Comparison of In-Vehicle Technologies with Traditional Safety Measures to Prevent Crashes along Curves and Shoulders

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Dedication

This thesis is dedicated to my dad and mom.

Abstract

Five hundred and ten people were killed in the state of Minnesota in 2007. Using MN/Dot values for crashes this costs the state more than $3.5 billions. Forty percent of these fatal crashes are road departure crashes and they mainly occur on rural roads. To prevent these road departure crashes and reduce the financial losses occurring due to them, safety systems have to be implemented. There are two types of systems which could be implemented:

- Traditional civil engineering solutions such as adding rumble strips, curve flattening, shoulder paving etc.

- Emerging technology-based solutions. 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 if necessary the driver is warned. In-vehicle technologies include both vision-based and DGPS-based lane departure warning systems.

Owing to the limited budget and necessity in curtailing the number of fatal crashes, these safety systems have been compared and studied to suggest an optimal solution which would be cost-effective and also effective in reducing traffic fatalities due to lane departures.

Presented herein is a follow up on a research initiated by CH2MHill [1.]. A sample set of 204 curves and 137 tangential sections was studied by them. Their research mainly consisted of two parts:

- A cross-sectional study to evaluate the effect of road geometry such as curve radius, width of shoulders, etc. on road departure crashes.

- A before:after analysis which studies the effect of certain civil engineering treatments in form of crash rate on the road section before and after implementing the treatment.

Based on the cross-sectional and the before:after analysis, the traditional safety treatments identified on road sections were evaluated against new technology-based safety systems through the following approach:

- **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 effectiveness was quantified for each safety system using either the before:after analysis, values provided by FHWA or analogies drawn on reduction in fatalities due to existing technologies such as seat belts and ABS.

- **Exposure –** Effectiveness of any technology is always a function of its exposure. This exposure is measured in terms of the number of vehicle miles the system is exposed to, public acceptability and market penetration.

- **Cost-effectiveness –**It is necessary to implement safety systems which are cost-effective for the government as well as the public to ensure effective use of the financial resources. Any change on the roads is cost-effective for the state if the money spent on implementing the change is compensated for by the reduction in losses occurred to the state due to crashes and fatalities. 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 to move towards Mn/DOT's goal of Towards 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 highest effectiveness of 66%. However, curve flattening is among the most expensive safety treatment. Using effectiveness numbers from the 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.* Hence the deployment factor was calculated for all the remaining safety systems maintaining the static signs as the baseline. For a given fixed safety budget, adding rumble strips gives the highest reduced number of fatalities or the highest deployment factor.

Similarly, for tangential sections, enhancing them gave the highest deployment factor. Also, evaluation of the in-vehicle technologies showed that the vision-based lane departure warning systems have deployment factors comparable to that of enhancing the road sections.

These results were obtained based on the data set that has been the background for our research. The above approach however should not be limited to one particular data set and can be used by engineers as a generic tool and approach to evaluate different safety systems for their cost-effectiveness and contribution to reduction in fatalities.

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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…….*"[2.]

"*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.*"[3.]

"*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*."[4.]

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 [5.]. 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 [6.]. AASHTO claims 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. 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 [6.] which could be translated into reduction in crashes. 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 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). The highlight of the SHSP was reduction in number of fatal crashes [7.]

1.2 Problem Statement

In the year 2007, 510 people died in the state of Minnesota due to traffic fatalities and 35318 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. Monetary values are assigned to them in Figure 1.1. A, B and C are severity types of crashes and PDO is property damage only.

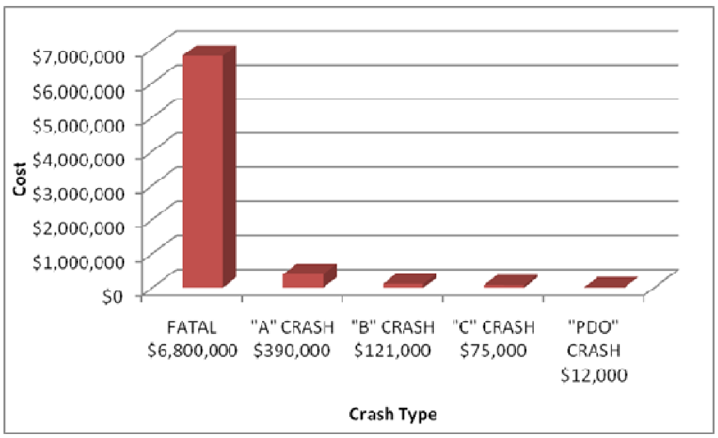

Figure 1.1 Cost as Per Crash Severity

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 [8.]. The percentage of each is given in Figure 1.2 below.

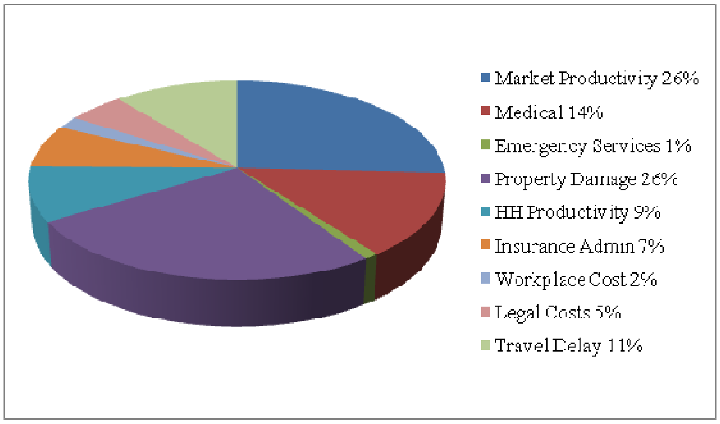

Figure 1.2 Components of the Total Cost of crashes[8.]

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 [8.].

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 [5.].

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 step of this project involved research conducted by CH2MHill where those sections of the roads were identified where road departure crashes were concentrated [1.].

Based on the identified at-risk road sections, these tasks were conducted:

- •Evaluating the crash effectiveness of infrastructure-based treatments
- •Suggesting alternative technology-based safety systems
- •Calculating 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 billions of dollars. Using safety systems, the number of 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. With fixed financial resources, the safety system suggested should reap the maximum benefits.

Safety systems can be broadly divided into two types

- •Traditional Civil Engineering-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 Towards Zero Deaths (TZD) 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 be cost-effective to justify the benefits reaped and be highly efficient to take the state towards its goal of TZD. This would give us a preferred solution in order to avoid crashes along curves and tangential sections.

Chapter 2: Review of Cross-Sectional Analysis and Before:After Analysis Conducted by CH2MHill

A study was conducted by CH2MHill [1.] to assess the importance of road geometry in crashes. This study forms the basis of the research since it provided the data set for the study. It was not practically possible to conduct our study on the entire horizontal curves and tangential sections located in the rural areas and hence a data sampling was required to identify the at-risk curves. The benefit:cost analysis was conducted based on this data. The following chapter is a paraphrase of the cross-sectional analysis and the before:after analysis conducted by CH2MHill.

The rural roadways have been divided into two sections: curves and tangential sections. Two studies have been conducted to evaluate these two sections for safety performance. The safety analysis included risk factors, the effects of road geometry, the effect of traffic control devices and the effectiveness of safety-based treatments including rumble strips and enhanced shoulders.

2.1 Cross-Sectional Analysis

The cross sectional analysis studies mainly the road geometry such as curves with varying radius and tangential sections with shoulders of various construction and widths.

2.1.1 Curves

A sample set of 204 curves with a total curve length of 35 miles was studied. The ADT on these curves ranged from 50 to 6,900 vehicles per day with the average length of the curves as 0.17 miles. The average number of crashes on these curves range from 0.1 to 0.2 crashes per curve per year. The distribution of crashes in the data set were:

- 3% of them are fatals,
- 44% are injury crashes and
- 53% are property damage crashes.

Thus the number of fatal crashes per curve per year is computed as 0.0045.

A term crash rate is defined to evaluate the risk factor at each curve. Crash rate can be defined as

$$CrashRate = \frac{NumberOfCrashes}{MillionVehicleMilesTraveledPerYear}$$

The cross-sectional analysis of curves mainly highlighted two points:

2.1.1.1 Effect of curve radius on crash rates

Crash rates were evaluated for curves of different radius. As the radius decreases, the crash rates tend to increase.

2.1.1.2 Effect of safety signs

The effect of static curve warning signs was also studied. Of the sample set, 80% of the curves already have some static advisory curve warning sign. This shows that the crashes occurred in spite of these static curve warning signs and hence there is a need for certain enhancements in terms of the safety systems used at the curves.

2.1.2 Tangential Sections

The sample set consisted of 137 tangential sections covering 930 miles. The ADT ranged from 7 to 12,000 vehicles per day. For analysis purpose, the tangential sections are divided into four categories based on shoulder construction:

- aggregate,
- paved,
- composite, and
- enhanced.

Composite shoulders are comprised of both aggregate and paved materials. Enhanced sections have either rumble strips (grooves lie outside the edgeline) or rumble stripes (edgeline lies above the grooves) on them. These four categories are further divided as per their widths.

The crash rate is higher for tangential sections with aggregate shoulders compared to paved, composite and enhanced shoulders. While comparing tangential sections of different width shoulders within the same category, narrow shoulders show higher crash rates compared to wider shoulders. Similar trend is followed by the fatal crash rates.

2.2 Before-After Analysis

In the before-after analysis, effect of certain safety treatments was considered on the crash rates and fatal crash rates. The average crash rates were documented for a set of curves and sections in two cases; before the treatment was implemented and after the treatment was implemented.

$$AverageCrashRate = \frac{TotalNumberOfCrashes}{TotalVMTForTheDataSet}$$

2.2.1 Curves

For curves the following treatments were studied:

- Curve flattening

- Paving narrow shoulders along curves
- Adding edge-line rumble strips

2.2.1.1 Curve flattening

Curve flattening includes completely reconstructing the curve and increasing its radius. This is consistent with the cross-sectional study which showed that the crash rates tend to decrease as the curve radius increases. Curve flattening showed reduced crash rates. The average crash rate was reduced from 1.2 to 0.4 crashes per million vehicle miles traveled when a curve was flattened.

2.2.1.2 Paving narrow shoulders along curves

The before-after analysis shows that the average crash rate increases from 5.4 to 11 crashes per million vehicle miles traveled when curve shoulders were paved.

2.2.1.3 Adding edge-line rumble strips

Adding rumble strips along curves reduces the average crash rate from 1.3 to 1.1 crashes per million vehicle miles traveled. The curves in this data set had radii between 2000 and 4000 feet.

2.2.2 Tangential Sections

The following treatments were studied along tangential sections:

- Paving aggregate shoulders
- Widening narrow paved shoulders
- Enhancing tangential sections

2.2.2.1 Paving aggregate shoulders

The average crash rate for shoulders decreases from 1.4 for aggregate shoulders to 1.2 crashes per million vehicle miles traveled for paved shoulders. This crash rate is averaged across tangential sections of different widths.

2.2.2.2 Widening narrow paved shoulders

The data set consists of just 1 tangential section which was widened from 0 to 2 feet to 4 to 6 feet. Hence the sample set is statistically insignificant to draw conclusions.

2.2.2.3 Enhancing tangential sections

Enhancing tangential sections includes adding rumble strips/stripEs to the sections. The average crash rate decreased from 1.6 to 1.0 crashes per million vehicle miles for enhancing aggregate sections and from 1.3 to 1.1 crashes per million vehicle miles traveled for enhancing already paved shoulders.

Table 2.2 Summary for before-after analysis

Treatment	Decrease in Average Crash Rate
CURVES	
Curve Flattening	60%
Paving Shoulders along curves	Average crash rate increases
Adding edge-line rumble strips	15%
TANGENTIAL SECTIONS	
Paving aggregate shoulders	16%
Widening narrow paved shoulders	7%
Enhancing aggregate shoulders	37%
Enhancing paved shoulders	15%

2.3 Summary

The cross-sectional analysis was used to compute the average fatal crash rate per curve per year as 0.0045. The study also told that 80% of the curves already had static curve warning signs and 16% had chevrons and still had high fatal crash rates. This illustrates the necessity for requirement of some other advanced safety solution at these curves and also gave the baseline for computing the deployment factor which is defined in Chapter No. 11. This deployment factor gives us the optimal solution. The study also divided the tangential sections in further categories. The benefit:cost analysis is applied to each of these categories separately.

The before:after analysis is used to calculate the effectiveness values for the various safety solutions which have already been applied on the horizontal curves and tangential sections. This quantified effectiveness values are a basis of comparison on already existing safety solutions with the new emerging ones.

Chapter 3: 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 [1.]. 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 traditional civil engineering treatments, infrastructure-based technology treatments and in-vehicle technologies.

3.1 Traditional Civil Engineering Treatments

3.1.1 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 [5.]. All these crashes are addressed by rumble strips.

Milled rumble strips are cut into existing asphalt shoulders and require narrow shoulders to install. They are usually not affected by snow and ice [9.]. Life of rumble strips is generally between 10 to 15 years.

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 where 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 per mile and hence this is the value used for our analysis.

3.1.2 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 and would be described in detail as the number of crashes reduced after implementing the treatment) 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.

3.1.3 Chevrons

Chevrons are supplemental warnings signs which are placed along a curve. Chevrons tell the driver the direction 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 3.1 Chevron

Retroreflectivity of signs is necessary so that they can be visible during the day as well as at night time [10.]. 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 3.1 Required chevron spacing as per speed limit [11.]

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% [12.].

3.1.4 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[11.].

Figure 3.2 Curve Warning Sign

When the advisory speed is less than 6 mi/h than the posted speed limit an advisory speed sign is coupled along with the curve warning sign [13.].

Figure 3.3 Curve Warning Sign with Advisory Speed

Almost 25 % of the crashes on curves occur due to speeding [5.] 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 [14.]. 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.

3.1.5 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. .

3.2 Infrastructure-Based Technology Safety Systems

3.2.1 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 3.4. These beacons flash light to communicate to the driver to reduce speed before the curve approaches.

Figure 3.4 Dynamic Curve Speed Warning Sign (with a flashing beacon and radar detection)

A solar beacon could be used for powering the LED lights in the flasher circuit.

The cost of this system ranges from $9,000 to about $14,000 per installation [11.], 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, and 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 [15.]. 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 [11.].

They have high efficiency value of 30% [14.].

3.3 In-Vehicle Technologies

3.3.1 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 3.6 illustrates how the DGPS system functions (in a survey context, but replacing "user" with "vehicle" accurately represents system functionality):

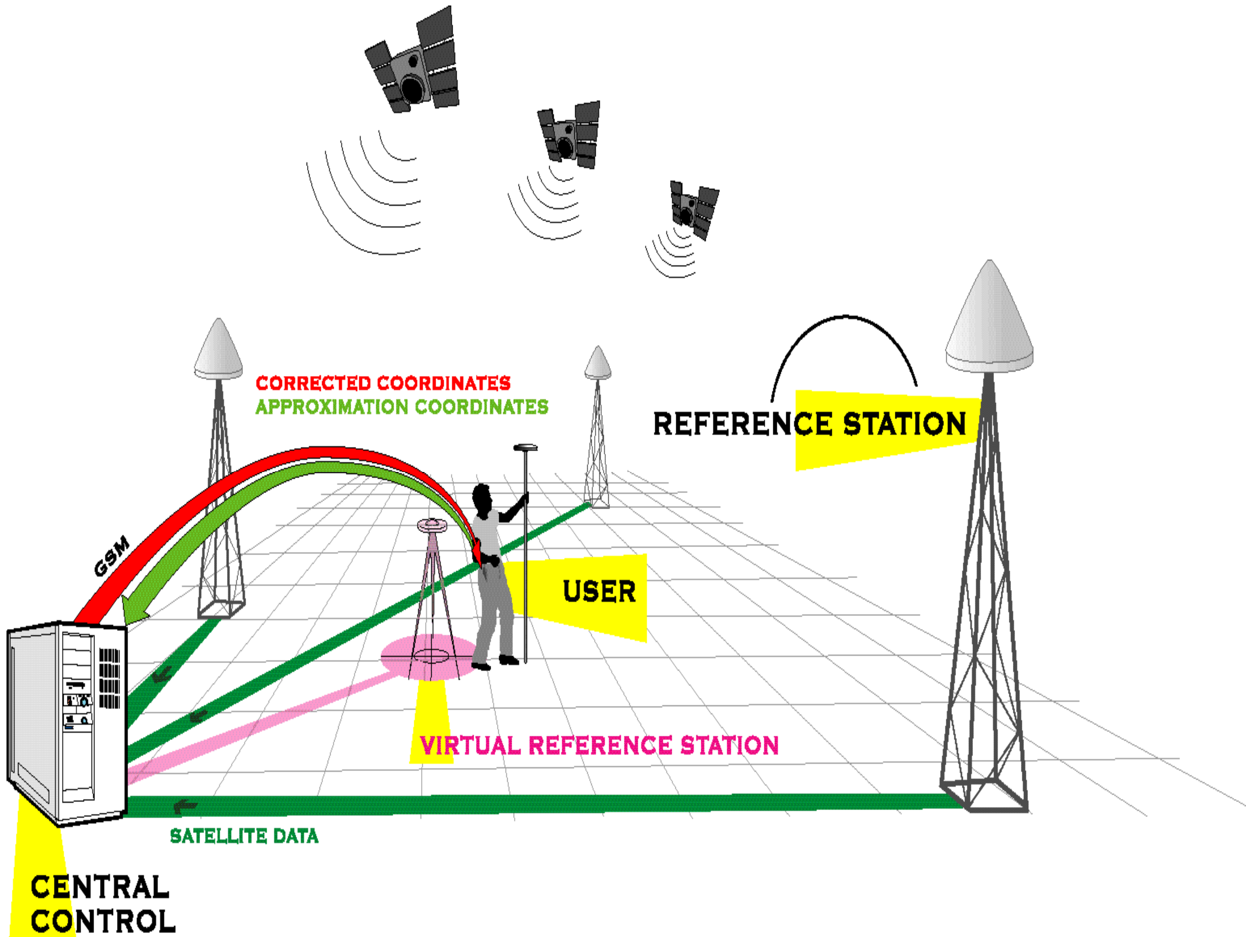

Figure 3.5 Data flow of a DGPS System

The moving vehicle requests 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 [17.].

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 or tactile display.

The state of Minnesota operates a GPS network throughout the state; this network is shown in Figure 3.7.

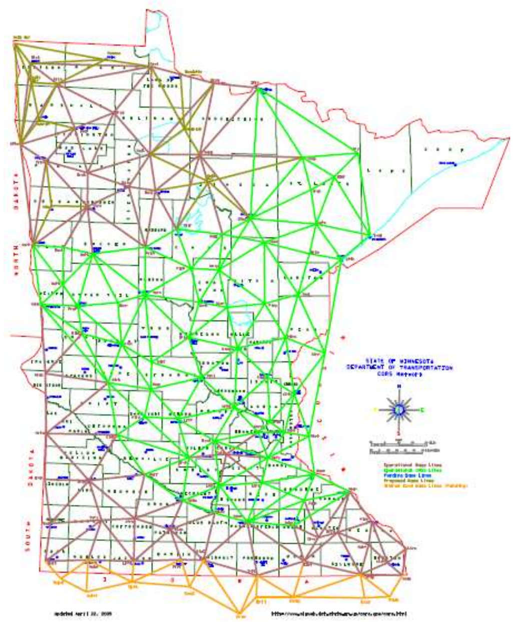

Figure 3.6 VRS Network in MN

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.

3.3.2 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. These are already offered by certain car manufacturers. Vision-based LDWS were introduced 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 [18.].

Figure 3.7 Vision-Based LDWS Driver Interface

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 [19.].

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 3.2 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 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 Intelligent Cruise Control Brake Assist with Preview 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 3.3 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 3.3 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 • Curve flattening • Paving shoulders along curves • Chevrons	• Dynamic curve speed warning signs	• Rumble strips • Paving shoulders along tangential sections • Pavement widening	• Vision-based LDWS • DGPS-based LDWS

Chapter 4: Effectiveness of Infrastructure Based Treatments

4.1 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 implementation.

In case of solutions which have already been implemented, the effectiveness is calculated based on the before:after analysis [1.] and a formula proposed by Evans in calculation of effectiveness of seat belts [20.].

4.2 Infrastructure-Based Treatments for Curves

There are six 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 3 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 4.1:

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

where VMT is the vehicle miles traveled.

Equation 4.2:

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

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

Equation 4.3:

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

Equation 4.4:

$$Effectiveness\ =\ 1 - CrashRatio$$

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

Table 4.1 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 4.2 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 4.2 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 curves 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 4.2 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

4.3 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.

4.3.1 Aggregate to Paved Treatment (AP)

4.3.1.1 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 A 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 4.1,

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

=1.4 crashes per million vehicle miles.

Using Equation 4.2,

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

=1.2 crashes per million vehicle miles.

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

4.3.1.2 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 A Table 1).

Sectional Efficiency for AP Tangential Sections

$$Sectional\ Crash\ Rate\ Before$$

$$= \frac{No. of\ crashes\ before\ for\ the\ section}{VMT\ before\ for\ the\ section} \times 1{,}000{,}000$$

$$= \frac{7}{2{,}088{,}968} \times 1{,}000{,}000$$

= 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 A.

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 4.1 and 4.2, 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 4.1.

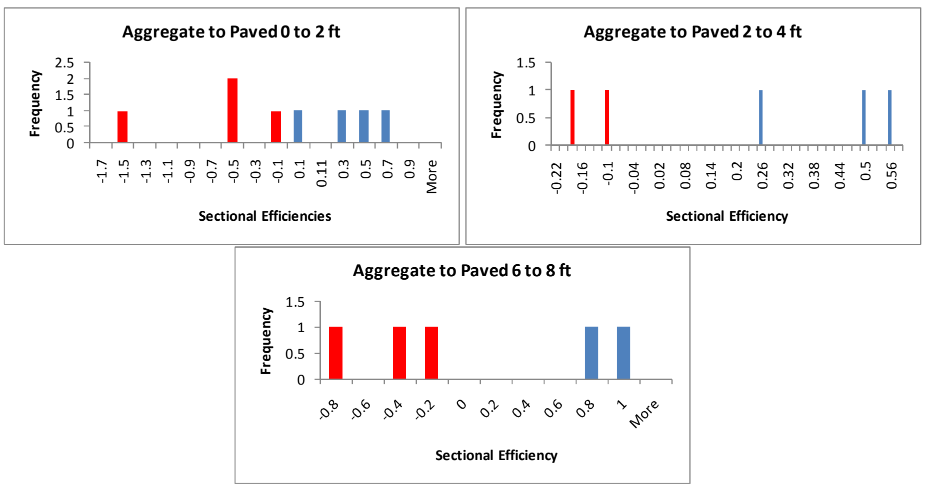

Figure 4.1 Distribution of Sectional Efficiencies for Aggregate to Paved Sections.

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.

4.3.1 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.

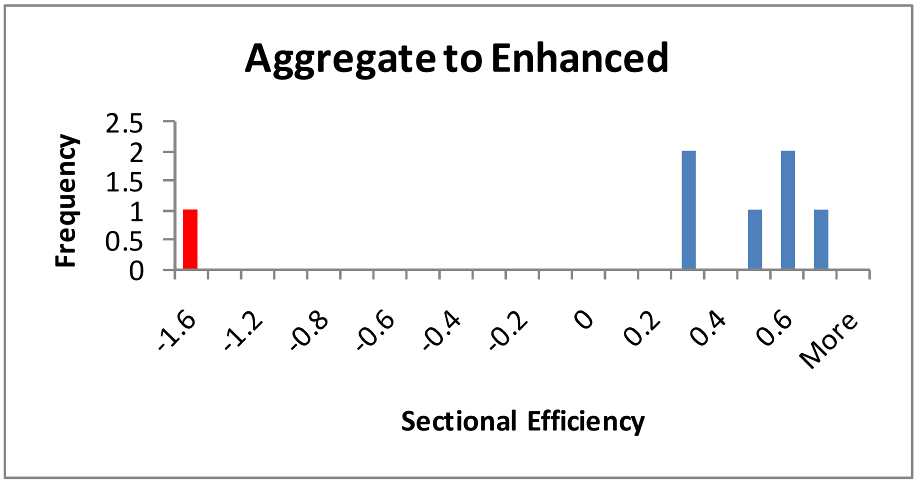

Figure 4.2 Distribution of Sectional Efficiencies of Aggregate to Enhanced (AE) Tangential Sections

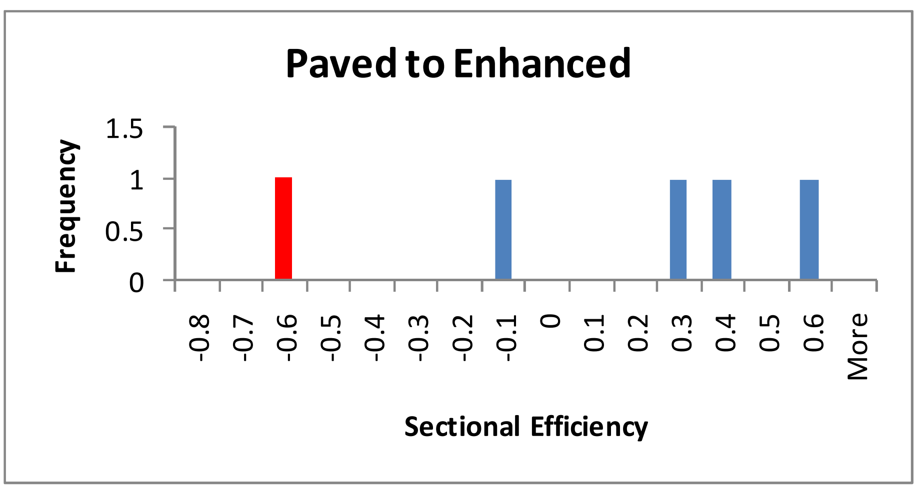

Figure 4.3 Distribution of Sectional Efficiencies for Paved to Enhanced (PE) Tangential Sections

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

Table 4.3 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.

4.4 Summary

4.4.1 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.

4.4.2 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 using the safety budget money, but while reconstructing shoulders or repairing them, it is a good habit to pave them. 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 5: 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 3.

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.

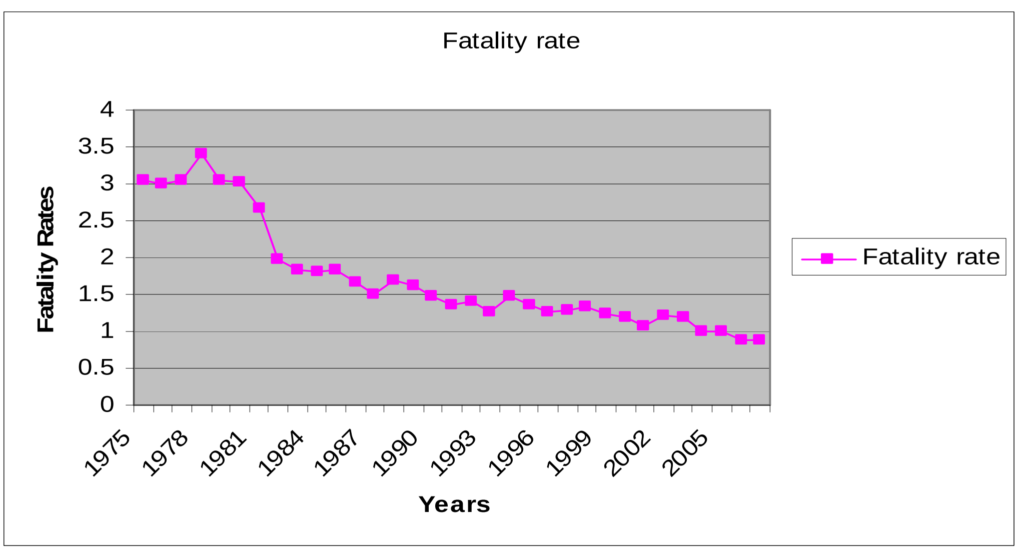

Figure 5.1 Fatality Rate in MN [5.]

In Figure 5.1, 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 [21.]. It was decided that if any states would refuse to comply with this act, their highway funds would be reduced. 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 [22.]. 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 then those having secondary or no laws [23.]. 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% [5.]. June 9th 2009 onwards Minnesota too will have a primary seat belt law.

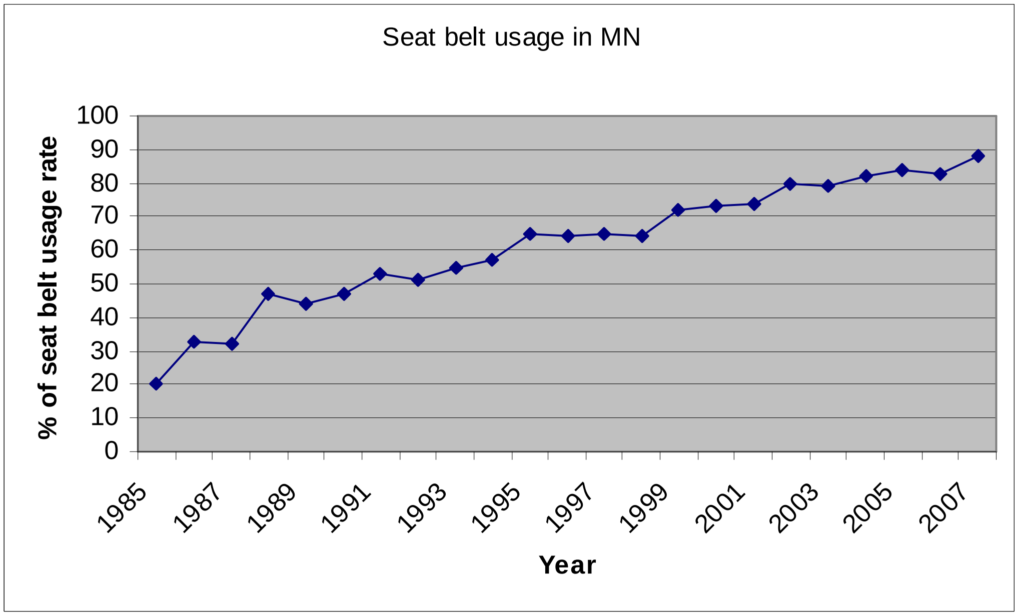

Figure 5.2 Seat Belt Usages in MN

Comparing Figures 5.1 and 5.2, 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 won'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.

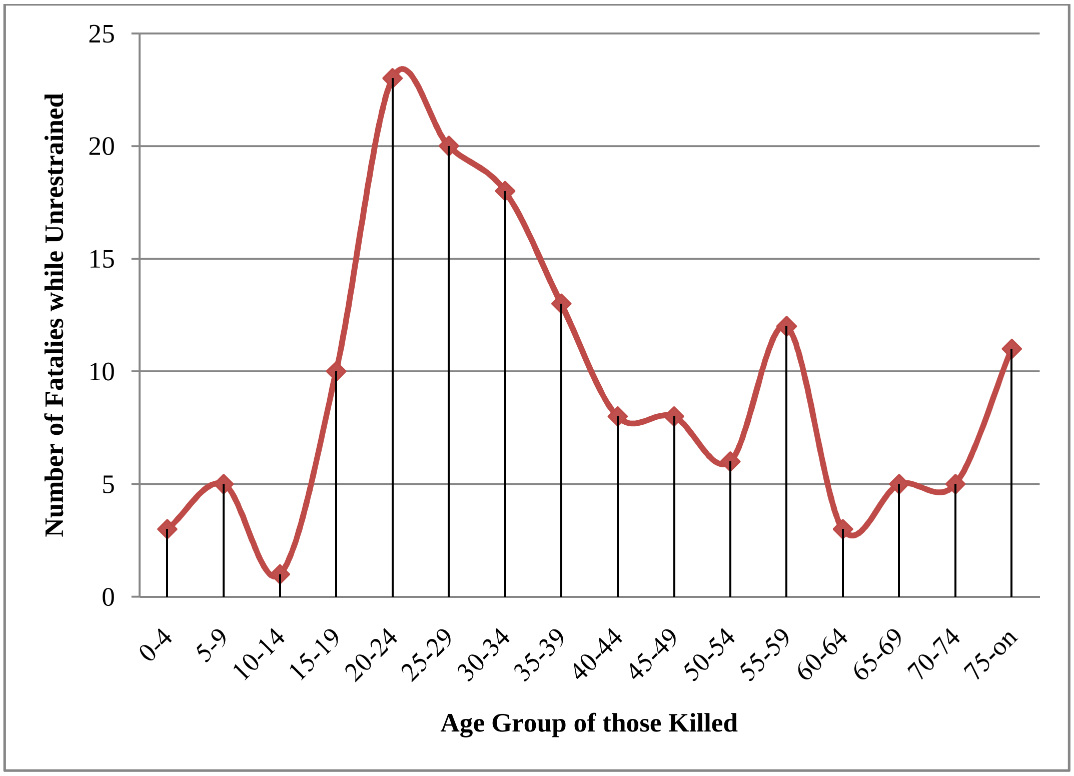

Figure 5.3 Number of Minnesotans not Using Restraints as per Age [24.]

However, Evans has proved by regression analysis that the effectiveness of airbags does not depend on the age factor [25.]. 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

$$Fatality\ Rate\ after\ using\ airbags = 30.87 - 0.339(Age)$$

$$Fatality\ Rate\ without\ using\ airbags = 54.27 - 0.339(Age)$$

In both of the regression equations, the coefficient on drivers' age are 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 B. The regression analysis of fatality rate as a factor of the seat belt usage in Minnesota gives the following equation:

Equation 5.1:

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

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 Systems (ABS) have been implemented in cars as a safety measure since 1984.

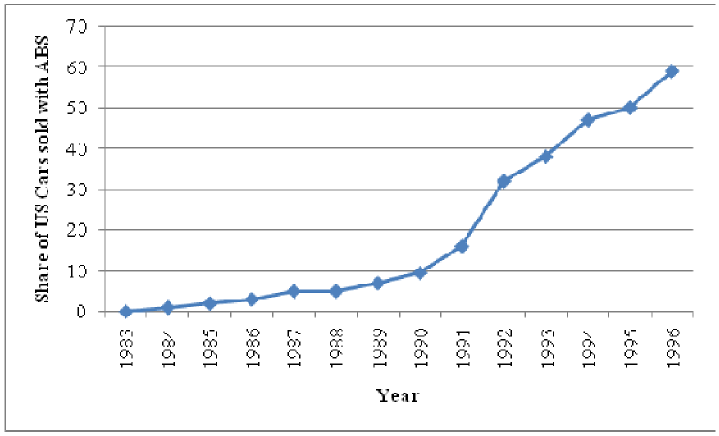

Figure 5.4 Market Penetration of ABS [26.]

Figure 5.4 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 involving cost effectiveness of automated highway systems [27.].

Figure 5.5 shows us the market penetrations of different automated ready vehicles (ARV). 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 5.5 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.

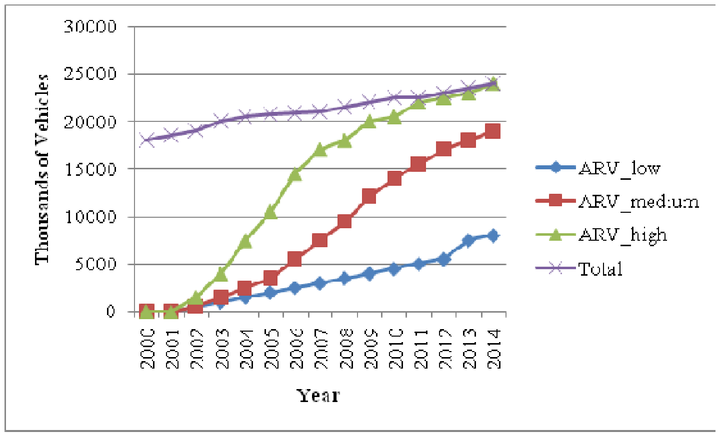

Figure 5.5 Market Penetration of Automated Highway Systems, where ARV stands for Automated Ready Vehicle [27.]

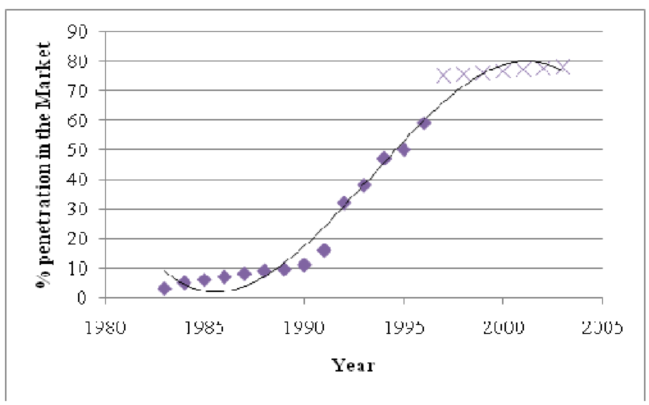

Figure 5.6 Assumed ABS Market Penetration for 20 Years

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.

5.1 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.

5.1.1 Step 1: Assuming Base Efficiencies

As mentioned before, field operation tests were conducted to evaluate the efficiency of vision-based LDWS at UMTRI in the year 2006. According to the drivers' response, the system was efficient by 68% in keeping the drivers within the lane markings after the alerts [28.]. 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. 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 [29.].

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.

5.1.2 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 [30.]. 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

5.1.2.1 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 [31.]. 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 5.7 shows the basic functioning of an ISA system.

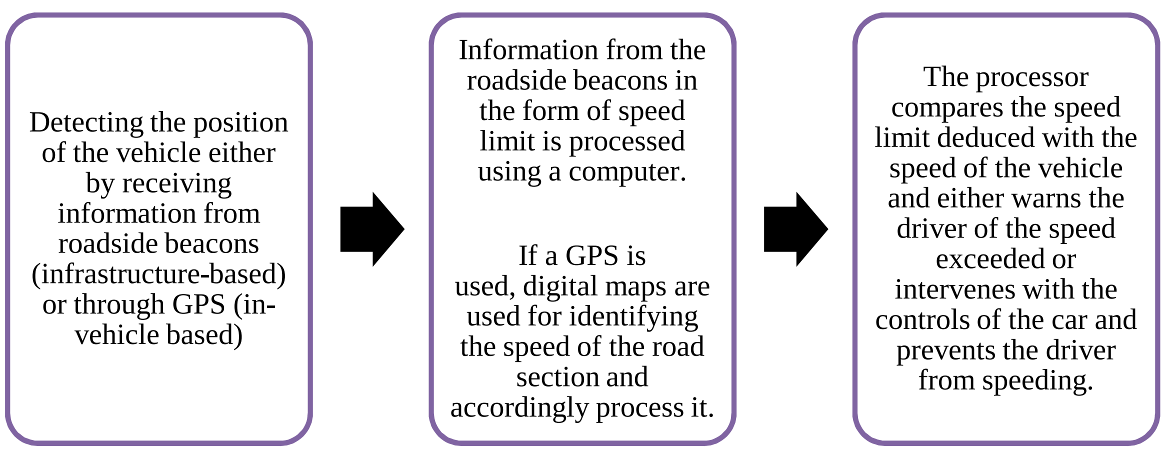

Figure 5.7 Basic Functioning of an ISA system

The system consists of three parts: identifying the position of the vehicle, identifying the prescribed speed limit the vehicle should not exceed, and warn the driver accordingly. The position of the vehicle is identified using either road side beacons or a GPS. 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 [31.]. 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 steering 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 [18.]. According to the previous discussion [31.] if such a system is introduced in the future in all systems, it may improve the efficiency of the LDWS.

5.1.2.2 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 [32.]. 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.

5.1.2.3 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 [33.]. 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 53% and 23% respectively, the end efficiencies in 2030 would be around 65% and 28%.

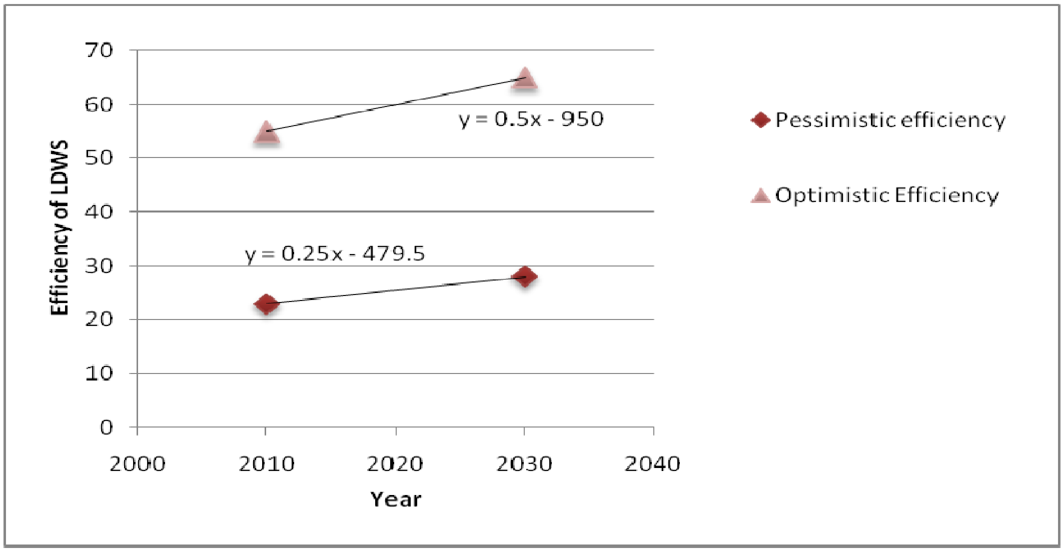

Figure 5.7 Increasing Efficiencies of LDWS

5.1.3 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 5.2

5.1.4 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 5.2) and ABS (Figure 5.6) as already discussed previously in this chapter. In Figure 5.2, 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 is not realistic 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 5.3

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

Individual values are available for the effective efficiency based on Equation 5.3. 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 C). 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.

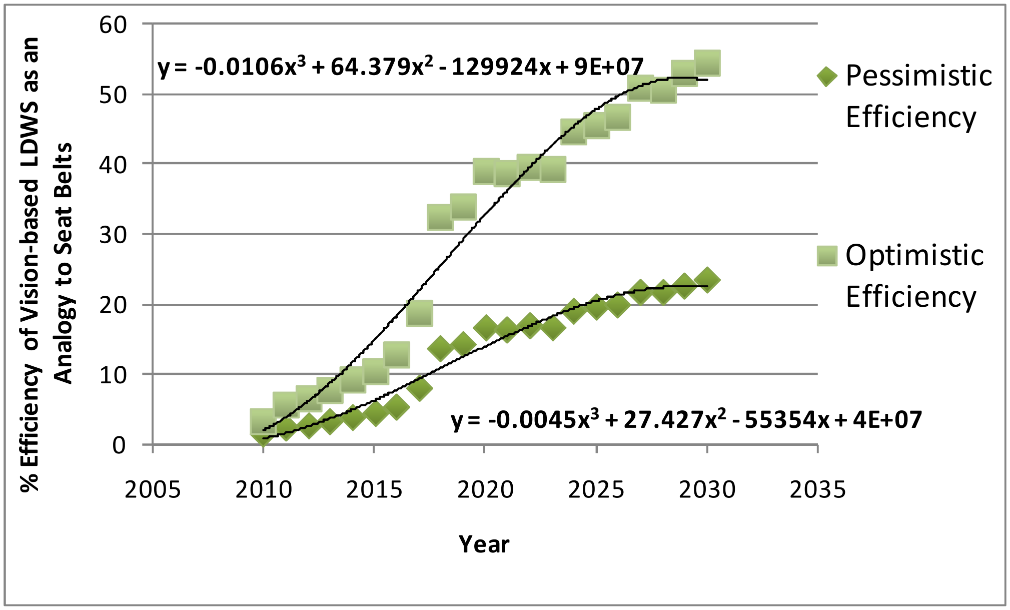

Figure 5.8 Effective Efficiency of Vision-based LDWS as an Analogy to Seat Belts

Using the same absolute efficiency rates in equation 5.3 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.

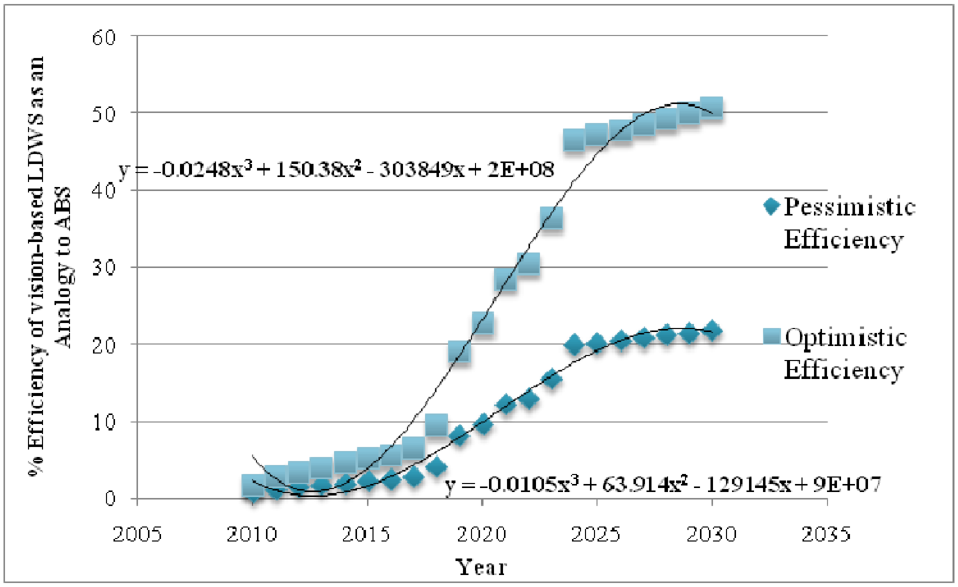

Figure 5.9 Effective Efficiency of Vision-based LDWS as an Analogy to ABS

In Figure 5.9, 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 5.1 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%	39%	545%	2%	23%	51%

Pessimistic Efficiency	1.4%	17%	24%	1.0 %	10%	22%

5.2 Efficiency of DGPS-based LDWS

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

5.2.1 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.

5.2.2 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.

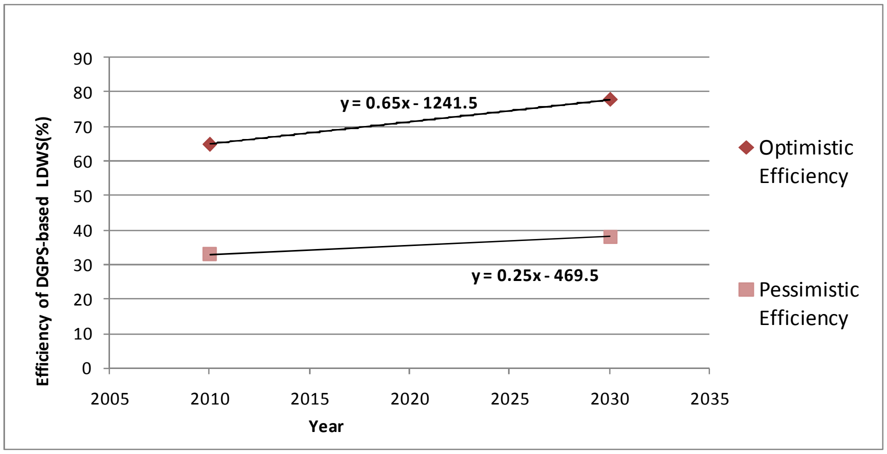

Figure 5.10 Increasing Efficiencies of DGPS-based LDWS

5.2.3 Absolute Efficiency

The intermediate absolute efficiencies are obtained for individual years based on the equation 5.2.

5.2.4 Effective Efficiency

Using Equation 5.3, the effective efficiencies can be calculated for DGPS-based LDWS to give the following curves (Appendix D).

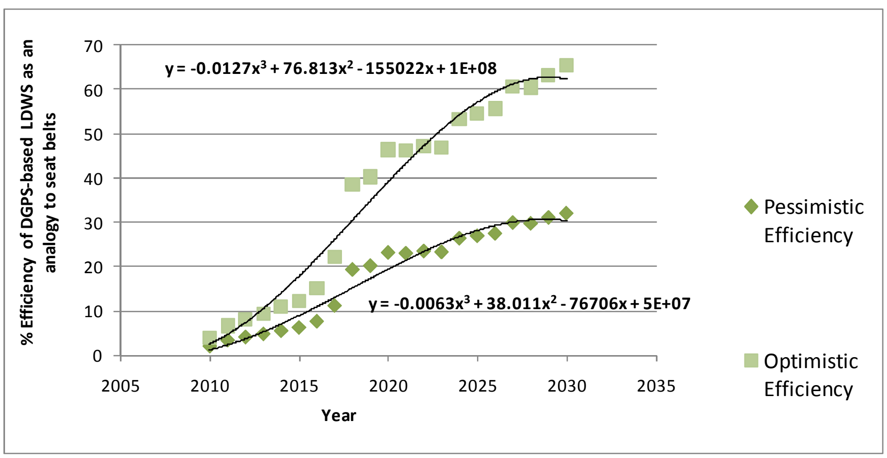

Figure 5.11 Effective Efficiency of DGPS-based LDWS as an analogy to Seat Belts

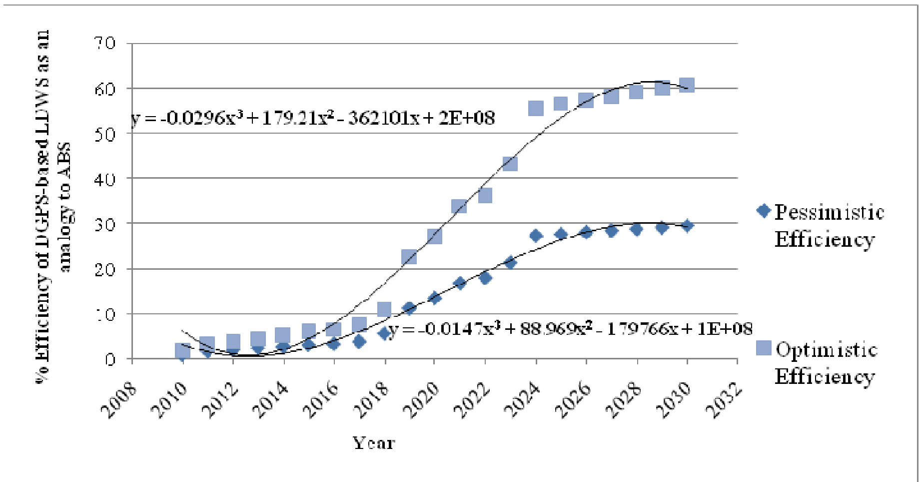

Figure 5.12 Effective Efficiency of DGPS-based LDWS as an analogy to ABS

Summarizing the efficiencies:

Table 5.2 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	4%	46%	66%	2%	27%	61%
Pessimistic Efficiency	2%	23%	32%	1%	13%	30%

5.3 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 6: 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 6.1, 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.

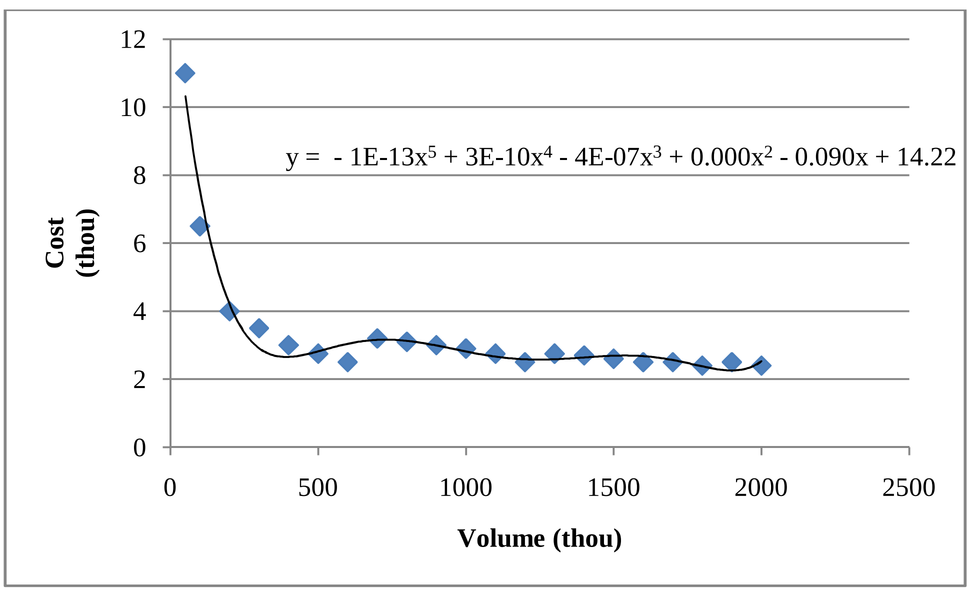

Figure 6.1 Cost v/s Volume Relationship [34.]

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

6.1 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 to the consumer. 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.

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.

$$\begin{aligned} &Number\ of\ cars\ with\ LDWS\ in\ MN \\ &\qquad = Number\ of\ cars\ in\ MN \times Market\ penetration \end{aligned}$$

The crash facts of Minnesota give the number of passenger cars registered in the years 2002 to 2007 [5.]. This can be extrapolated through 2030.

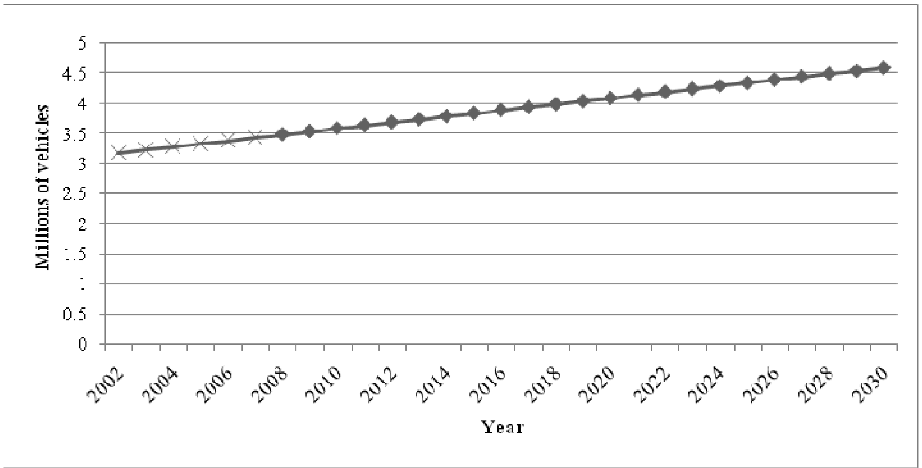

Figure 6.2 Number of Registered Vehicles in Minnesota

Based on the market penetration of seat belts and ABS, Figure 6.3 shows the number of vehicles that can be predicted to have LDWS in years 2010 to 2030 by equations 6.1 and 6.2:

Equation 6.1

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

Equation 6.2

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

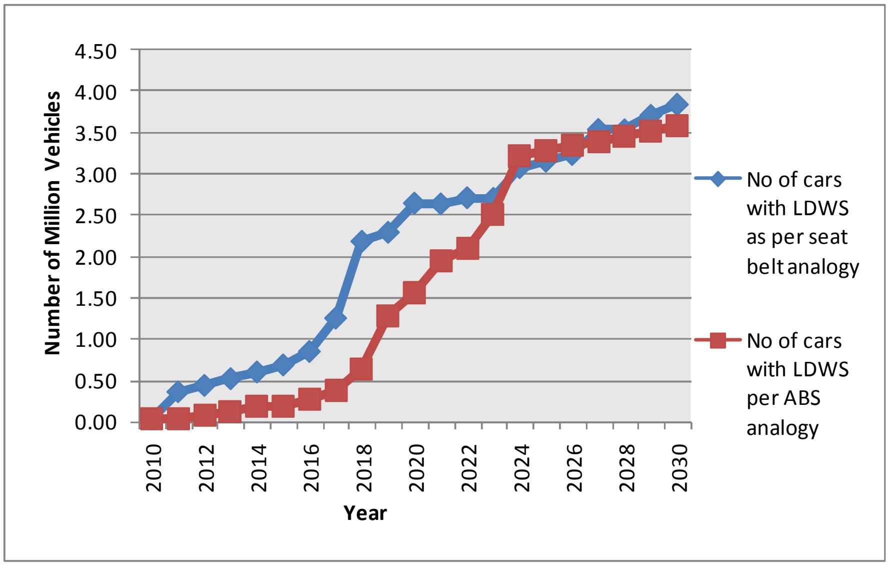

Figure 6.3 Number of Vehicles with Vision-based LDWS (Appendix E)

Using Figure 6.3, 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 E).

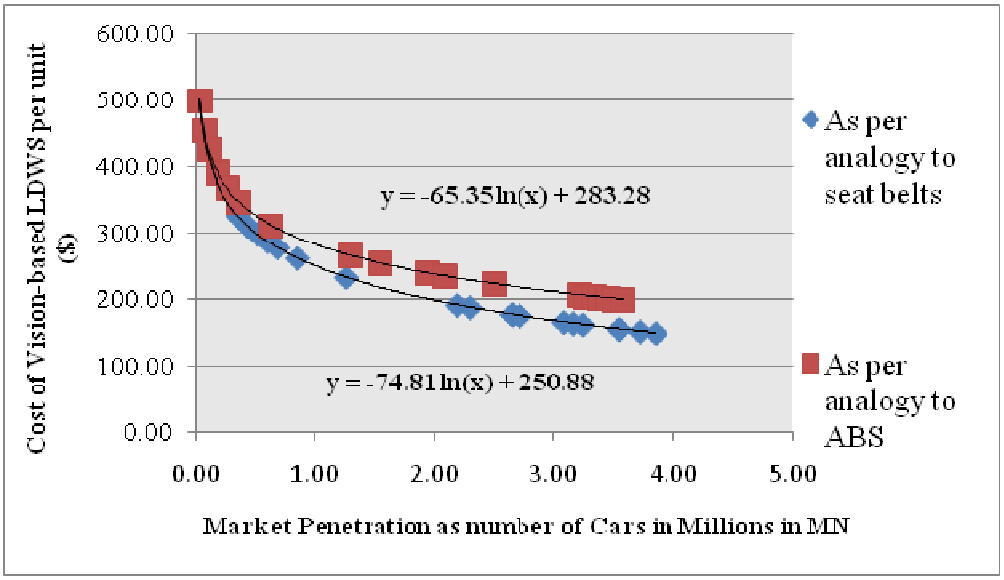

Figure 6.4 Cost Modeling for Vision-based Lane Departure Warning Systems

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

Equation 6.3:

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

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

Table 6.1 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	$178.00	$150.00	$4.7M	$5.7M
As per Analogy to ABS	$255.00	$200.00	$3.9M	$7.1M

6.2 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.

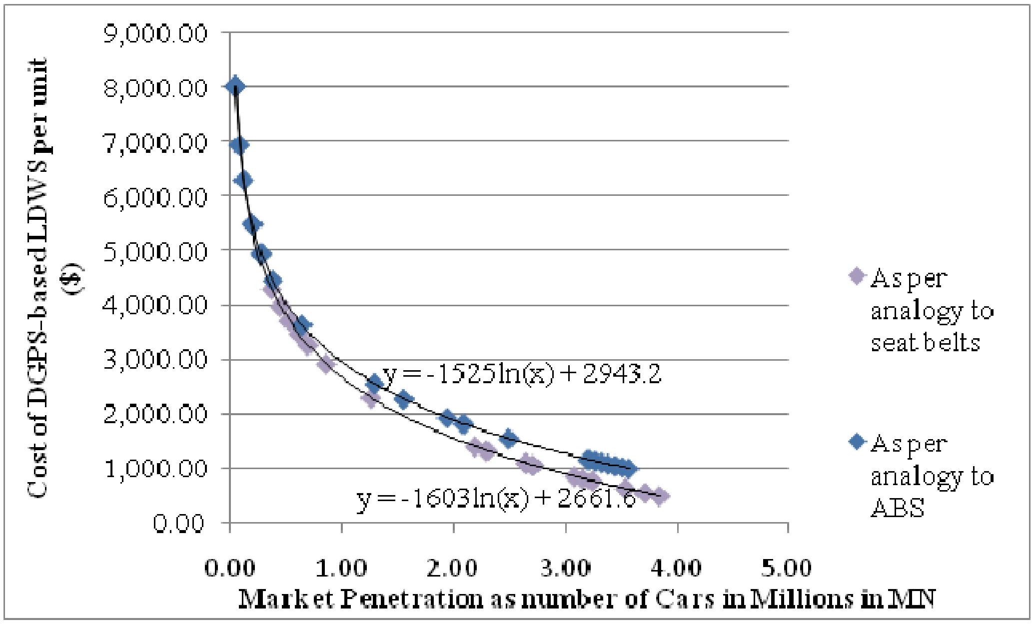

Figure 6.5 Cost Model of DGPS-Based LDWS

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 E). Equation 6.1 is used to give the following values for deploying the entire fleet with DGPS-based LDWS.

Table 6.2 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	$1,097.00	$ 500.00	$3B	$2B
As per Analogy to ABS	$2,274.00	$1,000.00	$3.5B	$3.5B

6.3 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 cost-benefit analysis and the approach taken to evaluate the infrastructure and technology-based treatments listed in the previous chapters.

Chapter 7: 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 are presented in this chapter.

7.1 Cost Effectiveness Analysis

Cost effectiveness analysis considers benefits in terms of a number, for example 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 example dollars per number of lives saved or dollars per number of crashes prevented.

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

Table 7.1 Cost effectiveness analysis

ADVANTAGES	DISADVANTAGES
• Simpler evaluation methods • Useful in calculating cost effectiveness for benefits for which its difficult to associate a monetary value	• It does not take into account the life of the project • 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 [27.]. 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.

7.2 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 example while considering the crashes avoided, it would also take into consideration the fatality measure and severity of the crash.

Table 7.2 Cost utility analysis

ADVANTAGES	DISADVANTAGES
• Useful in calculating cost effectiveness for benefits for which its difficult to associate a monetary value • 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. • Mainly based on surveys, hence biased by demographic differences. • 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.]. 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:

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

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.].

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 1.5.

7.3 Distributional Weighted Cost Benefit Analysis

Costs and benefits may be of different values 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 example 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 7.3 Distributed weighted CBA

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

7.4 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 7.4 Benefit:Cost Analysis

ADVANTAGES	DISADVANTAGES
• Based on willingness to pay and social welfare theory • Used in majority of traditional transportation economic evaluation projects • Takes into account the life of the project • Convenient for comparing alternatives with status quo • 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. • All benefits have to be monetized using shadow pricing.

7.5 Internal Rate of Return

The formula for net present value is

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

where NPV is Net Present Value, C is the cash flow, r is the rate of interest, and t is the time period.

When the NPV is zero that is the benefits are equal to the costs, 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 7.5 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 • Does not take into account the analysis period and the cash flow pattern • Not unique, there can be multiple IRR for a particular NPV. • 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 benefit:cost 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 8: 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 cost benefit 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. 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 solutions 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 8.1).

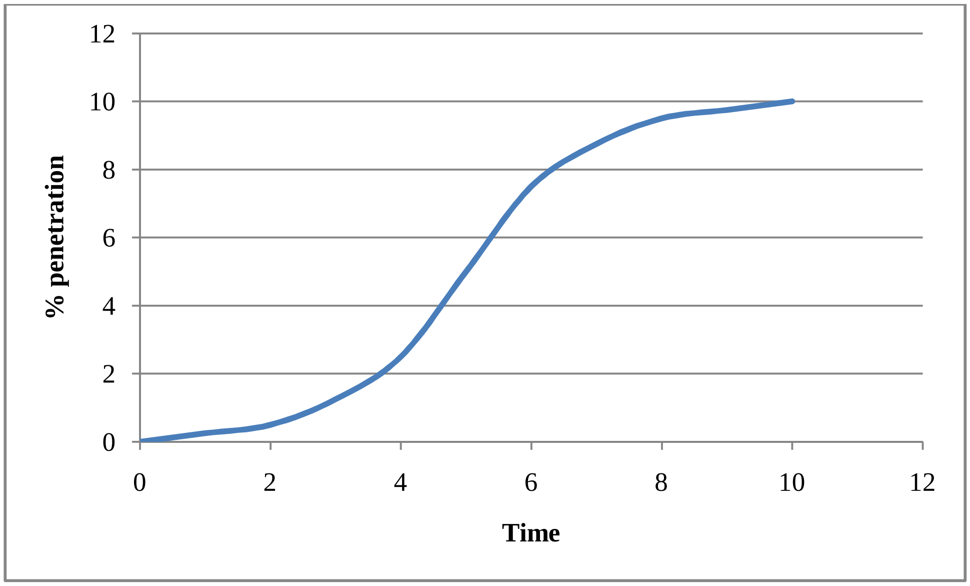

Figure 8.1 Technology diffusion S-curve [37.]

People show hesitation when technology is just introduced, so diffusion starts slowly, it then grows exponentially, peaks and then saturates. Accordingly the costs keep 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.

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 those 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 cost-benefit 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. Different confidence bounds are considered, and this

indicates if there is any significant difference in the end results due to these different variations [38.].

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 cost:benefit 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 9: Cost Benefit 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 fatals it could prevent 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 [5.]. Each fatal is assigned a cost of $6,800,000. The total economic loss due to fatals is thus about 3.5 billion dollars. The number of severe injuries was 1,736 [5.]. According to Figure 1.1, 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 fatals 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 fatals 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 cost benefit analysis primer [39.].

9.1 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 on these curves is 0.918. In other words, one fatal is expected at these curves every 13 months.

9.1.1 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 occurring 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 fatals could be prevented in the first 10 years. As per Mn/DOT's cost benefit 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:

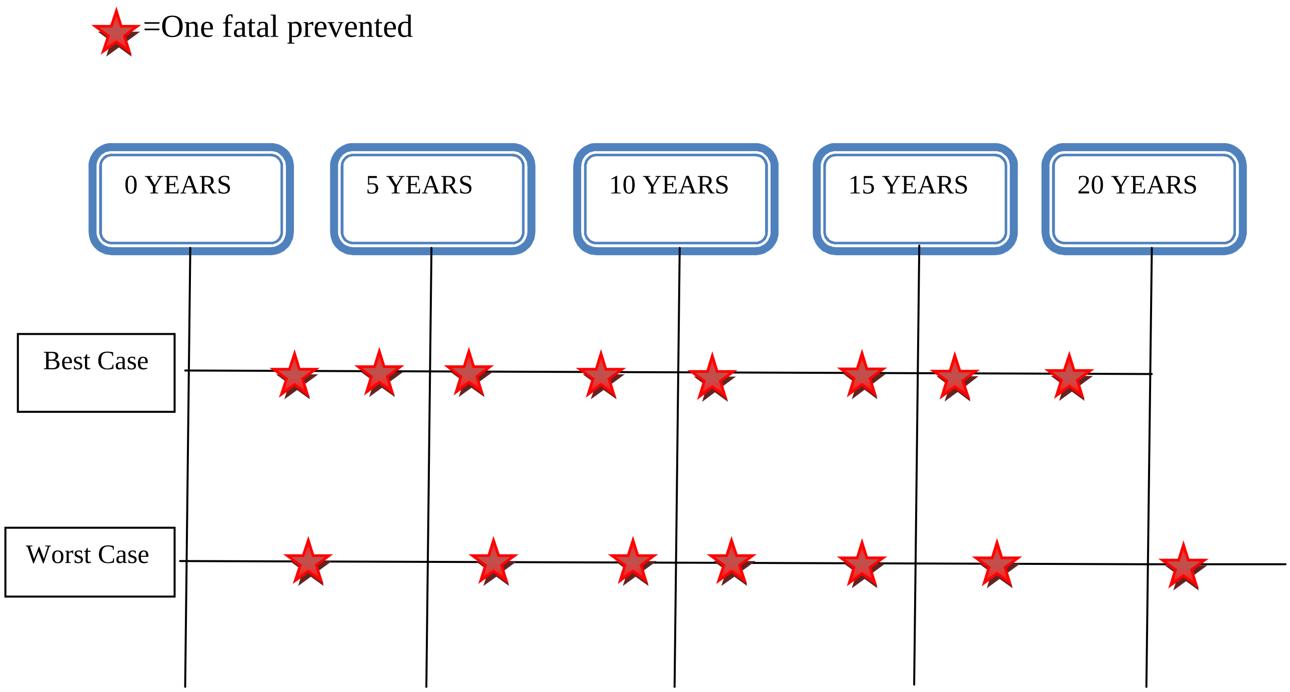

Figure 9.1 Example of Best Case and Worst Case

9.1.1.1 Condition 1

For a 10 year analysis, if 4 fatals 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 fatals, 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 fatals are prevented in the first 10 years.

9.1.1.2 Condition 2

- 3 fatals prevented in the first 10 years.

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

- While considering 3 fatals 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

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

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 F and the benefit-cost ratio is provided in the Table 9.1 below.

Table 9.1 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.

9.1.2 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 9.1:

$$Incremental\ Benefit{:}\,Cost\ Ratio_{\mathrm{AB}} = \frac{Benefit_{\mathrm{A}} - Benefit_{\mathrm{B}}}{Cost_{\mathrm{A}} - Cost_{\mathrm{B}}}\,[39.]$$

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 9.2 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 fatals prevented	3 fatals prevented
	WORST CASE	1 fatal prevented	2 fatals 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 fatals prevented	5 fatals prevented
	WORST	3 fatal prevented	

	CASE		
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.

9.2 Safety Systems for Tangential Sections

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

9.2.1.1 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,

$$Vehicle\ Miles\ Travelled\ (VMT) = 187{,}000{,}000$$

$$Total\ Miles\ of\ aggregate\ sections\ that\ were\ enhanced = 31.74$$

$$Total\ years\ for\ collecting\ data = 37$$

$$Annual\ VMT\ per\ mile\ of\ road = \frac{187{,}000{,}000}{31.744 \times 37} = 159{,}212.89$$

- 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 fatals 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 fatals 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 F).

9.2.2 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.

9.2.2.1 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 fatals 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

$$Number\ of\ fatals\ prevented\ in\ second\ year = Efficiency \times 253$$

$$= 0.06 \times 253 \sim 14$$

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

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

- Such cumulative fatals prevented are calculated for 10 years

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

- Monetizing the benefits as per fatals 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 F).

Table 9.3 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

9.3 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 10 to decide the optimal solution.

Chapter 10: Deployment Factor

As per Mn/DOT's TZD goal, it aims at reducing fatalities caused due to road accidents and ultimately reduce it to zero. 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. Thus the solution that is proposed by this research, 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. The optimal solution should be effective enough to reduce the fatalities for the financial resources expended.

10.1 Safety Systems for Curves

Rumble strips is the low cost treatment suggested for avoiding crashes along curves. However, their efficiency is low: 15 % versus 66% for 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, dynamic curve warning signs could be implemented to all the 4,350 curves

10.1.1 Towards TZD

10.1.1.1 For 100% of statewide at-risk curves: rumble strips

The number of fatal crashes per curve per year are 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 fatals 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 fatals is

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

Rumble strips are thus 1.19% successful towards TZD.

10.1.1.2 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% [14.], the number of fatals 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 G Table 1):

Table 10.1 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%	42.37
Dynamic Curve Speed Warning Sign	4,350	2.37%	6.6

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. 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.

10.1.2 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. 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 state safety 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 $400,000 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.

10.1.2.1 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 fatals 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.

10.1.2.2 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 fatals 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 10.2 gives the deployment factor for all the safety treatments for curves (Appendix G Table 2).

Table 10.2 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 9.3, for a given budget rumble strips have the highest deployment factor, that is they prevent the most number of fatals 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.

10.2 Safety Systems for Tangential Sections

Tangential sections cover a larger area. In the state of MN, there are estimated 53,000 miles of tangential sections. Given the number of road departure fatals in Mn was 253 in the year 2007, the fatal crashes for the tangential sections would be 0.005 per mile.

10.2.1 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 fatals 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 fatals 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 fatals prevented after enhancing tangential sections is

$$0.36 \times 7 \sim 2$$

Adding the cumulative fatals prevented in 10 years, the total number of fatals prevented in 10 years after enhancing 667 miles of tangential sections each year is 66. Assuming the number of road departure fatals to be constant at 253 each year, the total fatals 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%.

10.2.2 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 fatals 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 fatals thus prevented in 10 years is 42. Assuming the number of road departure fatals 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 10.3 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 thus could be comparable to enhancing tangential sections in future if the market penetration increases, leading to a decrease in cost and increase in their deployment factor.

Chapter 11: Conclusions and Recommendations

As per the Strategic Highway Safety Plan there are a large number of fatals occurring on the rural highways due to single vehicle road departure crashes. For this purpose the entire rural highway was divided into two sections of roads-curves and tangential sections. These were evaluated as part of the cross-sectional and before:after analysis conducted by CH2MHill [1.]. It was the objective of this study to use the data and results of the previous study by CH2MHill and provide an optimum solution either infrastructure-based or technology-based to reduce the road departure crashes.

These steps were followed:

- The solutions were divided into traditional safety systems and technology-based safety systems.
- The effectiveness values were calculated for the infrastructure-based solutions in terms of reduced crash rate which was listed in the before:after analysis [1.]. For the infrastructure-based solutions or technology-based solutions for which the crash rates were not available in the before:after analysis, efficiency values were used from the ones quoted in FHWA sites. For technology-based in-vehicle solutions, efficiencies were calculated by drawing analogies to the existing safety systems such as seat belts and ABS. Exposure in form of market penetration was also taken into consideration while computing these efficiencies.
- Using the efficiency values and the average fatal crash rate on curves and tangential sections based on the cross-sectional analysis, benefit:cost ratios were computed for each safety system.

- Since the SHSP stated reduction in the fatal crashes as the key objective, another factor to evaluate the safety systems was based on their contribution towards reducing fatal crashes or in other words their contribution in taking the state towards TZD. A statewide analysis was done for both a constrained and an unlimited budget. In practical, there would always be a fixed budget and the result of this analysis was defined as the deployment factor which gave the optimal solution. This safety system would be a balance between being cost-effective as well as effective in reducing the fatal crashes.

As per the above analysis, the following conclusions were drawn:

11.1 Curves

As per the benefit:cost analysis, rumble strips have a high benefit:cost ratio for both 10 and 20 year analysis. The cross-sectional analysis states that 80% of the curves already have static curve warning signs and still have a high fatal crash rate. This was hence used as a baseline since an additional safety feature is required at those curves. Calculations were done to compute the incremental benefit:cost ratio at those curves if a dynamic curve warning sign is installed and these numbers were positive and hence it is cost-effective to install these signs on extremely hazardous curves. The efficiency in reducing crashes for the dynamic curve warning sign and curve flattening too was high, but both of them are highly expensive treatments and hence have low deployment factor when a fixed budget is considered. Based on the deployment factor, rumble strips are the most optimal solution to reduce fatal crashes along curves.

11.2 Tangential Sections

Tangential sections were divided into categories as aggregate, paved, composite and enhanced. The treatments considered at these tangential sections were enhancing them or paving them. Also, two in-vehicle technologies: vision-based LDWS and DGPS-based LDWS were considered. 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.

As per the benefit:cost ratio, enhancing paved shoulders which are 0-2 ft and 2-4 ft wide is the most beneficial and enhancing tangential sections in general has a high deployment factor.

One of the objectives of this study was to evaluate whether new emerging safety systems such as lane departure warning systems could replace the existing safety systems. 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 at the beginning is low. In 10 years after deploying, as the cost decreases, the market penetration would increase. Thus as the number of cars equipped with the system increases; the deployment factor also may increase. In 10 years, the vision-based LDWS may be comparable to enhancing shoulders for the same amount of budget.

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Appendix A
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

Ave rage							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 B
Fatality Rates and Seat Belt Usage in M

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 C
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 D
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 1: As 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 E
Cost Modeling

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

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 F
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 FATALS PREVENTED EACH YEAR (optimistic)**	**No of fatals 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 FATALS PREVENTED EACH YEAR (pessimistic)	No of fatals prevented cumulative (pessimistic)	BENEFITS (pessimistic)	COSTS FOR ENTIRE FLEET (Seat Belt)	BENEFIT-COST RATIO (sb 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 FATALS PREVENTED EACH YEAR (optimistic)	No of fatals 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 FATALS PREVENTED EACH YEAR (pessimistic)	No of fatals 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 FATALS PREVENTED EACH YEAR (optimistic)	No of fatals prevented cumulative	BENEFITS (Optimistic)	COSTS FOR ENTIRE FLEET (Seat Belt)	BENEFIT-COST RATIO (sb 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 FATALS PREVENTED EACH YEAR (pessimistic)	No of fatals prevented cumulative (pessimistic)	BENEFITS (pessimistic)	COSTS FOR ENTIRE FLEET (Seat Belt)	BENEFIT-COST RATIO (sb 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 FATALS PREVENTED EACH YEAR (optimistic)	No of fatals 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 FATALS PREVENTED EACH YEAR (pessimistic)	No of fatals 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 G
Towards TZD

Table 1: Without budget constrains for curves

Solution	**Effectiveness**	**No of fatalitites 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 fatals exposed to every year	Number of fatals 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 FATALS EXPOSED TO	EFFICIENCY	NO OF FATALS 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 FATALS EXPOSED TO	EFFICIENCY	NO OF FATALS 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 FATALS EXPOSED TO	EFFICIENCY	NO OF FATALS 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 FATALS EXPOSED TO**	**EFFICIENCY**	**NO OF FATALS 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