 | 346.682738 | 2,357,442,615 | 681,772,118 | 3.45781611 |
| 20.84625 | 52.7410125 | 399.42375 | 2,716,081,500 | 690,149,018 | 3.93550006 |
| 21.175 | 53.57275 | 452.9965 | 3,080,376,200 | 698,524,520 | 4.4098326 |
| 21.50625 | 54.4108125 | 507.407313 | 3,450,369,725 | 706,898,130 | 4.88099993 |
| 21.84 | 55.2552 | 562.662513 | 3,826,105,085 | 715,260,000 | 5.34925074 |

## Table 6: DGPS-Based Lane Departure Warning Systems

| MANDATORY | | | | | |
|---|---|---|---|---|---|
| Optimistic efficiency | NO OF FATALITIES PREVENTED EACH YEAR (optimistic) | No of fatalities prevented cumulative | BENEFITS (Optimistic) | COSTS FOR ENTIRE FLEET (Seat Belt) | BENEFIT:COST RATIO (Seat Belt optimistic) |
| 3.9 | 9.867 | 9.867 | 67,095,600 | 286,320,000 | 0.234337804 |
| 6.565 | 16.60945 | 26.47645 | 180,039,860 | 1,555,631,620 | 0.115734251 |
| 7.956 | 20.12868 | 46.60513 | 316,914,884 | 1,753,839,049 | 0.180697815 |
| 9.373 | 23.71369 | 70.31882 | 478,167,976 | 1,933,717,152 | 0.247279172 |
| 10.816 | 27.36448 | 97.6833 | 664,246,440 | 2,097,312,834 | 0.316713096 |
| 12.285 | 31.08105 | 128.7644 | 875,597,580 | 2,246,082,862 | 0.38983316 |
| 15.158 | 38.34974 | 167.1141 | 1,136,375,812 | 2,488,767,732 | 0.456601794 |
| 22.256 | 56.30768 | 223.4218 | 1,519,268,036 | 2,885,409,213 | 0.526534687 |
| 38.61 | 97.6833 | 321.1051 | 2,183,514,476 | 3,077,008,277 | 0.709622555 |
| 40.3845 | 102.1728 | 423.2779 | 2,878,289,414 | 3,051,360,079 | 0.943280812 |
| 46.475 | 117.5818 | 540.8596 | 3,677,845,314 | 2,911,694,142 | 1.263129001 |
| 46.176 | 116.8253 | 657.6849 | 4,472,257,218 | 2,916,034,068 | 1.533677973 |
| 47.32 | 119.7196 | 777.4045 | 5,286,350,498 | 2,877,350,886 | 1.837228307 |
| 47.008 | 118.9302 | 896.3347 | 6,095,076,130 | 2,882,570,559 | 2.114458607 |
| 53.352 | 134.9806 | 1031.315 | 7,012,943,938 | 2,640,769,471 | 2.655644128 |
| 54.5675 | 138.0558 | 1169.371 | 7,951,723,208 | 2,579,738,554 | 3.082375613 |
| 55.796 | 141.1639 | 1310.535 | 8,911,637,592 | 2,514,668,019 | 3.54386246 |
| 60.84 | 153.9252 | 1464.46 | 9,958,328,952 | 2,241,567,652 | 4.442573457 |
| 60.593 | 153.3003 | 1617.76 | 11,000,770,924 | 2,246,033,751 | 4.897865368 |
| 63.427 | 160.4703 | 1778.231 | 12,091,969,032 | 2,068,826,180 | 5.844845329 |
| 65.52 | 165.7656 | 1943.996 | 13,219,175,112 | 1,925,700,000 | 6.864607733 |
| | | | | | |
| Pessimistic efficiency | NO OF FATALITIES PREVENTED EACH YEAR (pessimistic) | No of fatalities prevented cumulative (pessimistic) | BENEFITS (pessimistic) | COSTS FOR ENTIRE FLEET (Seat Belt) | BENEFIT:COST RATIO (Seat Belt pessimistic) |
| 1.98 | 5.0094 | 3.4914 | 23,741,520 | 286,320,000 | 0.082919531 |
| 3.325 | 8.41225 | 11.90365 | 80,944,820 | 1,555,631,620 | 0.052033411 |
| 4.02 | 10.1706 | 22.07425 | 150,104,900 | 1,753,839,049 | 0.085586474 |
| 4.725 | 11.95425 | 34.0285 | 231,393,800 | 1,933,717,152 | 0.119662692 |
| 5.44 | 13.7632 | 47.7917 | 324,983,560 | 2,097,312,834 | 0.154952354 |
| 6.165 | 15.59745 | 63.38915 | 431,046,220 | 2,246,082,862 | 0.191910204 |
| 7.59 | 19.2027 | 82.59185 | 561,624,580 | 2,488,767,732 | 0.225663718 |
| 11.12 | 28.1336 | 110.7255 | 752,933,060 | 2,885,409,213 | 0.260944984 |
| 19.25 | 48.7025 | 159.428 | 1,084,110,060 | 3,077,008,277 | 0.352326014 |
| 20.0925 | 50.83403 | 210.262 | 1,429,781,430 | 3,051,360,079 | 0.468571848 |

| | | | | | |
|---|---|---|---|---|---|
| 23.075 | 58.37975 | 268.6417 | 1,826,763,730 | 2,911,694,142 | 0.627388606 |
| 22.88 | 57.8864 | 326.5281 | 2,220,391,250 | 2,916,034,068 | 0.76144215 |
| 23.4 | 59.202 | 385.7301 | 2,622,964,850 | 2,877,350,886 | 0.911590193 |
| 23.2 | 58.696 | 444.4261 | 3,022,097,650 | 2,882,570,559 | 1.048403704 |
| 26.28 | 66.4884 | 510.9145 | 3,474,218,770 | 2,640,769,471 | 1.315608503 |
| 26.8275 | 67.87358 | 578.7881 | 3,935,759,080 | 2,579,738,554 | 1.525642617 |
| 27.38 | 69.2714 | 648.0595 | 4,406,804,600 | 2,514,668,019 | 1.752439911 |
| 29.8 | 75.394 | 723.4535 | 4,919,483,800 | 2,241,567,652 | 2.194662203 |
| 29.625 | 74.95125 | 798.4048 | 5,429,152,300 | 2,246,033,751 | 2.417217594 |
| 30.955 | 78.31615 | 876.7209 | 5,961,702,120 | 2,068,826,180 | 2.881683429 |
| 31.92 | 80.7576 | 957.4785 | 6,510,853,800 | 1,925,700,000 | 3.381032248 |
| | | | | | |
| Non-Mandatory | | | | | |
| Optimistic efficiency | NO OF FATALITIES PREVENTED EACH YEAR (optimistic) | No of fatalities prevented cumulative | BENEFITS (Optimistic) | COSTS FOR ENTIRE FLEET (ABS) | BENEFIT:COST RATIO (ABS optimistic) |
| 3.9 | 9.867 | 8.349 | 56,773,200 | 290,344,000 | 0.195537707 |
| 6.565 | 16.60945 | 24.95845 | 169,717,460 | 290,354,846 | 0.584517401 |
| 7.956 | 20.12868 | 45.08713 | 306,592,484 | 509,422,877 | 0.601842786 |
| 9.373 | 23.71369 | 68.80082 | 467,845,576 | 703,073,370 | 0.665429237 |
| 10.816 | 27.36448 | 96.1653 | 653,924,040 | 1,036,489,620 | 0.630902642 |
| 12.285 | 31.08105 | 127.2464 | 865,275,180 | 1,046,420,552 | 0.826890468 |
| 15.158 | 38.34974 | 165.5961 | 1,126,053,412 | 1,339,429,395 | 0.840696356 |
| 22.256 | 56.30768 | 221.9038 | 1,508,945,636 | 1,660,103,333 | 0.908946814 |
| 38.61 | 97.6833 | 319.5871 | 2,173,192,076 | 2,312,967,651 | 0.939568729 |
| 40.3845 | 102.1728 | 421.7599 | 2,867,967,014 | 3,295,931,385 | 0.870153738 |
| 46.475 | 117.5818 | 539.3416 | 3,667,522,914 | 3,526,904,084 | 1.03987033 |
| 46.176 | 116.8253 | 656.1669 | 4,461,934,818 | 3,750,132,740 | 1.189807169 |
| 47.32 | 119.7196 | 775.8865 | 5,276,028,098 | 3,802,143,447 | 1.387645725 |
| 47.008 | 118.9302 | 894.8167 | 6,084,753,730 | 3,864,585,542 | 1.574490631 |
| 53.352 | 134.9806 | 1029.797 | 7,002,621,538 | 3,737,617,955 | 1.873551985 |
| 54.5675 | 138.0558 | 1167.853 | 7,941,400,808 | 3,715,315,220 | 2.137476994 |
| 55.796 | 141.1639 | 1309.017 | 8,901,315,192 | 3,691,158,475 | 2.411523442 |
| 60.84 | 153.9252 | 1462.942 | 9,948,006,552 | 3,665,136,035 | 2.714225736 |
| 60.593 | 153.3003 | 1616.242 | 10,990,448,524 | 3,637,236,286 | 3.021648213 |
| 63.427 | 160.4703 | 1776.713 | 12,081,646,632 | 3,607,447,687 | 3.349084361 |
| 65.52 | 165.7656 | 1942.478 | 13,208,852,712 | 3,576,300,000 | 3.693440906 |
| | | | | | |
| Pessimistic efficiency | NO OF FATALITIES PREVENTED EACH YEAR (pessimistic) | No of fatalities prevented cumulative (pessimistic) | BENEFITS (pessimistic) | COSTS FOR ENTIRE FLEET (ABS) | BENEFIT:COST RATIO (ABS pessimistic) |
| 1.98 | 5.0094 | 3.4914 | 23,741,520 | 290,344,000 | 0.081770314 |

| | | | | | |
|---|---|---|---|---|---|
| 3.325 | 8.41225 | 11.90365 | 80,944,820 | 290,354,846 | 0.278778953 |
| 4.02 | 10.1706 | 22.07425 | 150,104,900 | 509,422,877 | 0.294656771 |
| 4.725 | 11.95425 | 34.0285 | 231,393,800 | 703,073,370 | 0.329117571 |
| 5.44 | 13.7632 | 47.7917 | 324,983,560 | 1,036,489,620 | 0.313542513 |
| 6.165 | 15.59745 | 63.38915 | 431,046,220 | 1,046,420,552 | 0.411924459 |
| 7.59 | 19.2027 | 82.59185 | 561,624,580 | 1,339,429,395 | 0.41930137 |
| 11.12 | 28.1336 | 110.7255 | 752,933,060 | 1,660,103,333 | 0.4535459 |
| 19.25 | 48.7025 | 159.428 | 1,084,110,060 | 2,312,967,651 | 0.468709564 |
| 20.0925 | 50.83403 | 210.262 | 1,429,781,430 | 3,295,931,385 | 0.43380194 |
| 23.075 | 58.37975 | 268.6417 | 1,826,763,730 | 3,526,904,084 | 0.517951066 |
| 22.88 | 57.8864 | 326.5281 | 2,220,391,250 | 3,750,132,740 | 0.592083375 |
| 23.4 | 59.202 | 385.7301 | 2,622,964,850 | 3,802,143,447 | 0.689864779 |
| 23.2 | 58.696 | 444.4261 | 3,022,097,650 | 3,864,585,542 | 0.781997867 |
| 26.28 | 66.4884 | 510.9145 | 3,474,218,770 | 3,737,617,955 | 0.929527526 |
| 26.8275 | 67.87358 | 578.7881 | 3,935,759,080 | 3,715,315,220 | 1.059333824 |
| 27.38 | 69.2714 | 648.0595 | 4,406,804,600 | 3,691,158,475 | 1.19388117 |
| 29.8 | 75.394 | 723.4535 | 4,919,483,800 | 3,665,136,035 | 1.34223771 |
| 29.625 | 74.95125 | 798.4048 | 5,429,152,300 | 3,637,236,286 | 1.492658676 |
| 30.955 | 78.31615 | 876.7209 | 5,961,702,120 | 3,607,447,687 | 1.652609445 |
| 31.92 | 80.7576 | 957.4785 | 6,510,853,800 | 3,576,300,000 | 1.820555826 |

# Appendix L
# Towards TZD

**Table 1: Without budget constrains for curves**

| **Solution** | **Effectiveness** | **No of fatalities reduced at curves** | **Towards TZD** |
|---|---|---|---|
| Rumble Strips | 0.15 | 2.4 | 1.19% |
| Curve flattening | 0.66 | 10.56 | 5.22% |
| Chevrons | 0.2 | 0.8 | 1.34% |
| Dynamic Curve Speed Warning sign | 0.3 | 4.8 | 2.37% |

## Table 2: With Budget Constraint for Curves

| Treatment | Efficiency | No.of curves it can be implemented to in $1,600,000 | No of curves it can be implemented to in $400,000 | Total no of curves implemented to in $2,000,000 | No of fatalities exposed to | No of fatalities reduced | TZD for fixed amount (%) |
|---|---|---|---|---|---|---|---|
| Rumble Strips | 0.15 | 3109.00 | 777.14 | 3886.14 | 17.49 | 2.62 | 1.04 |
| Curve Flattening | 0.66 | 5.33 | 1.33 | 6.67 | 0.03 | 0.02 | 0.01 |
| Chevrons | 0.20 | 0.00 | 400.00 | 400.00 | 1.80 | 0.36 | 0.14 |
| Static Curve warning | 0.18 | 0.00 | 2352.94 | 2352.94 | 10.59 | 1.91 | 0.75 |
| Static Curve speed warning | 0.22 | 0.00 | 1739.13 | 1739.13 | 7.83 | 1.72 | 0.68 |
| Dynamic curve warning | 0.30 | 133.33 | 33.33 | 166.67 | 0.75 | 0.23 | 0.09 |

## Table 3: Deployment Factor for Enhancing Tangential Sections

| Year | No of miles enhanced | Number of fatalities exposed to every year | Number of fatalities prevented every year |
|---|---|---|---|
| 1 | 667 | 3.335 | 1.2006 |
| 2 | 1334 | 6.67 | 2.4012 |
| 3 | 2001 | 10.005 | 3.6018 |
| 4 | 2668 | 13.34 | 4.8024 |
| 5 | 3335 | 16.675 | 6.003 |
| 6 | 4002 | 20.01 | 7.2036 |
| 7 | 4669 | 23.345 | 8.4042 |
| 8 | 5336 | 26.68 | 9.6048 |
| 9 | 6003 | 30.015 | 10.8054 |
| 10 | 6670 | 33.35 | 12.006 |

## Table 4: Deployment Factor for In-Vehicle Technologies for Tangential Sections

**VISION-BASED LDWS**

**MANDATORY**

| YEAR | UNIT PRICE IN THAT YEAR | NO OF CARS WITH LDWS BASED ON UNIT PRICE IN THAT YEAR | TOTAL CUMULATIVE CARS | TOTAL NUMBER OF CARS IN MILLIONS | TOTAL NO OF FATALITIES EXPOSED TO | EFFICIENCY | NO OF FATALITIES PREVENTED |
|---|---|---|---|---|---|---|---|
| 1 | 500.00 | 4000 | 4000 | 3.58 | 0.28 | 55 | 0 |
| 2 | 326.70 | 6122 | 10122 | 3.63 | 0.71 | 55.5 | 0 |
| 3 | 312.03 | 6410 | 14122 | 3.68 | 0.97 | 56 | 1 |
| 4 | 299.49 | 6678 | 24244 | 3.73 | 1.64 | 56.5 | 1 |
| 5 | 288.49 | 6933 | 38365 | 3.78 | 2.57 | 57 | 1 |
| 6 | 278.69 | 7176 | 62609 | 3.83 | 4.14 | 57.5 | 2 |
| 7 | 262.71 | 7613 | 100974 | 3.88 | 6.58 | 58 | 4 |
| 8 | 233.71 | 8558 | 163583 | 3.93 | 10.53 | 58.5 | 6 |
| 9 | 192.24 | 10403 | 264557 | 3.98 | 16.82 | 59 | 10 |
| 10 | 188.63 | 10603 | 428140 | 4.03 | 26.88 | 59.5 | 16 |

**NON-MANDATORY**

| YEAR | UNIT PRICE IN THAT YEAR | NO OF CARS WITH LDWS BASED ON UNIT PRICE IN THAT YEAR | TOTAL CUMULATIVE CARS ASSUMING CARS LAST FOR 7 YEARS | TOTAL NUMBER OF CARS IN MILLIONS | TOTAL NO OF FATALITIES EXPOSED TO | EFFICIENCY | NO OF FATALITIES PREVENTED |
|---|---|---|---|---|---|---|---|
| 1 | 500.00 | 4000 | 4000 | 3.58 | 0.28 | 55 | 0 |
| 2 | 499.99 | 4000 | 8000 | 3.63 | 0.56 | 55.5 | 0 |
| 3 | 453.79 | 4407 | 12000 | 3.68 | 0.83 | 56 | 0 |
| 4 | 426.41 | 4690 | 20000 | 3.73 | 1.36 | 56.5 | 1 |
| 5 | 392.15 | 5100 | 32000 | 3.78 | 2.14 | 57 | 1 |
| 6 | 391.29 | 5111 | 52000 | 3.83 | 3.44 | 57.5 | 2 |
| 7 | 368.45 | 5428 | 84001 | 3.88 | 5.48 | 58 | 3 |
| 8 | 347.65 | 5753 | 136001 | 3.93 | 8.76 | 58.5 | 5 |
| 9 | 312.75 | 6395 | 220002 | 3.98 | 13.99 | 59 | 8 |
| 10 | 266.63 | 7501 | 356003 | 4.03 | 22.35 | 59.5 | 13 |

**MANDATORY**

| YEAR | UNIT PRICE IN THAT YEAR | NO OF CARS WITH LDWS BASED ON UNIT PRICE IN THAT YEAR | TOTAL CUMULATIVE CARS ASSUMING CARS LAST FOR 7 YEARS | TOTAL NUMBER OF CARS IN MILLIONS | TOTAL NO OF FATALITIES EXPOSED TO | EFFICIENCY | NO OF FATALITIES PREVENTED |
|---|---|---|---|---|---|---|---|
| 1 | 8000.00 | 250 | 250 | 3.58 | 0.02 | 65 | 0 |
| 2 | 4286.31 | 467 | 717 | 3.63 | 0.05 | 65.65 | 0 |
| 3 | 3971.99 | 504 | 967 | 3.68 | 0.07 | 66.3 | 0 |
| 4 | 3703.12 | 540 | 1683 | 3.73 | 0.11 | 66.95 | 0 |
| 5 | 3467.60 | 577 | 2650 | 3.78 | 0.18 | 67.6 | 0 |
| 6 | 3257.60 | 614 | 4333 | 3.83 | 0.29 | 68.25 | 0 |
| 7 | 2915.01 | 686 | 6983 | 3.88 | 0.46 | 68.9 | 0 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 8 | 2293.74 | 872 | 11316 | 3.93 | 0.73 | 69.55 | 1 |
| 9 | 1405.17 | 1423 | 18299 | 3.98 | 1.16 | 70.2 | 1 |
| 10 | 1327.79 | 1506 | 29614 | 4.03 | 1.86 | 70.85 | 1 |
| **NON-MANDATORY** | | | | | | | |
| **YEAR** | **UNIT PRICE IN THAT YEAR** | **NO OF CARS WITH LDWS BASED ON UNIT PRICE IN THAT YEAR** | **TOTAL CUMULATIVE CARS ASSUMING CARS LAST FOR 7 YEARS** | **TOTAL NUMBER OF CARS IN MILLIONS** | **TOTAL NO OF FATALITIES EXPOSED TO** | **EFFICIENCY** | **NO OF FATALITIES PREVENTED** |
| 1 | 8000.00 | 250 | 250 | 3.58 | 0.02 | 65 | 0 |
| 2 | 8000.30 | 250 | 500 | 3.63 | 0.03 | 65.65 | 0 |
| 3 | 6922.26 | 289 | 750 | 3.68 | 0.05 | 66.3 | 0 |
| 4 | 6283.22 | 318 | 1250 | 3.73 | 0.08 | 66.95 | 0 |
| 5 | 5483.78 | 365 | 2000 | 3.78 | 0.13 | 67.6 | 0 |
| 6 | 5463.62 | 366 | 3250 | 3.83 | 0.21 | 68.25 | 0 |
| 7 | 4930.61 | 406 | 5250 | 3.88 | 0.34 | 68.9 | 0 |
| 8 | 4445.26 | 450 | 8500 | 3.93 | 0.55 | 69.55 | 0 |
| 9 | 3630.90 | 551 | 13750 | 3.98 | 0.87 | 70.2 | 1 |
| 10 | 2554.70 | 783 | 22250 | 4.03 | 1.40 | 70.85 | 1 |