Safety Benefits of Highway Infrastructure Investments

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AAA Foundation for Traffic Safety

Title

Safety Benefits of Highway Infrastructure Investments *(May 2017)*

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Foreword

Investments in proven highway safety countermeasures have the potential to effectively reduce motor vehicle crashes and associated injuries and fatalities. The work presented in this report offers current knowledge on the crash reduction effectiveness of specific infrastructure improvements and quantifies the important role of highway infrastructure upgrades in improving traffic safety.

This technical document can be a useful resource for Federal, state, and local transportation agencies on infrastructure improvements that can yield impactful safety benefits. Additionally, traffic safety professionals can reference information presented in this report to devise improvement alternatives.

C. Y. David Yang, Ph.D.

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About the Sponsor

AAA Foundation for Traffic Safety
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Founded in 1947, the AAA Foundation in Washington, D.C. is a not-for-profit, publicly supported charitable research and education organization dedicated to saving lives by preventing traffic crashes and reducing injuries when crashes occur. Funding for this report was provided by voluntary contributions from AAA/CAA and their affiliated motor clubs, from individual members, from AAA-affiliated insurance companies, as well as from other organizations or sources.

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Summary

The United States faces a major challenge in improving the traffic safety performance of our road and street network. An evaluation of historical traffic crash data shows that while substantial improvements in roadway safety have been made in the United States, especially within the last decade, the most recent data show a reversal in this trend with substantial increases in fatalities in both 2015 and 2016 from the previous several years. A review of recent data found that:

- Among developed nations, the United States ranks nearly last in terms of annual traffic fatalities per 100,000 population.
- A total of 35,092 people died, and hundreds of thousands more were seriously injured, in traffic crashes on roads and streets in the United States during 2015.
- The economic impact of crashes in the United States in 2010 was $242 billion in costs related to medical care, emergency services, legal and court issues, insurance administration, congestion, property damage and lost wages—this was roughly equivalent to 1.6 percent of the U.S. Gross Domestic Product (GDP). This cost increased to $836 billion when quality of life considerations are taken into account.
- From 1949 to 2014, the fatality rate fell from 7.13 to 1.08 fatalities per 100 million vehicle-miles of travel, even as Americans drove more and more miles. The number of traffic-related fatalities fell from a peak of 54,500 in 1972 to a low of 32,675 in 2014. However, fatalities increased by 7 percent in 2015, and were on trend for a similar increase in 2016.

A renewed focus is needed in roadway safety in the United States. Improvements will be needed in every area, including infrastructure, driver education, traffic law enforcement, emergency medical services, and vehicle safety technology. Highway infrastructure investments, in particular, must play a prominent role in our national strategy to decrease traffic fatalities and serious injuries.

Highway infrastructure improvements have the potential to reduce both the likelihood and consequences of crashes caused not only by the roadway environment but also by driver error. Improvements to highway infrastructure features, including the roadway, roadside, and traffic control devices, can constrain driver behavior even without the need for a conscious decision by drivers to behave differently. In addition, infrastructure improvements may provide the most certain approach to reducing fatalities and serious injuries because many have been widely implemented, providing years of performance data and allowing researchers to quantify their typical or average effects on safety. In fact, the expected safety benefits of many infrastructure treatments have been cataloged in many sources, including the AASHTO *Highway Safety Manual* and the FHWA CMF Clearinghouse. Methodologies for incorporating these safety benefits into the planning and design processes are implemented in safety prediction tools, such as the U.S. Road Assessment Program (usRAP) software for developing safer roads investment plans, ViDA.

The report documents recent U.S. research on the effectiveness of infrastructure improvements in reducing crash frequency and/or severity. Seven case studies of actual infrastructure improvement projects are presented to illustrate the crash reduction benefits that can be attained by highway agency action.

The research team was able to estimate the nationwide infrastructure safety improvement needs, and the potential benefits of addressing those needs, for several roadway types using safer roads investment plans developed for over 12,000 mi of roads and streets in the United States as part of usRAP. Specifically, sufficient data were available for the following roadway types to include them in the assessment of needs and potential benefits:

- Rural two-lane undivided roads
- Rural four-lane undivided roads
- Rural four-lane divided roads
- Rural four-lane freeways
- Rural six-or-more-lane freeways
- Urban two-lane undivided streets
- Urban four-lane undivided streets
- Urban six-or-more-lane undivided streets
- Urban one-way streets
- Urban four-lane divided roads and streets
- Urban six-or-more-lane divided roads and streets
- Urban four-lane freeways
- Urban six-lane freeways
- Urban eight-or-more-lane freeways

The roadways in the usRAP studies were representative of the following functional classes of roadways:

- Rural major and minor collectors
- Rural minor and principal arterials
- Rural freeways
- Urban principal arterials
- Urban freeways

Only paved roads and streets were considered. The National Highway Traffic Safety Administration (NHTSA) Fatality Analysis Reporting System (FARS) database indicates that approximately 64 percent of traffic fatalities in the United States occur on roadways of the roadway types and functional classes considered in the study. This indicates that the estimates of highway infrastructure needs described in this study are conservative. If usRAP study data had been available for a broader range of road types and functional classes, larger estimates of highway infrastructure improvement needs would likely have been obtained.

Nationwide needs for highway infrastructure improvements were estimated by scaling up the usRAP safer roads investment plans developed for the 12,000 mi of roads and streets to the national level. It was assumed that the usRAP safer roads investment plans for any given combination of roadway type and traffic volume level were representative of improvement needs for all roads of that roadway type and traffic volume levels within the functional classes studied.

Cost-effective infrastructure investments (i.e., those for which the benefits exceed the costs) represent an opportunity to improve safety on U.S. highways and streets. This report makes a conservative estimate of such current infrastructure improvement needs. The estimates developed in this report indicate that current infrastructure improvement needs in the U.S. for the roadway types and functional classes listed above would cost $146 billion to address. If all of these needs were addressed, the present value of the 20-year safety benefits would be $348 billion, with a benefit-cost ratio of 2.4. In other words, benefits of $2.40 could be achieved for every $1.00 spent on infrastructure improvement. Addressing these needs could reduce 63,700 fatalities and more than 350,000 serious injuries over 20 years.

The improvements considered in the safer roads investment plans include:

- Adding passing lanes
- Widening lanes

- Widening shoulders
- Widening the cross section to include a median
- Adding a center two-way left-turn lane
- Adding median barrier
- Improving the roadside by clearing roadside objects, improving sideslopes, or installing barriers
- Installing centerline or shoulder rumble strips
- Adding a bicycle lane or path
- Adding pedestrian facilities (refuge island, marked crossings)
- Improving delineation
- Adding intersection left-turn lanes
- Converting an intersection to a roundabout
- Providing grade separation at an intersection
- Signalizing an intersection
- Updating rail crossings

Most of the improvements were assigned a service life of 20 years. A few of the improvements, including improving delineation and adding rumble strips, have been assigned a service life of 5 years. The investments would need to be repeated every 5 years to maintain the benefits over a full 20-year period. The initial investment to obtain the benefits of this program would be $134 billion with further investments of $6 billion every 5 years to maintain the improved delineation and rumble strips in place. The investment level of $146 billion presented above is the present value of the initial investment of $134 billion plus three $6 billion investments at 5, 10, and 15 years into the program. It should be emphasized that while the benefits of the improvement program would persist over (at least) 20 years, the identified needs exist now and most of the investment is needed now.

The scale of these infrastructure improvement needs is large, but so is the scale of the traffic safety challenge to be met in the United States. Meeting the $146 billion in current infrastructure improvement needs would still reduce only 16 percent of the expected fatalities and 12 percent of the expected injuries on the roads evaluated.

Given the limitations on the funds available for infrastructure investments for safety improvement, most highway agencies have preferred to focus on investments with the greatest return. As we demand higher benefit-cost ratios from our investments, both the funds needed and the benefits derived from the investment programs become smaller. If we focused only on investments with benefit cost ratios of at least 2.0, as some highway agencies prefer, the size of the infrastructure investment program would be reduced to $64 billion and the benefits of the program would be reduced by 22 percent. If we focused only on investments with benefit-cost ratios of at least 5.0, the infrastructure improvement program would be only $16 billion (i.e., just 9 percent of the $146 billion in needs noted above), but the benefits of the improvement program would be cut almost in half. Thus, a smaller improvement program would be more efficient, but would accomplish only about half as much in reducing fatalities and serious injuries.

Six categories of countermeasures collectively will provide nearly 95 percent of the anticipated crash reduction from the infrastructure investment program. The safety needs and benefits assessment found that:

- Almost 30 percent of the overall fatality and serious injury reduction could come from intersection improvements. The intersection improvement with the greatest potential for fatality and serious injury reduction is conversion of existing intersections to roundabouts.
- Nearly 20 percent of the overall reduction in fatalities and serious injuries could come from roadside improvements. The analysis results indicate that installing roadside barriers should

constitute the largest component of the improvement program, while clearing roadside objects would have the highest benefit-cost ratio.

- Nearly 20 percent of the fatality and serious injury reduction could come from the addition or improvement of pedestrian facilities. The analysis results show that most of these improvements would come from providing sidewalks where none currently exist, but addition or improvement of signalized and unsignalized pedestrian crossings should also be an element of the infrastructure improvement program.
- About 14 percent of the overall benefits of the recommended infrastructure investment program could come from installation of median barriers on existing divided highways.
- Nearly 9 percent of the overall benefits of the recommended infrastructure investment program could come from rumble strips. The analysis indicates that shoulder rumble strips are needed at the most locations, but centerline rumble strips can have key benefits on undivided roadways. The need for centerline rumble strips may even be underestimated in the analysis results.
- Finally, nearly 3 percent of the overall benefits could come from shoulder paving and widening.

Current investments in highway infrastructure improvements in the U.S. are substantially lower than the identified needs. There are no comprehensive data on how much U.S. highway agencies currently spend on traffic safety improvements. FHWA provides approximately $2 billion annually to state and local agencies in the Highway Safety Improvement Program (HSIP). State and local governments also invest funds of their own in safety improvement projects, although no national estimates of state and local government expenditures on traffic safety are available. In addition, general highway improvement programs make many improvements that benefit safety as well as meeting other objectives. However, even if, as a nation, we are spending $4 or $5 billion on infrastructure improvements for safety, this is only a small portion of the identified needs.

Highway infrastructure improvements can serve an important role in moving Toward Zero Deaths, but infrastructure improvement programs must begin to address a much greater portion of the identified needs. The $146 billion in identified needs do not necessarily all need to be addressed in the first year of an investment program, but these needed investments should not be deferred too long because new needs develop each year. If we continue to underinvest in infrastructure improvement, the backlog of unaddressed needs will grow rather than shrink.

Section 1. Introduction

This report reviews and quantifies the important role of highway infrastructure improvements in improving traffic safety. The United States faces a major challenge in improving the traffic safety performance of our road and street network. Many types of improvements will be needed, including highway infrastructure improvements, as well as further vehicle safety technology improvements, increased enforcement, improved driver education, and better emergency medical services. While all of these improvement types are needed, infrastructure improvements may provide the most certain approach to reducing fatalities and serious injuries. Many infrastructure improvements have been widely implemented, providing years of performance data and allowing researchers to quantify their typical or average effects on safety. More than for any other type of investment in crash reduction, the benefits of infrastructure improvements can be estimated with a high degree of confidence.

This report presents a summary of current knowledge on the crash reduction effectiveness of specific infrastructure improvements and illustrates the crash reduction benefits possible at individual locations through several case studies that showcase real projects implemented by State DOTs. This report presents quantitative estimates of fatal and serious injury crash reductions that could be realized from specific levels of infrastructure investment by Federal, state, and local agencies.

1.1 Traffic Safety in the United States

A total of 35,092 people died, and hundreds of thousands more were seriously injured, in traffic crashes on roads and streets in the United States during 2015. In addition to the direct effects of these crashes on the individuals and families involved, the impact of crashes on the U.S. economy exceeds 1.6 percent of our Gross Domestic Product (GDP) (Blincoe et al., 2015). Reducing the annual toll of traffic deaths and serious injuries can bring large benefits to our society in both human and economic terms.

Among developed nations, the United States ranks nearly last in terms of annual traffic fatalities per 100,000 population. In the United States, 10.6 of every 100,000 citizens die in traffic fatalities every year, while for the best performing countries in the world (Sweden and the United Kingdom), the comparable fatality rate is less than 3.0 fatalities per 100,000 population. Table 1 shows the fatality rate per 100,000 population and per 100 million vehicle-miles of travel for developed countries, illustrating the poor safety performance of the United States relative to other countries. Since rural roads have higher risk of fatalities and serious injuries than urban roads, part of the difference between the United States and other countries can be explained by the rural character of much of the U.S. Even so, the safety performance of U.S. roads and streets still needs substantial improvement to approach the performance of the best countries in the world.

Over the past few decades, the Unites States has made significant strides reducing fatalities and injuries on our highways and streets, as illustrated in Figure 1. Traffic fatalities peaked in 1972, when over 54,500 people died in traffic crashes. By 2014, this number had fallen to 32,675 fatalities—the lowest since 1949, when Americans were driving approximately 425 billion vehicle-miles per year, and the fatality rate was 7.13 fatalities per 100 million vehicle-miles of travel. By comparison, in 2014, vehicle-miles of travel exceeded 3 trillion, and the fatality rate was 1.08 fatalities per 100 million vehicle-miles of travel. Over the 65 years from 1949 to 2014, traffic fatalities decreased by 40 percent, and the fatality rate per 100 million vehicle-miles of travel decreased by 85 percent. Put another way, if the fatality rate per 100 million vehicle-miles of travel was still at its 1949 level, the U.S. would today be experiencing 231,700 fatalities per year, instead of the actual 35,000 fatalities per year. So, substantial progress has been made.

Despite this progress, U.S. traffic fatalities increased by 7 percent in 2015, as compared to 2014, bringing the number of fatalities to its highest level in seven years, and this increase has continued in 2016. This experience indicates that traffic safety improvement needs a focused, continuous effort over many years because gains in our national fatality toll made in one year can be easily reversed the next.

The progress made in the past in reducing traffic fatalities and serious injuries has resulted from a combination of initiatives:

- Improved highway infrastructure
- Improved vehicle design and technology
- Increased enforcement
- Public education
- Improved emergency medical services for crash victims

While past efforts have clearly been effective, the toll of highway fatalities and serious injuries remains unacceptably high and the United States still has a long way to go in improving the traffic safety performance of our roads and streets.

Many countries, including the United States, have adopted goals to substantially reduce or eliminate the annual toll of deaths and serious injuries in traffic crashes. Sweden was the first country to envision that it is a feasible and obtainable goal to operate the road system with no deaths or serious injuries. Sweden's program to achieve this goal, known as Vision Zero, has been actively working toward the goal of zero fatalities and serious injuries since 1997. By 2013, fatalities in Sweden had fallen by 50 percent, despite seeing an increase in both the number of vehicles on the road and the number of vehicle-miles driven. As a result, Sweden today has essentially the safest roads in the world, with a rate of only 2.8 traffic fatalities per 100,000 population.

The Swedish approach has spread to other countries, with each country choosing their own name for the program. For example, the Netherlands has set out to achieve Sustainable Safety, while Australia has adopted the Safe Systems approach.

The U.S. plan to reduce, and eventually eliminate, traffic fatalities and serious injuries has been given the name Toward Zero Deaths (TZD). The U.S. Department of Transportation has adopted a goal to reduce the fatality rate to less than 1.03 fatalities per 100 million vehicle-miles of travel by 2018. This represents an 18-percent decrease from the 2008 rate of 1.26 fatalities per 100 million vehicle-miles of travel (Performance.gov). More than 30 individual states have adopted goals related to the TZD theme in their strategic highway safety plans. Researchers recently evaluated the four oldest state programs that stated a zero-fatality goal and found that the decrease in fatal crashes was accelerated in these states (Munnich et al., 2012). Improvements in all of the areas listed above – highway infrastructure, vehicle design and technology, enforcement, public education, and emergency medical services – will be needed to meet these goals. The National Safety Council has established a Road to Zero Coalition with over 200 member organizations with the goal of eliminating traffic fatalities in the U.S. within 30 years.

Most state traffic safety goals in the U.S. are presented in terms of reducing fatalities and serious injuries. This focus does not mean that minor injuries and property damage in traffic crashes are unimportant, but it recognizes the high economic and social costs of the most severe crashes. Strategies intended to reduce fatalities and serious injuries not only address the crashes that are the most devastating to families and communities, but also tend to have the highest benefit-cost ratios. Furthermore, many of the improvements made to reduce fatalities and serious injuries should reduce minor injuries and property damage in traffic crashes as well.

1.2 Role of Infrastructure Improvements in Traffic Safety

Road and street infrastructure improvements have had, and will continue to have, an important role in reducing fatalities and serious injuries. While research has shown driver errors to be a contributing factor in the majority of traffic crashes, driver behavior is difficult to change directly. Infrastructure improvements are an important part of traffic safety programs because design changes to the roadway, roadside, and traffic control devices can reduce both the likelihood and consequences of driver errors. For example, rumble strips can help a drowsy driver correct his or her path before leaving the roadway. Behavioral countermeasures, such as targeted enforcement of aggressive driving and driving under the influence of drugs or alcohol, school campaigns encouraging kids to buckle up, and increased penalties for exceeding the speed limit in certain areas, are an important part of the overall strategy to improve highway safety. Both infrastructure investments and behavioral countermeasures will have an important role in moving Toward Zero Deaths in the U.S.

Recent changes in vehicle design and technology have improved the crashworthiness of vehicles, making collapse of the vehicle structure into the passenger compartment less extensive and less likely, while airbags restrain driver and passenger movement and cushion impacts during collisions to reduce injury. Vehicle technologies including anti-lock braking systems, electronic stability control systems, and adaptive cruise control reduce the likelihood of crashes. Drivers and passengers can attain these benefits merely by purchasing a new or late-model used vehicle, even if drivers make no conscious changes in their driving behavior.

Improvements to road and street infrastructure are effective in reducing traffic crashes because they constrain driver behavior even without the need for a conscious decision by drivers to behave differently. Infrastructure improvements that improve safety include high-cost improvements such as:

- provision of fully access-controlled freeways with no at-grade intersections or driveways where vehicle paths can conflict
- provision of grade separations at intersections and for pedestrian crossings
- addition of medians to undivided roadways

The first two improvement types eliminate right-angle and turning conflicts where driver misjudgments can result in collisions. The third improvement type separates the traffic lanes in opposing directions of travel and makes head-on collisions less likely. The U.S. has already made substantial investments in such high-cost improvements, not least of which has been the construction of the Interstate highway system and other freeways.

There are also, however, many medium- and low-cost infrastructure improvements with the potential to reduce crashes by constraining or directing driving paths and driver decisions. Medium- and low-cost improvements are often more cost-effective than high-cost improvements. Examples of such improvements include:

- provision of channelization and turn lanes for at-grade intersections to reduce the potential for vehicle-vehicle conflicts
- provision of traffic signals at intersections, which separates potentially conflicting vehicle movements in time
- conversion of at-grade intersections to roundabouts, which eliminates the potential for right-angle conflicts between vehicles and, therefore, makes right-angle collision far less likely

- improvement of delineation, including pavement markings, post-mounted delineators, and/or chevron warning signs at curves, showing drivers the alignment of the roadway ahead and guiding drivers in steering and sped choice, as appropriate
- provision of widened and paved shoulders to provide a primary recovery area for drives that run off the road and give drivers additional time to undertake corrective action that if no shoulders were present; shoulders can also provide a travel path, outside the traveled way, for any pedestrians and bicyclist traveling along the roadway
- implementation of roadside improvements including clearing roadside objects, flattening roadside slopes, and installing guardrail and other roadside and median barriers
- addition of shoulder rumble strips to provide an aural and tactile warning to drivers that their vehicle is leaving the roadway and calling drivers' attention to the need to take corrective action
- addition of centerline rumble strips provide an aural and tactile warning to drivers on undivided roads that their vehicle is crossing the roadway centerline and calling drivers' attention to the need to take corrective action
- construction of sidewalks provides a surfaced facility for pedestrian travel along the roadway outside the traveled way
- construction of bicycle lanes or bicycle paths provides a surfaced facility for bicycle travel either adjacent to or separated from the lanes reserved for motor-vehicle travel

All of these medium- and low-cost improvements have been implemented extensively on U.S. roads and streets but, as this report will demonstrate, very substantial needs for further improvements still exist.

1.3 Highway Infrastructure Improvement Needs in the U.S.

There have been several recent efforts to estimate highway infrastructure improvement needs in the U.S. For example, the American Society of Civil Engineers (ASCE) prepares a Report Card for America's Infrastructure once every four years. In the 2013 report card, ASCE estimated that the total investment in infrastructure improvements in the U.S. needed over the seven-year period to 2020 was $3.6 trillion (ASCE, 2013). A recent infrastructure needs assessment for one state estimated that up to $60 billion in road and street improvements was needed over the next five years in Illinois (IRTBA, 2013). These national and state assessments, while including safety improvements within their scope, primarily focused on the poor condition of roads and bridges and the high levels of existing congestion. This report focuses exclusively on infrastructure investment needs to improve safety.

1.4 Estimation of Infrastructure Improvement Needs to Reduce Fatal and Serious Injury Crashes

A key objective of this report is to quantify the role that infrastructure improvements should play in future traffic safety improvement programs. There are no published estimates of the magnitude of infrastructure improvement needs or future funding levels for infrastructure improvements specifically to improve safety. Highway agencies typically operate by performing annual screening of highway networks to identify the highest priority improvement needs and programming those infrastructure improvements that can be made within the available budget.

In the past, the data needed to make such estimates may not have been available. The U.S. Road Assessment Program (usRAP) has now completed an assessment of infrastructure improvement needs for over 12,000 mi of roads and streets in the U.S. These usRAP safer roads investment plans identify the type and location of specific needed improvements for a broad range of improvement or countermeasure types. While this sample of roads is relatively small, it is sufficiently diverse that the usRAP safer roads investment plans can be scaled up to estimate national infrastructure improvement needs for a broad range of road and crash countermeasure types. The usRAP results are sufficiently robust to estimate the magnitude of nationwide infrastructure improvement needs. Better estimates can undoubtedly be prepared in the future as the road and street mileage covered by usRAP safer roads investments plans grows.

1.5 U.S. Road Assessment Program Overview

Since usRAP results serve as the basis for the estimates of nationwide infrastructure improvement needs presented in this report, a brief overview of the usRAP program is presented here. A more detailed discussion of the usRAP program is presented in Section 4.

The usRAP program (www.usrap.org) began in 2004 and is modeled after the successful European Road Assessment Program (EuroRAP), which was started in 2000, and Australian Road Assessment Program (AusRAP), which began in 2003. The usRAP program was sponsored by the AAA Foundation for Traffic Safety from 2004 through 2014. The Roadway Safety Foundation began sponsoring the program in 2015. usRAP works in partnership with the International Road Assessment Program (iRAP), which was founded in 2005. iRAP works to coordinate the activities of the three founding programs and also performs safety planning studies in low- and middle-income countries.

usRAP star ratings for specific road and street sections are based on a scoring system that considers the presence or absence of specific design and traffic control features. The scores developed with the scoring system are formulated so that they are generally proportional to the risk of fatal and serious injuries in traffic crashes. Separate scoring systems are used to assess the risk of fatal and serious injuries to vehicle occupants, motorcyclists, pedestrians, and bicyclists. Separate risk factors represent crash likelihood and crash severity.

The star ratings for roads and streets range from one to five stars. A one-star road is typically a basic two-lane undivided road lacking most of the design and traffic control features that contribute to safety. A five-star road is typically a multilane divided freeway with most or all of the design and traffic control features that contribute to safety.

Safer roads investment plans are based on assessment of the need for and the potential cost-effectiveness of over 70 crash countermeasures that represent infrastructure improvements. The need for each countermeasure is considered for each 100-m (327-ft) segment of the road and street network being assessed. If a countermeasure makes engineering sense for implementation on a specific road segment, it is considered to be “triggered” as a candidate countermeasure for that segment. A benefit-cost analysis is then conducted for each candidate countermeasure, and countermeasures with benefit-cost ratios that exceed a minimum benefit-cost ratio chosen by the responsible highway agency become part of the recommended investment plan.

1.6 Organization of the Remainder of This Report

Section 2 of this report summarizes current knowledge on the crash reduction effectiveness of specific infrastructure improvement or countermeasure types. This demonstrates the important role that infrastructure improvements can have in reducing fatalities and serious injuries.

Section 3 presents case studies of specific infrastructure improvement projects, giving practical examples of the effectiveness of the crash reduction effectiveness of infrastructure improvements.

Section 4 presents the process by which usRAP safer roads investment plans are developed and describes how the usRAP results were used in developing estimates of nationwide infrastructure investment needs.

Section 5 presents the estimates of nationwide infrastructure improvement needs for reducing fatalities and serious injuries in traffic crashes that were developed in the research and discusses their implications for future infrastructure investment in the U.S.

Section 6 discusses the potential role of star ratings in management of safety improvement programs.

Section 7 summarizes the conclusions and recommendations of the study.

Appendix A presents the estimation methodology for national estimates of infrastructure improvement needs in greater detail than Section 4.

Appendix B summarizes the unit construction costs for infrastructure improvements used in developing the national estimates for infrastructure improvements in Section 4 and Appendix A.

Section 2.
Crash Reduction Effectiveness of Highway Infrastructure Improvements

This section summarizes the crash reduction effectiveness estimates for highway infrastructure improvements and demonstrates that infrastructure improvements can have an important role in reducing crashes. The effectiveness estimates have been presented as percentage reductions in crashes.

Infrastructure improvements can substantially reduce crash occurrence or crash severity by limiting the consequences of poor driver behavior. Highway infrastructure improvements can reduce both the likelihood and severity of crashes in several ways, including by:

- Separating motor vehicles in time and space
- Reducing the potential for vehicle-vehicle, vehicle-bicycle, and vehicle-pedestrian conflicts
- Reducing vehicle speed
- Limiting the angle at which vehicles can collide
- Reducing the likelihood and consequences of collisions with roadside objects

Examples of highway infrastructure improvements that have proven effective in reducing severe crashes include:

- Lane widening
- Shoulder paving and widening
- Alignment improvements (flattening curves, improving superelevation)
- Median treatments
- Adding passing lanes
- Improving roadway delineation
- Installing rumble strips
- Improving the roadside (removing objects, installing barriers, flattening slopes)
- Adding turn lanes at intersections
- Improving signal phasing
- Converting intersections to roundabouts
- Providing or improving pedestrian facilities along the roadside and at crossings
- Providing bicycle facilities

The crash reduction effectiveness of each of these highway infrastructure improvement types is discussed below. The crash reduction effectiveness estimates presented here are drawn primarily from the *Highway Safety Manual,* (AASHTO, 2010; AASHTO, 2014) published by the American Association of State Highway and Transportation Officials, which is based primarily on U.S. research. Other domestic and international research is used for improvement types that the *Highway Safety Manual* does not directly address.

For many improvement types, the usRAP Tools and ViDA software used in past usRAP studies uses algorithms to estimate crash reduction effectiveness that are too complex to present here, but provide crash reduction effectiveness estimates that are similar in magnitude to those presented in this section.

2.1 Lane Width

Widening through travel lanes has proven effective in reducing crashes on rural two-lane highways, rural multilane highways, and rural and urban freeways, particularly for roads with existing lane widths of 10 ft or less. Table 2 summarizes the crash reduction effectiveness of widening lanes by specific amounts on roads with higher volume roads with annual average daily traffic (AADT) volumes of 2,000 veh/day or more (AASHTO, 2010; AASHTO, 2014). The values shown in Table 2 represent the expected percentage reduction in crashes that would result from specific changes in lane width. For example, widening existing 9 ft lanes to 10 ft on a rural two-lane highway would be expected to reduce crashes by 8.9 percent.

By contrast, lane width effects appear minimal on urban and suburban arterials. The AASHTO *Policy on Geometric Design of Highways and Streets* (AASHTO, 2011), commonly known as the *Green Book*, provides substantial flexibility in the use of 10-, 11-, and 12-ft lanes on urban and suburban arterials. In many cases, use of narrow lanes on urban and suburban arterials may have minimum effect on crashes while making room to provide features with known safety benefits including medians, turn lanes, bicycle lanes, and shorter pedestrian crossings.

2.2 Shoulder Width and Type

Shoulders can reduce the likelihood of crashes in several ways, including providing a location for emergency stops and broken down vehicles outside the traveled way, providing a space for drivers of errant vehicles to make steering corrections before leaving the roadway, and providing space for evasive maneuvers. Shoulders also provide space for enforcement activities, maintenance activities, and bicycle accommodations. Table 3 summarizes the crash reduction effectiveness of widening shoulders on higher volume roads with AADTs of 2,000 veh/day or more (AASHTO, 2010; AASHTO, 2014).

Shoulder type also has an effect on crash frequency, although not as substantial as shoulder width. The magnitude of the benefit associated with improving shoulder type depends on the shoulder width; shoulder type improvements have more benefit when the shoulder is wider. The HSM only quantifies the benefits of shoulder improvement for rural two-lane roads and rural multilane undivided roads. The benefits of improving the shoulder on other roadway types is not known, but it is likely that shoulders on urban roadways and freeways are generally paved. Table 4 summarizes the reduction in total crashes that can be realized by paving an existing 6-ft turf, composite, or gravel shoulder on higher volume roads with AADTs of 2,000 veh/day or more (AASHTO, 2010).

2.3 Alignment Improvements

Roadway alignment has an effect on crash likelihood. More crashes are expected along curves than along straight sections of roadway (tangents), and the longer and sharper the curve, the more crashes we expect to see. Vertical curves (hillcrests and sags) can also impact safety if the hill blocks the driver's view of driveways, curves, or obstacles. On some roadway types, the grade of the road has an impact on safety, with more crashes occurring on steep sections of road than on flat sections. The superelevation, or banking, of the roadway on horizontal curves can have an effect on crashes, as well, when it does not provide enough friction to keep car tires from sliding when traveling along a curve, especially in wet or snowy conditions. Crash reduction effectiveness is discussed below for horizontal curves, superelevation, and grade.

Horizontal Curves

The *Highway Safety Manual* (AASHTO, 2010; AASHTO, 2014) quantifies the effect of horizontal curves on crashes for rural two-lane roads and freeways. Horizontal curves generally experience more crashes of all severity levels than tangent roadways. The increase in crash frequency on a horizontal curve, relative to a tangent roadway, generally increases for shorter curves and increases for sharper (i.e., smaller radius) curves. For example, on a rural two-lane road, increasing a curve radius from 500 ft. to 1,000 ft. would decrease crashes along that curve by 30 percent (AASHTO, 2010). On a freeway, increasing a curve radius from 1,000 ft. to 2,000 ft. would reduce crashes by 49 percent (AASHTO, 2014).

Superelevation

The *Highway Safety Manual* (AASHTO, 2010) evaluates the safety impact of superelevation as a comparison of the provided superelevation to the design superelevation indicated by the *Green Book* (AASHTO, 2011). When the *Green Book* design criteria are not met, increasing the superelevation to meet the design standard can reduce crashes along the horizontal curve. For example, for a curve on a rural two-lane road on which the superelevation is 0.03, but AASHTO policy requires a superelevation of 0.06, improving the superelevation to meet this standard is expected to reduce crashes by 8 percent. The safety effect of improving superelevation on other roadway types has not been documented.

Grade

The *Highway Safety Manual* (AASHTO, 2010) describes the expected safety impact of grade on rural two-lane highways. Roadway sections with grades between 3 and 6 percent are expected to have 10 percent more crashes than roadway sections that are level or have grades less than 3 percent. Steep roadway sections, with grades greater than 6 percent are expected to have 16 percent more crashes than flat roadway sections. The effect of grade on other roadway types has not been documented.

2.4 Median Treatments

Medians between opposing lanes of travel separate vehicles traveling in opposite directions and reduce chances for conflict between them. They also provide a space to include left turn lanes at intersections. Converting an undivided roadway to a divided roadway has substantial safety benefits. For roadways with existing medians, some reduction in crashes can be achieved by increasing the median width. Table 5 shows typical crash reductions expected as a result of converting an undivided highway to a divided highway and increasing the width of the median. To determine the anticipated crash reduction of converting an undivided highway to a divided highway, a traffic volume of 10,000 vehicles per day was assumed. The percent crash reduction for median widening is independent of volume. These values also assume that no barrier is present in the median.

2.5 Passing Lanes

Providing passing lanes on rural two-lane highways not only increases operational efficiency, but results in safety benefits as well. When the passing lane is warranted and the correct length for operational conditions is chosen, it is expected to reduce crashes along the segment of roadway with the passing lane by 25 percent (AASHTO, 2010). When a passing lane is provided in both directions of travel to create a short four-lane section, crashes along that segment of roadway can be reduced by 35 percent (AASHTO, 2010). Passing lanes are generally not applicable on other roadway types.

2.6 Roadway Delineation

Roadway delineation treatments include providing wider centerline and edge line striping, rumble stripes (where the edge line or centerline stripe is painted over rumble strips), raised pavement markers, flexible delineators, or other treatments that help the drivers see the boundaries of the driving lanes so they can more easily stay within them. These treatments are especially beneficial at night and on wet pavement, when traditional striping may be less visible. Delineation treatments can have the highest benefit-cost ratio when installed in conjunction with resurfacing or other roadway work. Table 6 shows anticipated percent fatal-and-injury crash reductions for various delineation treatment packages by roadway type (Potts et al., 2011).

2.7 Rumble Strips

Rumble strips can be placed on the shoulder (or edge line of the road) or on the centerline of undivided highways to alert drivers through noise and vibration when one or more of the vehicle's tires begin to encroach on either the shoulder or opposing lanes of traffic. Shoulder (or edge line) rumble strips are used to alert drivers who begin to run off the road and, therefore, reduce run-off-the-road crashes. Centerline rumble strips are used on undivided roads to alert drivers that they are crossing the roadway centerline and, therefore, to reduce cross-centerline collisions. The *Highway Safety Manual (*AASHTO, 2010) quantifies the safety effect of centerline rumble strips on rural two-lane highways and shoulder rumble strips on freeways. On rural two-lane highways, centerline rumble strips can reduce total crashes by 6 percent (AASHTO, 2010). On freeways, shoulder rumble strips installed on only one side of the traveled way (outside or inside shoulder in both directions of travel) can reduce total crashes by 2.5 percent, and rumble strips installed on both the inside and outside shoulder can reduce total crashes by 5.0 percent (AASHTO, 2014). Rumble strips are most effective at reducing severe single-vehicle crashes, so even the modest reduction in total crashes can provide a large safety benefit in terms of reducing some of the most severe crashes.

2.8 Roadside Improvements

The roadside hazard rating (RHR) is a rating scale from 1 (best) to 7 (worst) used to evaluate the safety of roadsides along two-lane roads. The scale accounts for clear zones, roadside surface, roadside barriers, roadside fixed objects, sideslopes, and other factors. The *Highway Safety Manual* (AASHTO, 2010) uses RHR to quantify the benefit of improving the roadside on rural two-lane roads; expected percent crash reductions are shown in Table 7.

For multilane undivided highways, the safety effectiveness of sideslope improvements is quantified in the *Highway Safety Manual* (AASHTO, 2010). The percentage crash reduction that can be achieved by flattening sideslopes is shown in Table 8.

For urban and suburban arterials, the *Highway Safety Manual* (AASHTO, 2010) quantifies the safety impact of the density of fixed objects along the roadside and the distance those objects are from the traveled way. Table 9 shows the percentage reduction in total crashes typical for various cross sections of urban/suburban arterial as the density of fixed objects is reduced. (Fixed objects are those with a diameter 4 inches or greater without breakaway design. Continuous objects are recorded as a point object for every 70 ft of length.) Table 10 presents comparable data for changes in offset to fixed objects assuming a constant fixed object density of 50 objects per mile.

2.9 Adding Turn Lanes at Intersections

At intersections with minor-road stop control, providing left-turn lanes on the major-road (uncontrolled) approaches, provides turning vehicles a place to wait for gaps in opposing traffic without impeding through traffic. This minimizes the likelihood that left-turning vehicles will be struck from behind by same-direction through traffic, and eliminates queues that would otherwise form in the travel lane as left-turning drivers waited for gaps. In addition, left-turning drivers are less likely to accept very short gaps, which put them at risk for angle collisions with opposing traffic, because they do not experience pressure from the presence of following drivers who must wait for the turning vehicle before they can continue through the intersection. At signalized intersections, left-turn lanes perform a similar function—removing the left-turn driver from the path of through vehicles so that through traffic is not impeded when a driver is waiting for a gap to make the turn.

Right-turn lanes serve a similar role in that they allow slow-moving turning vehicles to decelerate to a safe turning speed outside of the path of through-moving vehicles.

The *Highway Safety Manual* (AASHTO, 2010) has quantified the safety benefit of adding left- and right-turn lanes to the major-road (uncontrolled) approaches at two-way stop-controlled intersections and to all approaches at signalized intersections. The typical percent crash reductions for adding turn lanes to an intersection with no turn lanes is presented in Table 11 for urban and suburban arterials and in Table 12 for rural highways (AASHTO, 2010). No comparable information is available for three-leg signalized intersections on rural highways.

2.10 Improving Signal Phasing and Timing

Protected left-turn signal phasing, in which left-turning drivers are given a green arrow display during the signal phase in which left-turns are permitted, eliminates the need for drivers to judge whether gaps in oncoming traffic are long enough to safety complete the turn. During a protected phase, opposing traffic is shown a red indication, so no opposing traffic will conflict with the left-turn movement. Permissive/protected (or protected/permissive) phasing uses a combination of the green arrow (protected phase) and green ball (permissive phase) for left-turning drivers, so that some amount of time during each signal cycle is allocated for left-turning drivers to make the turn without having to judge gaps in oncoming traffic.

The *Highway Safety Manual* (AASHTO, 2010) quantifies the safety benefit of changing permissive only left-turn phasing to permissive/protected or protected only phasing on urban and suburban arterials. Typical crash reductions are shown in Table 13.

2.11 Converting Conventional Intersections to Roundabouts

While a conventional four-leg intersection has up to 32 points at which vehicle-vehicle conflicts can occur and 24 points at which vehicle-pedestrian conflicts can occur, a roundabout only has 8 of each type of conflict point. In addition, the design of a roundabout is such that the conflicts between vehicles that do occur are at flat angles and are unlikely to result in potentially severe right-angle collisions. Because of these factors, roundabouts generally experience both lower crash frequencies and severities than conventional intersections. The *Highway Safety Manual* (AASHTO, 2010) indicates that converting a stop-controlled intersection to a roundabout can reduce injury crashes by 82 percent, while converting a signalized intersection to a roundabout can reduce injury crashes by 78 percent.

2.12 Providing or Improving Pedestrian and Bicycle Facilities

This section addresses the crash reduction effectiveness of pedestrian and bicycle facilities. These estimates are less certain that the preceding estimates, because evaluation research often has limited data on pedestrian and bicycle flows at the sites being evaluated.

Table 14 shows the typical percentage reduction in pedestrian fatalities and serious injuries from installation of a pedestrian crossing facility at a location where there is existing pedestrian crossing flow but no crossing facility (iRAP, 2014). These estimates assume that the pedestrian flow crossing the road does not change from before to after implementation of the pedestrian crossing. Research has also shown that improving an existing pedestrian crossing facility of poor quality (e.g., poor signing, poor marking, and/or limited sight distance) can reduce fatal and serious injury crashes by 50 percent (iRAP, 2013).

Table 15 shows the typical percentage reduction in pedestrian fatalities and serious injuries from installation of a sidewalk or shoulder to facilitate pedestrian movement where there is existing pedestrian flow along a roadway but no sidewalk or shoulder (iRAP, 2014a). These estimates assume that the pedestrian flow along the roadway does not change from before to after implementation of the sidewalk or shoulder.

Table 16 shows the typical percentage reduction in bicyclist fatalities and serious injuries from installation of a bicycle facility or shoulder to facilitate bicycle movement where there is existing bicycle flow along a roadway but no bicycle facility or shoulder (iRAP, 2014b). These estimates assume that the bicycle flow along the roadway does not change from before to after implementation of the bicycle facility or shoulder.

Section 3.
Case Studies of the Crash Reduction Effectiveness of Highway Infrastructure Improvements

This section presents seven case studies that each show the safety benefits that were realized after the implementation of a specific highway infrastructure improvement in a real-world project. These case studies were developed with the assistance of the state departments of transportation in Iowa, Kentucky, Minnesota, Missouri, Nevada, Utah, and Washington. The infrastructure improvements highlighted in this chapter include:

- Case Study 1—Roadside slope improvement (rural two-lane highway)
- Case Study 2—Addition of 2-ft paved shoulder (rural two-lane highway)
- Case Study 3—Continuous centerline rumble strips (rural two-lane highway)
- Case Study 4—Shoulder rumble strips (rural four-lane divided highway)
- Case Study 5—Improvement of curve quality (rural two-lane highway)
- Case Study 6—Provision of passing lanes (rural two-lane highway)
- Case Study 7—Cable median barrier (rural four-lane divided highway)

Each case study includes a description of the improvement being highlighted and location at which it was implemented; a discussion of specific application of the improvement in the showcased project; the safety benefits of the treatment in terms of crash reduction (usually highlighting specific reductions in targeted crash types and severity levels); the change in the usRAP star rating of the roadway from the before condition to the after condition; the cost of improvement installation and maintenance; and any other relevant considerations for the improvement, such as operational impacts.

None of the case study projects involved right-of-way acquisition. The project costs presented in the case studies represent what was spent on a specific project at a specific site by a specific agency, but is not necessarily representative of all similar projects. Project costs may vary from site to site and agency to agency.

The case studies are not formal evaluations of the crash reduction effectiveness of the infrastructure improvements. Formal effectiveness evaluations need multiple sites to provide reliable effectiveness estimates. Rather, these case studies are intended to provide practical examples showing that the crash reduction effects of infrastructure improvements shown in Section 2 are not just theoretical; real-world projects show substantial crash reduction benefits. Naturally, these benefits do not exactly match the effectiveness estimates presented in Section 2; those estimates are average values based on safety research. Real-world projects can provide benefits either higher or lower than the estimates in Section 2. Rather, the case studies provide a few examples of actual benefits realized from implementation of infrastructure improvements.

3.1 Case Study 1: Flattening the Roadside Slope

Case Study 1 illustrates the effectiveness of a roadside slope improvement on safety for a rural two-lane undivided highway. Forgiving roadside slopes are intended to reduce the severity of run-off-the-road crashes—one of the most common crash types on rural highways—by reducing the likelihood that out-of-control vehicles will roll over after they leave the roadway and by increasing the likelihood that a driver on the roadside will be able to recover control of the vehicle and return to the roadway. Since rollover crashes are typically very severe, decreasing the likelihood of rollover provides a substantial safety benefit in reduced crash severity even if the total number of run-off-the-road events does not change. The crash data evaluation presented in this case study shows a large reduction in both total crashes and fatal and severe injury crashes.

Description of Infrastructure Improvement

Between 2005 and 2013, the Nevada Department of Transportation (NDOT) conducted several projects to improve roadside slopes in rural areas of the state. Case Study 1 considers one such project on a 10-mi section of rural two-lane highway connecting two small towns. In this 2008 project, the focus was slope flattening, although centerline rumble strips were added and guardrail was installed in a few locations. The existing 1:2 to 1:3 slopes were flattened to 1:6. Figure 2 presents a photograph of a typical portion of the project prior to the roadside slope improvement, while Figure 3 shows a typical portion of the project after the improvement was made. Typical roadway characteristics for the sections are summarized in Table 17. Three years of crash data before construction and three years of crash data after construction as well as roadway characteristics typifying this section were obtained and compared.

Project Benefits

Table 18 presents the observed crash frequencies and rate for the 10-mi section before and after the project. In the three-year period before the slopes were improved there were 58 total crashes and 26 injury crashes. In the three-year period after the slopes were improved there were only 26 total crashes (a 55-percent reduction), with only 6 injury crashes (a 75-percent reduction). Because the traffic volumes in the before and after analysis periods were similar, the percent change in crash rate was very similar to the percent change in crash frequency.

Project Costs

According to Nevada Department of Transportation officials, the roadside slope improvement for this site cost $4,400,000.

Star Ratings

Prior to the roadside slope improvement project, a representative section of the project was rated at two stars for vehicle occupants according to usRAP criteria. The slope improvement raised the star rating of the roadway in the after period to three stars.

3.2 Case Study 2: Adding a Narrow Paved Shoulder

Case Study 2 illustrates the effectiveness of adding a narrow paved shoulder on a rural two-lane highway. This improvement directly addresses the frequency and severity of single-vehicle run-off-road (SVROR) crashes by providing additional area for recovery maneuvers when a driver drifts from the travel lane and, depending on design, can also provide a visual, audible, and tactile signal to alert the driver as they leave the travel lane. The benefits of providing paved shoulders include reduced crash frequency for certain crash types (e.g. roadway departure), reduced maintenance needs, and improved facilities for bicyclists and other road users. Paved shoulders reduce crash severity by reducing the likelihood that vehicles will run off the road onto the roadside and strike fixed objects or roll over on steep slopes. Paved shoulders also have the potential to reduce head-on and sideswipe crashes by making it easier for drivers to move out of the path of opposing-direction vehicles that cross the roadway centerline.

Description of Infrastructure Improvement

The existing rural two-lane highway for Case Study 2 was a 4.3-mi section of rural secondary (county) road with gravel shoulders approximately 6 ft. wide on both sides of the road. The shoulder width varied somewhat, particularly with wider shoulders near intersections and narrower shoulders near bridges. Pavement/shoulder edge drop-offs had developed at various locations along the corridor.

The improvement for Case Study 2 was the provision of 2-ft paved shoulders along the study corridor. The paved shoulders consisted of asphalt with a depth of 6 in. This created a composite shoulder consisting of a 2-ft paved shoulder, outside of which was a 4-ft gravel shoulder. The project was funded by the Iowa Department of Transportation with high risk rural roads (HRRR) funds because it was experiencing higher rates of severe crashes than other similar roadway segments in the state.

Figure 4 illustrates the shoulder paving improvement for Case Study 2 with a post-project photograph of a shoulder transition at one end of the project. This photo shows the roadway cross section both with and without the added 2-ft paved shoulder. A pavement/shoulder edge drop-off is visible in Detail A of Figure 4. Figure 5 shows a typical section of the roadway after construction of the 2-ft paved shoulder.

As part of the HRRR program, severe (fatal and serious injury) crash density and rate were computed for all eligible roadways throughout the state using data from 2001 to 2007. A 1.9- mi portion of this project had a crash density in the top five percent of eligible routes statewide leading to an application for funding. In this application, the county engineer proposed addition of the 2-ft wide, 6-in thick hot-mix asphalt paved shoulder. The objective of the project was to alleviate a shoulder-rutting problem which had been a safety issue in the past.

In addition, the corridor was identified as having "an extraordinary amount of commuter traffic" which was expected to continue without improvements to other alternate routes. In 2009, the 2-ft paved shoulders were added to both sides of the existing two-lane roadway. Table 19 shows the representative roadway characteristics along the project.

Project Benefits

The objective of this project was to reduce the frequency and severity of crashes along the corridor—particularly crashes related to shoulder rutting and pavement/shoulder edge drop-offs, which are typically SVROR crashes. Table 20 presents a summary of crash experience along the project corridor for the five years before and five years after the project. Crash frequencies and rates are presented by crash severity level for all crash types combined and for SVROR crashes. SVROR crashes are explicitly considered because they are indicative of crashes traditionally mitigated by the addition of paved shoulders.

Table 20 shows that crash rates in the project corridor for all crash severity levels combined decreased by 41 percent between the periods before and after the project. Fatal and all injury crash rates decreased by 60 percent, while fatal and serious injury crashes decreased by 100 percent. SVROR crashes decreased by 73 percent for all crash severities combined, by 72 percent for fatal and all injury crashes, and by 100 percent for fatal and serious injury crashes.

Crash frequencies and rates also decreased on comparable nearby roads, as shown in Table 21. This indicates that the estimates in Table 20 may overstate the project effectiveness, but this effect can be easily adjusted for. The net project effects, considering the results in both Tables 20 and 21, can be estimated as follows. For all crash types combined, the project is estimated to have reduced crashes of all severity levels by 17 percent, fatal and all injury crashes by 36 percent, and fatal and serious injury crashes by 99 percent. For SVROR crashes, the project is estimated to have reduced crashes of all severity levels by 61 percent, fatal and all injury crashes by 52 percent, and fatal and serious injury crashes by 99 percent.

Project Costs

The estimated cost of construction of 2-ft paved shoulder for a two-lane undivided roadway ranged from $68,200 to $73,800 per mile for both directions of travel combined. The estimated cost for the full 4.3-mi project was $305,000.

Star Ratings

Prior to the addition of the paved shoulder, the usRAP star rating for the roadway was three stars for vehicle occupants. After the shoulder paving, the usRAP star rating was still within the three-star band, but the star rating score increased by 4.6 percent.

3.3 Case Study 3: Providing Centerline Rumble Strips on an Undivided Highway

Case Study 3 illustrates the effectiveness of installing centerline rumble strips on a rural two-lane undivided highway. When a vehicle traverses a centerline rumble strip, it creates aural and tactile sensations that warn the driver that the vehicle is leaving its lane and entering a lane reserved for traffic in the opposing direction of travel. This increases the likelihood that the driver will take early corrective action to return to the proper side of the roadway. Centerline rumble strips are intended to reduce the incidence of head-on collisions, opposite-direction sideswipe collisions, and run-off-the-road crashes that occur on the left side of the road (i.e., after an out-of-control vehicle completely crosses the opposing lanes). Lane-departure crashes of these types are often very severe.

Centerline rumble strips are milled-in transverse cuts, approximately 1-ft wide, placed continuously along the centerline of an undivided road. Often centerline striping is painted after milling which provides a vertical face which enhances pavement marking retroreflectivity. Examples of centerline rumble strips are shown in Figure 6.

Description of Infrastructure Improvement

The Kentucky Transportation Cabinet (KYTC) embarked on a statewide centerline rumble strip program in the early 2000s. As part of this program, 34 rural two-lane highway sections were improved with installation of centerline rumble strips in 2011. Four years of crash data from both before and after centerline rumble strip installation were obtained and analyzed.

Case Study 3 addresses the collective crash reduction effectiveness for the installation of rumble strips on all 34 highway sections combined. Typical roadway characteristics for the sections are summarized in Table 22.

Project Benefits

An assessment of project effectiveness was conducted using four years of crash data from periods both before and after installation of the rumble strips. Crash data for the centerline rumble strip installation year (2011) were excluded from the analysis.

Table 23 presents crash frequency and crash rate data for the periods before and after centerline rumble strip installation for the 34 improved highway sections combined. Because the average traffic volumes for the 34 highway sections were the same both before and after rumble strip installation, the percentage change in crash frequency and crash rate is the same for both measures. In the four-year period before the rumble strips were installed, there were 23 fatal crashes in the sections. In the four-year period after the rumble strips were installed, there were only 12 fatal crashes—a decrease of 48 percent. By contrast, statewide fatal crashes in Kentucky decreased only 13 percent between the same periods. Table 23 shows that the decreases in nonfatal injury crashes and property-damage-only crashes were smaller than the decrease in fatal crashes. There was a decrease of 8 percent in all injury crashes combined and an increase of 2 percent in property-damage-only from before to after rumble strip installation; both of these results roughly correspond to the statewide changes in crash frequencies between the same periods. Thus, it appears that centerline rumble strips were most effective in reducing fatal crashes on these sites.

Similar analyses found an 80-percent reduction in fatalities in head-on crashes from before to after and a 29-percent reduction in fatalities in lane-departure crashes.

Project Costs

The estimated installation cost for centerline rumble strips in Kentucky is $0.30 per foot or approximately $1,500 per mi. Therefore, the approximate rumble strip installation cost for all 34 improved highway sections combined was $163,500.

Star Ratings

Prior to the addition of the centerline rumble strips, the usRAP star rating for the roadway was three stars for vehicle occupants. After the rumble strip installation, the usRAP star rating was still within the three-star band, but the star rating score increased by 6 percent.

3.4 Case Study 4: Installing Shoulder Rumble Strips

Case Study 4 illustrates the effectiveness of shoulder rumble strips in reducing the number and severity of roadway departure crashes, which account for about one-third of fatalities and major injuries each year on U.S. highways. Shoulder rumble strips are grooved (milled or rolled into the pavement) or raised strips placed longitudinally on the paved shoulder close to the outside edge of the traveled way. When a vehicle traverses a shoulder rumble strip, it creates aural and tactile sensations that warn the driver that the vehicle is leaving the road. This increases the likelihood that the driver will take early corrective action to return to the road. Shoulder rumble strips do not reduce the overall frequency of roadway departures, but do reduce the likelihood that a roadway departure will become a run-off-road crash.

Description of Infrastructure Improvement

The Utah Department of Transportation (UDOT) began installing centerline and shoulder rumble strips on selected corridors in 2009 and, by 2012, had installed over 220 mi of centerline and shoulder rumble strips.

Case Study 4 addresses shoulder rumble strips installed in 2011 on a 12.1-mi section of rural freeway. UDOT installed continuous shoulder rumble strips with a width of 12 in on the inside and outside shoulders of the freeway in both directions of travel. The offset from the edge of the traveled way to the shoulder rumble strip was approximately 12 in for the outside shoulder and 8 in for the inside shoulder. Both shoulders already had intermittent shoulder rumble strips at 50-ft intervals that were approximately 5-ft long and 2-ft wide toward the outside edges of both the outside and inside shoulders. The project in Case Study 4 supplemented the intermittent shoulder rumble strips with continuous shoulder rumble strips. The intermittent shoulder rumble strips were left in place, although they will likely not be retained after the next shoulder resurfacing.

Figure 7 shows a typical location on the freeway before continuous shoulder rumble strips were installed. The red boxes on the shoulder indicate the position of the existing intermittent rumble strips. Figure 8 shows the installation of the continuous shoulder rumble strips on the same segment of roadway. The black arrows reveal the locations of continuous rumble strips on both the outside and inside shoulders. The red boxes also show the continued presence of existing intermittent rumble strips and the distance between them.

The roadway attributes for this project are shown in Table 24.

Project Benefits

Table 25 presents crash frequency and crash rate data for the periods before and after shoulder rumble strip installation for Case Study 4. The table shows that all crashes decreased by 47 percent from before to after the project. Road-departure crashes decreased by 72 percent for all crash severity levels combined, with the largest decreases for fatal-and-injury crashes. The table shows that on a rural freeway like the case-study site, run-off-road crashes are often the predominant crash type (71 percent of total crashes in the before period, in this case).

Star Ratings

Prior to the installation of the shoulder rumble strips, this freeway section has a usRAP star rating of four stars for vehicle occupants. The addition of the rumble strips improved the star rating to five stars.

Project Costs

Installation of the continuous shoulder rumble strips along this 12.1-mile section of rural freeway was funded through a larger multi-site rumble strip project. Therefore site specific project costs could only be estimated. The estimated cost was $69,000 to $100,000 depending on which project elements are considered. For example, the low estimate includes only construction mobilization and traffic control costs, while the high estimate also includes preconstruction and construction engineering, pavement marking installation, and administration costs. The overall cost for adding continuous shoulder rumble strips was approximately $0.27 to $0.39 per linear foot.

3.5 Case Study 5: Improving Curve Delineation

Case Study 5 illustrates the effectiveness of improving delineation of a horizontal curve by installing chevron signs to alert drivers to changes in the horizontal roadway alignment and help guide them through a curve or series of curves. Curve delineation improvement has the potential to reduce the incidence of run-off-road crashes or cross-centerline crashes related to overcorrection in steering on curves. According to the Federal Highway Administration, 58 percent of roadway fatalities are lane departures and 40 percent of fatalities are single-vehicle run-off-road (SVROR) crashes. Curve delineation improvement is one treatment to address these types of crashes.

Properly installed chevron signs can be used to indicate the direction and sharpness of a curve to drivers. Chapter 2 of the MUTCD (FHWA, 2009) covers standard application of chevrons. Table 2C-2 of the MUTCD recommends the size of chevron alignment (W1-8) signs by roadway type. Chevron sizes range from 18 in by 24 in for conventional roads to 36 in by 48 in for freeways. Several agencies have applied a larger chevron size to a roadway than suggested by the MUTCD in order to further increase the visibility of the signs to drivers. These larger chevrons may be especially helpful if sight distance is limited.

Description of Infrastructure Improvement

The Minnesota Department of Transportation (MnDOT) initiated a statewide horizontal curve improvement program in 2013 and 2014. As part of this program, 54 curves that had experienced one or more crashes during a three-year period were treated with high-visibility chevrons. A typical chevron installation for a horizontal curve on a rural two-lane highway in Minnesota is shown in Figure 9. Case Study 5 documents the crash reduction effectiveness of the chevrons installed for improved delineation at the 54 curve sites. Typical roadway characteristics for the 54 curves are summarized in Table 26.

Project Benefits

The effectiveness of chevron sign installation for this set of curves was assessed with one to three years of crash data before and after installation of each set of curve chevrons. The duration of the assessment periods before and after chevron installation was the same. Crash data for the year of installation was excluded from the analysis.

Table 27 presents data for total crash frequency and crash frequency per year for the 54 improved curves after installation of the chevron signs. In the one- to three-year periods before the chevrons were installed, a total of 65 crashes of all crash severity levels combined occurred along the curves. In the one- to three-year periods after the chevrons were installed, a total of only five crashes occurred, a reduction in crash frequency of 92 percent.

Project Costs

MnDOT estimates an average cost of $3,000 per curve for installation of chevrons.

Star Ratings

Prior to the installation of the curve chevrons, a representative curve in the data set has a usRAP star rating of two stars for vehicle occupants. The addition of the curve chevrons raised the star rating of the curve to three stars.

3.6 Case Study 6: Installing Passing Lanes

Case Study 6 illustrates the effectiveness of installing passing lanes on rural two-lane roads. Passing lanes are intended to reduce the incidence of head-on and opposite-direction sideswipe collisions during passing maneuvers and may have an effect on same-direction sideswipe crashes and run-off-the-road crashes, as well. These crash types are typically very severe.

Passing lanes are typically added on rural two-lane roads to improve traffic operations by providing assured passing opportunities and breaking up traffic platoons without the need for passing vehicles to wait for a gap in opposing traffic. Passing lanes also have documented crash reduction benefits.

Description of Infrastructure Improvement

The Missouri Department of Transportation (MoDOT) added passing lanes for approximately 75 mi of a rural two-lane highway in the southeastern part of the state. One 12-mi passing lane project was chosen to demonstrate the effectiveness of this type of improvement. The project was implemented by restriping the roadway to provide an added passing lane and reducing the shoulder width on the two-lane side of the road to 2 ft. Centerline rumble strips were also installed as part of the project. Figure 10 shows a typical section of the project corridor prior to the installation of the passing lane. Figure 11 shows the road section after the passing lane was constructed in 2008. Five years of crash data before and after construction were obtained and analyzed.

Roadway attributes for the passing lane improvement site are summarized in Table 28.

Project Benefits

Table 29 presents the observed crash frequencies and rates for the 11.47-mi road section before and after the project. The crash rate for fatal and all injury crashes combined decreased by 10 percent from before to after the project, while the crash rate for property-damage-only crashes increased by 8 percent.

The project also provided an improvement in the traffic operational level of service for the roadway.

Project Costs

The cost of the project was minimal because the passing lanes were implemented by restriping the existing travel lanes and shoulders.

Star Ratings

The roadway had an overall usRAP star rating of three stars both before and after the project. There was a slight increase in the star-rating score with passing lane installation because the shoulder on the side on the two-lane side of the road was narrowed and a portion of the traffic stream moved closer to roadside objects on that side of the road.

3.7 Case Study 7: Installing Median Cable Barrier

This case study illustrates the effectiveness of installing cable barrier in freeway medians to constrain out-of-control vehicles that run into the median from continuing across the median, entering the opposing traffic lanes, and colliding with an opposing vehicle. Such cross-median crashes are often very severe – typically much more severe than the outcome of the out-of-control vehicle striking the cable barrier.

Description of Infrastructure Improvement

Median cable barriers are used to prevent vehicles from crossing through the median and colliding with an opposing vehicle after a vehicle runs off the left (median) side of the road on a divided highway or freeway. Figure 12 shows a typical cable barrier on a freeway in Missouri. The cables absorb the impact of the vehicle and redirect its path along the cable, often bringing the vehicle to a stop rather than allowing the vehicle to continue toward opposing traffic or back into adjacent travel lanes. Most cable barrier systems use three or four strands of twisted wire rope spaced at intervals vertically above the level of the shoulder and traveled way. The cables are mounted to weak posts (i.e. posts that can break away when a vehicle strikes the barrier). The posts are spaced at regular intervals of 6 to 20 ft. along the length of the barrier.

Low-tension median cable barriers use large springs at both ends of the cable run that are compressed only enough to eliminate sag between the posts supporting the cables. Low-tension cables deflect laterally as much as 12 feet when struck by a vehicle; therefore these systems are appropriate for use on highways with medians at least 30 ft. wide. Low-tension cable systems become disabled during a vehicle strike and must be repaired before they can function properly again.

High-tension cable barrier systems consist of wire rope placed on the posts of the barrier system with the cables then tensioned to between 2,000 and 9,000 lb. The posts rest loosely in sleeves mounted in concrete footings. During a vehicle impact, the posts are designed to slip out of their sleeves, but the tensioning keeps the cables at the proper height even when several posts have come out of their sleeves. While not designed to withstand a subsequent impact, high-tension cable barriers have been shown to be able to do so. The cable runs can be long, breaking only for median openings or bridges; generally the end anchorages are from 300 ft. to 1 mi apart. High-tension cable barriers have less lateral deflection than low-tension cables and can therefore be placed close to the shoulder of the roadway and used in narrower medians.

Cable barrier is often chosen over other types of median barrier such as concrete barriers or steel W-beam guardrail because cable barriers are generally less expensive per mile to install and because they are less likely than other barrier types to redirect out-of-control vehicles back into the adjacent lanes of traffic.

The Missouri Department of Transportation (MoDOT) began installing median guard cable on a systemwide basis in 2002, prioritizing sites based on the following factors:

- Interstate system first
- Highest volumes first
- More than 0.8 cross-median crashes/100 million veh-mi of travel
- Median width/conditions

The early success of these installations led to additional installations across the state. MoDOT completed their initial median cable barrier installation program in 2009 with over 600 mi of cable installed on interstates major freeways and some divided highways (nonfreeways). More than 200 additional mi of median cable barrier were installed on Missouri freeways between 2010 and 2013.

This case study illustrates the safety effectiveness of cable barriers installed in the median on a 42-mi section of freeway in Missouri. The cable median barrier on this roadway section was installed in December 2008. The roadway attributes for this project are summarized in Table 30. These roadway attributes varied little along the 42-mi corridor.

Table 31 summarizes the characteristics of the median cable barrier installation. The median cable barrier was installed on December 15, 2008. The effectiveness evaluation for the project used January 1, 2003, to September 30, 2008, as the study period before barrier installation and January 1, 2009, to December 31, 2014, as the study period after barrier installation.

Table 32 presents the weighted average of annual average daily traffic volume (AADT) along the length of the study corridor for each year of data included in the analysis. The total two-directional AADT is also shown as well as the total vehicle miles traveled along the corridor in each year of the study. Note that the installation date of the cable barrier was December 2008 so the months of October through December 2008 were considered the construction period and excluded from the analysis period.

Project Benefits

The safety benefits of cable median barrier are best realized when the treatment is applied on a system-wide or systematic basis to all sites that meet certain criteria. The benefits of the treatment are reduced when the barrier is placed only at locations where cross-median crashes have previously occurred. This is because the location of crashes and especially fatal crashes along highways is somewhat random; location of one fatal cross-median crash does not necessarily help predict the location of the next.

After systemwide installation of cable median barrier on Interstate freeways with narrower medians, MoDOT stated the following in 2009:

- On Interstate Route 70 in 2002, there were 24 fatalities involving cars that crossed over the median. In 2007, a year after guard cable was completely installed on all of I-70 there were two fatalities involving a cross-median crash. In 2008, there was one fatality involving a cross-median crash.
- On Interstate Route 44, the number of fatalities from 2002 to 2005 rose significantly from 16 fatalities in 2002 to 25 fatalities in 2005. In 2007, a year after guard cable was completely installed on all of I-44, there was one fatality involving a cross-median crash. In 2008 there were no cross-median fatalities on I-44.
- A study completed on Interstate 70 showed that guard cable succeeded in stopping cars from crossing into the opposing lanes of traffic 94 percent of the time.

This case study addresses only a limited 42-mi portion of the freeway system on which MoDOT installed median cable barrier in December 2008. The change in crashes due to installation of the median cable barrier is shown in terms of crash frequency and crash rate (crashes per million vehicle miles traveled). Crash rate takes into account changes in AADT from year to year, available years of crash data, and segment length so that values from year to year can be compared. The comparison is shown for all severity levels combined all fatal and severe injury crashes (F&S) and all fatal and injury crashes (including minor and apparent injuries). These severity categories are presented for both total crashes (all crash types) as well as cross-median and barrier crashes. Note that barrier crashes were not possible in the years 2003 through 2008 (the before period) because the barrier had not yet been installed; however both cross-median and barrier crashes were possible after the installation of the barrier because in some cases the vehicle may have traveled over or under the barrier or crossed the median in one of the small areas where no barrier was installed. Crash frequencies and crash rates are presented in Table 33 for the periods before and after project implementation.

Median barrier cable is effective in reducing fatalities and serious injuries because it essentially reduces the severity of crashes that occur when a driver leaves the travel lanes and enters the median. These vehicles are prevented from entering the opposing lanes of travel and hitting another vehicle head on. Head-on crashes on high-speed facilities tend to be some of the most severe crashes so reducing these crash types tends to produce higher benefits. At the same time the median cable barrier can result in a higher number of property damage only (PDO) crashes since it can entangle vehicles of drivers who may have otherwise been able to recover in the median and re-enter the proper travel lanes to complete the trip. Generally the cost associated with the increase in total crashes is more than offset by the benefits of reducing fatal and serious injury crashes. Agencies generally see a decrease in total crash costs as well as average cost per crash.

Table 33 presents the observed before-after changes in specific safety measures for the 42-mi median cable barrier installation. There was an overall increase of about 2.5 percent in the crash rate per 100 million veh-mi of travel from before to after the median cable barrier installation for all crash types and severity levels combined along the corridor. However fatal crashes decreased by over 50 percent and serious injury crashes decreased by more than a third. Cross-median crashes decreased by over 90 percent after installation of the median cable barrier. Fatal and serious injury cross-median crashes went from nine in the before period to zero in the after period. In the six-year period after the cable median barrier was installed there were 36 barrier-related crashes along the 42-mi corridor and 11 of these resulted in a fatality or injury (1 fatal crash 2 disabling injury crashes and 8 minor injury crashes). When looking at all cross-median crashes and barrier-related crashes combined crashes of all severity levels combined decreased by 33 percent and fatal and serious injury crashes decreased by 67 percent.

Project Costs

Installation of high tension cable median barrier is approximately $100,000 to $125,000 per mile. Annual maintenance costs vary with the frequency the cable barrier is struck which is primarily a function of AADT and proximity of the barrier to the travel lane. Maintenance costs have averaged approximately $10,000 to $12,000 per mile for MoDOT.

Star Ratings

Prior to the installation of the cable median barrier, this 42-mi freeway section was rated with four stars for vehicle occupants by iRAP criteria. The addition of the median cable barrier raised the star rating of the freeway section to five stars.

Section 4.
Data Sources and Methodology for Developing Estimates of Nationwide Infrastructure Improvement Needs

This section of the report described the processes used in the usRAP program in greater detail to better explain the usRAP results used in Section 5 and 6. This section also documents the methodology used to scale-up the usRAP results to nationwide estimates of infrastructure improvement needs.

4.1 usRAP Star Ratings and Safer Roads Investment Plans

As indicated in the overview in Section 1 of this report, the usRAP program has two key capabilities:

- development of star ratings for roads based on the presence or absence of geometric design and traffic control features that are known to be related to safety
- development of safer roads investment plans that present site-specific recommendations for cost-effective infrastructure improvements to reduce fatal and serious injury crashes.

Each of these capabilities is discussed in more detail below.

Star Ratings

usRAP star ratings are based on a scoring system that considers the presence or absence of specific design and traffic control features. The scores developed with the scoring system are formulated so that they are generally proportional to the risk of fatal and serious injuries in traffic crashes. Separate scoring systems are used to assess the risk of fatal and serious injuries to vehicle occupants, motorcyclists, pedestrians, and bicyclists. Separate risk factors represent crash likelihood and crash severity. Figures 14 through 16 illustrate the individual factors that are considered in star ratings for vehicle occupants/motorcyclists, pedestrians, and bicyclists.

The star ratings for roads and streets range from one to five stars. A one-star road is typically a basic two-lane undivided road lacking most of the design and traffic control features that contribute to safety. A five-star road is typically a multilane divided freeway with most or all of the design and traffic control features that contribute to safety.

Figure 13 shows the general structure of the scoring system for estimation of the risk of vehicle occupant fatalities and serious injuries in the usRAP models. Separate estimates are made for the risk of run-off-road, head-on, and intersection collisions. These collision types collectively account for over 75 percent of fatalities and serious injuries to vehicle occupants. The figure shows the roadway attributes that are generally used in scoring risk for these collision types. Separate approaches based on these roadway attributes are used for scoring crash likelihood and crash consequences. The structure shown in Figure 13 is also used for scoring risk to motorcyclists, although the values of the risk factors for motorcyclists differ from those for occupants of larger vehicles.

Figure 14 shows the general structure of the scoring system for risk of pedestrian fatalities and serious injuries. Separate estimates are made of crash risk for pedestrian movement along the road and across the road. The figure shows the roadway attributes that are generally used in scoring risk for these collision types.

Figure 15 shows the general structure of the scoring system for risk of bicyclist fatalities and serious injuries. Separate estimates are made of crash risk for bicyclist movement along the road, across the road, and at intersections. The figure shows the roadway attributes that are generally used in scoring risk for these collision types.

A key feature of all of risk assessment approaches shown in Figures 13 through 15 is that they all consider the effect of the traffic speed on specific roadways, which has a pronounced effect of crash consequences.

Roadway Attributes Considered

To develop the star ratings and safer roads investment plans for a given road network, data for more than 50 roadway attributes are collected for each 100-m (327-ft) interval along the road network. Table 34 presents a list of some key roadway attributes that are included in usRAP study data sets. Data for roadway attributes on undivided roads are collected in one direction of travel and data for divided roads are generally collected in both directions of travel. These data are used both to compute the star rating for each 100-m (327-ft) interval and to formulate a safer roads investment plan for that interval. The star ratings and safer roads investment plans are developed with a risk-based approach, using crash prediction models, and do not require detailed site-specific crash data. Network-wide crash data can be used for calibration of the crash predictions. If site-specific crash data are available, they can be used in engineering studies as part of the implementation of the safer roads investment plan.

Calibration of Crash Predictions

Calibration of the crash predictions for a given road network is based on available fatality and serious injury data for that road network, if available. Crash data for a period of up to five years are used for calibration, whenever possible. Calibration is generally performed separately for traffic crashes involving motorcyclists, pedestrians, bicycles, and other vehicle types. The calibration process can accomplish two adjustments:

- Calibration of total fatalities for each user type to match the totals for the study network as a whole
- Calibration of the ratio of serious injuries to fatalities to match the ratio for the study network as a whole

If no crash data are available for calibration or if the sample size of crash data available for calibration is small, calibration factors can be estimated from a similar road network in another jurisdiction.

Safer Roads Investment Plans

A safer roads investment plan is a site-specific plan for cost-effective infrastructure improvements to reduce fatal and serious injury crashes. The plan includes recommended improvements for each 100-m (327-ft) interval on the road network where computations indicate that such improvements would be cost-effective. Both intersection and non-intersection countermeasures are considered; if a 100-m (327-ft) interval contains an intersection, that intersection is likely to dominate both the safety performance of the interval and the countermeasures recommended for it. Safer roads investment plans are developed in the following steps:

- star ratings are developed for the roadway in each 100-m (327-ft) interval for the roadway's existing condition
- the potential need for each of more than 70 infrastructure improvements or countermeasures is reviewed for each 100-m (327-ft) interval; if the countermeasure makes engineering sense for

implementation at a specific 100-m (327-ft) interval, it is considered to be "triggered" as a candidate countermeasure for that interval.

- the estimated crash reduction effectiveness of candidate countermeasures is determined by the risk factors that would change the star rating score for the 100-m (327-ft) interval if the countermeasure were implemented
- a benefit-cost analysis is conducted for each countermeasure that has been "triggered" as potentially needed. Countermeasures are incorporated in the safer roads investment plan for a given 100-m (327-ft) interval if:
  - the countermeasure is not already installed at the location in question
  - the benefit-cost ratio exceeds a minimum benefit-cost ratio specified by the user
  - the countermeasure is compatible with other cost-effective countermeasures for the same location
  - the countermeasure is not overridden by a mutually exclusive countermeasure for the same location that is more cost-effective
  - the countermeasure is consistent with countermeasures recommended for adjacent road segments

Two software tools have been used in the usRAP program to formulated safer roads investment plans. The usRAP Tools software was first formulated in 2008 and continued in general use until 2013. usRAP Tools used a scoring system to determine countermeasure effectiveness, designated as the Version 2.2 model. In 2013, development of a new software tool known as ViDA was completed. ViDA not only has expanded data management capabilities and improved user friendliness, but also uses an improved scoring system, designated as the Version 3.0 model, that considers more countermeasures and, for some countermeasures, has increased accuracy. Both of these software tools were developed by iRAP, in partnership with usRAP. The software tools can display the safer roads investment plans developed in the form of tables and maps. The software can also generate a download file, in a format compatible with Microsoft Excel®, that shows the exact location and extent of each recommended countermeasure (in terms of distance along the road and latitude and longitude), as well as the benefits, costs, and benefit-cost ratio for each recommended countermeasure.

Figure 16 shows a typical safer roads investment plan for a roadway network. Each row of the table represents a specific countermeasure type. The columns of the table show the size, benefits, and costs of the safer roads investment plan, for each countermeasure type, and for all recommended countermeasures on the roadway network combined. The columns in the main portion of the table, from left to right, represent the following:

- Countermeasure—name of countermeasure
- Length/Sites—total length of sites (km) recommended for roadway segment countermeasures and total number of sites recommended for intersection or other point-location countermeasures
- FSIs Saved—number of fatalities and serious injuries that would be reduced by installation of the recommended countermeasures of this type over a 20-year period
- PV of Safety Benefit—the present value of the estimated benefit (in dollars) from fatality and serious injury reduction over 20 years
- Estimated Cost—the estimated 20-year cost (in dollars) of the countermeasures of this type; for countermeasures with a service life less than 20 years, this is the present value of the cost for initial installation of the countermeasure and renewing the countermeasure at the end of each service life)
- Cost per FSI Saved—the estimated cost divided by the number of fatalities and serious injuries saved; the cost per dollar spent is a cost-effectiveness measure for the countermeasure in question

- Program BCR—the benefit-cost ratio for the countermeasure type in question, i.e., the present value of safety benefit divided by the estimated cost

The countermeasures studied may have other benefits in addition to their safety benefits, including delay reduction, noise reduction, air quality improvement, and reduction in energy consumption for motor vehicle improvements and long-term fitness and health benefits from walking and cycling encouraged by improved pedestrian and bicycle facilities. However, this study focuses on the traffic safety benefits of these countermeasures.

usRAP Results Used in Estimating Nationwide Infrastructure Improvement Needs

The usRAP safer roads investment programs developed to date for nearly 12,000 mi of roads in the U.S. are summarized in the next section of this report, which explains the methodology used to scale up these results to develop nationwide estimates of infrastructure improvement needs.

4.2 Overview of Estimation Methodology

The estimation methodology used to obtain national estimates of infrastructure improvement needs is summarized in Figure 16.

Results of Past usRAP Studies

usRAP studies to develop safer roads investment plans have been completed for approximately 12,600 mi of roads. Of these 12,600 mi of road, 11,916 mi are on the roadway types selected for inclusion in this study, as shown in Table 35. Table 35 is based on roadway centerline miles; i.e., divided highway mileage is counted in one direction of travel only, whereas in usRAP studies many divided highways are analyzed separately by direction of travel. Table 36 summarizes the distribution of road mileage in the road networks for which past usRAP studies were conducted by roadway type and traffic volume (AADT) level. The 11,916 mi of roads for which usRAP safer roads investment plans have been developed include roads and streets on state highways, county roads, and city streets in nine states: Alabama, Illinois, Iowa, Kansas, Kentucky, Michigan, Utah, Washington, and Wisconsin. The specific mileage in each jurisdiction within the states listed above is presented in Table A-1 in Appendix A.

The past usRAP studies include roadway networks analyzed with both usRAP Tools (based on the Version 2.2 model) and ViDA (based on the Version 3.0 model). Since the data requirements for these two software tools and model version differ, each agency's data was reanalyzed with the same software used in the original usRAP study. A total of 7,118 mi (or 60 percent of the total study mileage) were analyzed with the usRAP Tools software and the Version 2.2 model, while 4,798 mi (or 40 percent of the total study mileage) were analyzed with ViDA software and the Version 3.0 model.

Review of the usRAP study results concluded that the infrastructure improvement/countermeasure types shown in Table 37 are present to a sufficient extent in the safer roads investment plans to provide a reasonable basis for national estimates. The original safer roads investment plans for each state, county, or city were based on estimates of unit construction costs and crash costs consistent with the experience and practice of the specific highway agencies involved. Thus, the assumed unit construction costs and crash costs varied considerably from agency to agency. For this study, the usRAP analyses were redone and the safer roads investment programs were revised with a common set of assumptions concerning unit construction costs and crash costs that are considered reasonably representative of national experience and practice (see below).

Table 38 presents a summary of the safer roads investment plans for the usRAP study networks in the nine states combined. The crash reduction benefits and improvement costs in this and all similar tables in this report are present values of the total benefits and costs over a 20-year analysis period. The summary in Table 38 is for a safer roads investment program with a minimum benefit-cost ratio of 1.0; i.e., including every recommended improvement that is potentially cost-effective. Every recommended improvement in Table 38 has a benefit-cost ratio of at least 1.0, and often substantially more. The overall improvement program in Table 38 has a benefit-cost ratio of 2.7, meaning that, if fully implemented, it would provide 2.7 dollars in benefits for each dollar spent on infrastructure improvement. Similar safer roads investment program tables for minimum benefit-cost ratios from 2.0 to 5.0 are presented in Table A-7 through A-10, respectively, in Appendix A.

Table 39 summarizes the results of the past usRAP studies for the full range of minimum benefit-cost ratios from 1.0 to 5.0. The table shows that, as the minimum benefit-cost ratio increases, the size of the improvement program (represented by its total cost) decreases, but the overall benefits per dollar spent (represented by the benefit-cost ratio) increases.

HPMS Estimates of Nationwide Road Mileage

The FHWA Highway Performance Monitoring System (HPMS) database includes data from each state (and the District of Columbia) for all or a sample of roads in specific functional classes. Each record in HPMS includes a factor that can be used to scale up the HPMS samples to statewide and nationwide estimates. For example, if a particular functional class (e.g., Interstate freeways) were represented by a 100 percent sample, the scale factor would be 1.0; if another functional class were represented by a 25 percent sample, the scale factor would be 4.0.

An analysis of the HPMS database for 2014 indicates that there are 824,000 mi of roads and streets of the roadway types shown in Table 35 that appear to be comparable in functional class to the roadways in the usRAP studies. The functional class that are considered to be comparable are minor collectors, major collectors, minor arterial, principal arterials, and freeways for rural roads and principal arterials and freeways only for urban roads and streets. Table 40 presents a summary of the nationwide HPMS mileage estimates by roadway type and traffic volume (AADT level). Appendix A discuss limitations of the HPMS database that may affect the accuracy of this estimate, since AADT levels and functional classes are not available for all of the roads sampled in the HPMS database.

Scaling-Up Past usRAP Study Results to National Estimates

The next step in preparing national estimates of infrastructure improvement needs was to scale-up the infrastructure improvement programs from past usRAP studies from the usRAP study network to a national road network, assuming that the usRAP road networks, collectively, are representative of the national road network. A scale factor was computed for each combination of roadway type and AADT level as the ratio of the nationwide road mileage for that combination in Table 40 to the mileage for that same combination for the usRAP study networks in Table 36. The infrastructure improvement needs for the usRAP network for each minimum benefit-cost ratio was multiplied by that scale factor.

Section 5.
Assessment of Nationwide Infrastructure Improvement Needs

This section of the report presents and discusses the nationwide estimates of infrastructure improvement needs developed with the methodology presented in Section 4. More details of the methodology used to develop these estimates are presented in Appendix A. These nationwide estimates apply to roads of selected roadway types in the following functional classes: rural minor and major collectors, minor and principal arterials, and freeways; and urban principal arterials and freeways.

5.1 Basic Nationwide Estimates of Infrastructure Improvement Needs

Table 41 summarizes the estimates of nationwide infrastructure improvement needs by improvement type, computed as described in Section 4 and Appendix A, including all improvements with a minimum benefit-cost ratio of 1.0. The table shows the crash countermeasure categories in which infrastructure investments are recommended, the individual crash countermeasure names and, for each individual crash countermeasure, the model used to obtain the estimate (usRAP Tools or ViDA or both), the estimated road length or number of sites that would benefit from improvement, the estimated crash reduction benefits (expressed as the present value for a 20-year program), the estimated improvement costs (expressed as the present value for a 20-year program), and the number of fatalities and serious injuries reduced over 20 years.

Table 41 indicates that, if every cost-effective improvement were to be made, the improvement program would cost $146.5 billion. These cost-effective improvements represent an estimate of nationwide infrastructure needs to reduce fatalities and serious injuries. If all of these needs were addressed, the present value of the 20-year safety benefits would be $348.4 billion, with a benefit-cost ratio of 2.4. In other words, benefits of $2.40 could be achieved for every $1.00 spent on infrastructure improvement. Addressing these needs could reduce 63,700 fatalities and more than 350,000 serious injuries over 20 years.

Most of the improvements represented in Table 41 are permanent or semi-permanent in nature and have been assigned a service life of 20 years. A few of the improvements including improving delineation and adding rumble strips have been assigned a service life of 5 years. The investments would need to be repeated every 5 years to maintain the benefits over a full 20-year period. The initial investment to obtain the benefits of this program would be $134.1 billion with further investments of $6.1 billion every 5 years to maintain the improved delineation and rumble strips in place. The investment level of $146.5 billion presented above is the present value of the initial investment of $134.1 billion plus three $6.1 billion investments at 5, 10, and 15 years into the program. It should be emphasized that while the benefits of the improvement program would persist over (at least) 20 years, the identified needs exist now and most of the investment is needed now.

The scale of these infrastructure improvement needs is large, but so is the scale of the traffic safety challenge to be met in the United States. Meeting the $146 billion in current infrastructure improvement needs would still reduce only 16 percent of the expected fatalities and 12 percent of the expected injuries on the roads addressed. Thus, while infrastructure investments have a key role in moving Towards Zero Deaths, other elements of a coordinated crash reduction program – including alcohol and speed enforcement, seat belt programs, vehicle technology improvements, and emergency medical services improvements – will also be needed. Nevertheless, highway infrastructure improvements are a critical component of the overall program because they can help all the other portions of the program function more effectively.

5.2 Key Crash Countermeasures in an Infrastructure Investment Program

Table 42 is analogous to Table 41, but summarizes the infrastructure improvements by crash countermeasure category, combining the estimates for individual countermeasure types within each category. Table 42 indicates that the countermeasure types likely to make the greatest contribution to reduction of fatalities and serious injuries are:

- intersection improvements
- roadside improvements
- pedestrian facilities
- median barriers
- rumble strips
- shoulder widening

These six countermeasure categories collectively will provide nearly 95 percent of the anticipated crash reduction from the infrastructure investment program.

Tables 41 and 42 clearly indicate that intersection improvements should be a key component of any infrastructure investment program. Indeed, almost 30 percent of the overall fatality and serious injury reduction could come from intersection improvements. The intersection improvement with the greatest potential for fatality and serious injury reduction is conversion of existing intersections to roundabouts. Detailed engineering studies of sites where roundabouts are recommended might ultimately recommended an alternative intersection improvement, but the analysis results indicate an important role for roundabouts in reducing crashes. For example, France has built over 20,000 roundabouts in the last 15 years as a key safety improvement to their road system.

Roadside improvements provide nearly 20 percent of the overall reduction in fatalities and serious injuries from the investment program. The components of a roadside improvement program include clearing roadside objects, improving side slopes, and installing roadside barriers. The analysis results indicate that installing roadside barriers should constitute the largest component of the improvement program, while clearing roadside objects would have the highest benefit-cost ratio. The optimal mix of clearing roadside objects, improving side slopes, and installing roadside barriers will require detailed engineering analysis of individual sites, but the analysis results indicate clearly that roadside improvements should be a key component of any infrastructure investment program.

Addition or improvement of pedestrian facilities can also provide nearly 20 percent of the fatality and serious injury reduction from the infrastructure improvement. The analysis results show that most of these improvements would come from providing sidewalks where none currently exist, but addition or improvement of signalized and unsignalized pedestrian crossings should also be an element of the infrastructure improvement program.

Installation of median barriers on existing divided highways are estimated to provide about 14 percent of the overall benefits of the recommended infrastructure investment program. Detailed engineering studies of individual roadways would be needed to choose the most appropriate barrier type – metal guardrail, concrete barrier, or cable barrier – for each roadway.

Rumble strips are estimated to provide nearly 9 percent of the overall benefits of the recommended infrastructure investment program. The analysis indicates that shoulder rumble strips are needed at the most locations, but centerline rumble strips can have key benefits on undivided roadways. The need for centerline rumble strips may even be underestimated in the analysis results.

Finally, shoulder widening and paving are expected to provide nearly 3 percent of the overall benefits from the infrastructure improvement program.

5.3 Additional Funding Needs for Infrastructure Investment Programs

Current investments in highway infrastructure improvements in the U.S. are substantially lower than the identified needs. There are no comprehensive data on how much U.S. highway agencies currently spend on traffic safety improvements. FHWA currently provides approximately $2.2 billion annually to state and local agencies in Highway Safety Improvement Program (HSIP) under the Fixing America's Surface Transportation (FAST) Act (www.fhwa.dot.gov/fastact/factsheets/hsipts.cfm) . State and local governments also invest funds of their own in safety improvement projects, although no national estimates of state and local government expenditures on traffic safety are available. In addition, general highway improvement programs make many improvements that benefit safety as well as meeting other objectives. However, even if, as a nation, we are spending $4 or $5 billion on infrastructure improvements for safety, this is only a small portion of the identified needs.

All Federal-aid expenditures for highway infrastructure improvements (including other Federal-aid programs, as well as safety) total $40 billion per year, and Federal, state, and local capital expenditures for road infrastructure total $91 billion per year (ASCE, 2013).

Highway infrastructure improvements can serve an important role in moving Toward Zero Deaths, but infrastructure improvement programs must begin to address a much greater portion of the identified needs. The $146 billion in identified needs do not necessarily all need to be addressed in the first year of an investment program, but these needed investments should not be deferred too long because new needs develop each year. If we continue to underinvest in infrastructure improvement, the backlog of unaddressed needs will grow rather than shrink.

Beyond merely increasing funding for safety improvement programs, new approaches are needed in managing safety investment programs. Design and project-development procedures should become more performance-based, focusing on investments that provide demonstrable benefits and avoiding investments with limited safety benefits. This can be accomplished with tools like the *Highway Safety Manual* (AASHTO, 2010; AASHTO, 2014) that can be applied to estimate the long-term expected benefits of projects. It will also be desirable to encourage inclusion of safety improvements in projects funded for other reasons so that every project becomes, at least in part, a safety project.

5.4 Infrastructure Investment Levels for a Range of Minimum Benefit-Cost Ratios

Results similar to Table 41 for the range of minimum benefit-cost ratios of 2.0, 3.0, 4.0, and 5.0 are presented in Tables A-17 to A-20, respectively, in Appendix A. These results are summarized in Table 43.

Given the limitations on the funds available for infrastructure investments for safety improvement, most highway agencies have preferred to focus on investments with the greatest return. Table 43 shows that, as we demand higher benefit-cost ratios from our investments, both the funds needed and the benefits derived from the investment programs become smaller. If we focused only on investments with benefit cost ratios of at least 2.0, as some highway agencies prefer, the size of the infrastructure investment program would be reduced to $64 billion and the benefits of the program would be reduced by 22 percent. If we focused only on investments with benefit-cost ratios of at least 5.0, the infrastructure improvement program would be only $16 billion (i.e., just 9 percent of the $146 billion in needs noted above), but the benefits of the improvement program would be cut almost in half. Thus, a smaller improvement program would be more efficient, but would accomplish only about half as much in reducing fatalities and serious injuries. Today, we are not investing in crash reduction efforts even the amounts identified for a minimum benefit-cost ratio of 5.0 in Table 43.

Highway agencies are acting rationally in choosing investments with higher payoffs, given existing funding levels. However, in the long run, if the U.S. is to truly move Toward Zero Deaths, substantially increased funding levels for infrastructure investments will be needed.

5.5 Strengths and Limitations of the Estimates of Infrastructure Improvement Needs

The key strengths of the estimates of infrastructure improvement needs presented here is that are based on:

- assessment of a broad range of infrastructure-related crash countermeasures for the full extent of each roadway network studied
- assessment of road networks of the highest functional classes of road that are likely to have the highest traffic volumes and the highest payoff in crash reduction
- assessment with a benefit-cost approach so that priorities can be placed on improvement types with the highest potential payoff
- assessment with software that makes the development of infrastructure investment plans efficient

The limitations of the estimates of infrastructure improvement needs presented here are that:

- The needs have been estimated from a relatively small sample of roads from the past usRAP studies (about 12,000 mi). While the roadway network addressed in limited in length, it is quite diverse in terms of the types of roads addressed.

- The needs have been estimated only for paved roads and only for selected functional classes of roads similar to those addressed in the past usRAP studies. Specifically, the estimates do not address the following roadway classes:
  - rural local roads
  - urban minor arterials, major collectors, minor collectors, and local roads
  - unpaved roads

- The needs have been estimated for most, but not all, roadway types of potential interest. Specifically, the estimates do not address the following roadway types:
  - roadways with center two-way left-turn lanes
  - conventional roadways with more than six lanes
  - freeways with more than eight lanes
  - interchange ramps and other connector roadways
  - other unusual or atypical roadway cross sections

- The needs have been addressed for many, but not all, infrastructure improvement types of potential interest. The countermeasures considered in the research represent about 50 percent of HSIP expenditures. Specific examples of improvement types that have not been addressed include:
  - right-turn lanes at intersections
  - driveway improvements

- horizontal curve reconstruction
- superelevation restoration
- cross-slope restoration

  Because it has not been possible to consider all infrastructure improvement types in this study, the proportions of specific improvement types in the overall program, discussed on page 34, may be overestimated. But, for example, even if roadside or pedestrian facility improvements ultimately constitute less than 20 percent of overall infrastructure improvement needs, such improvements should still have a substantial role in future safety improvement programs.

- The estimated safety benefits of the program are likely an underestimate since the effects of future growth in traffic volumes has not been considered. The estimates of 16-percent reduction in fatalities and 12-percent reduction in serious injuries if the identified infrastructure improvement needs are addressed is correct, but the actual number of crashes reduced would likely be larger than shown in Table 43 if future traffic volumes grow substantially.

The limitation resulting from the limited length of the roadway network considered in past usRAP studies can be addressed as usRAP studies are performed for additional highway agencies and jurisdictions. A statewide program in Alabama is now underway and work on county roads is underway in several additional states.

The limitations related to not addressing all functional classes, roadway types, and countermeasure types of potential interests clearly implies that the estimates of infrastructure improvement needs presented above are conservative. Data from NHTSA's Fatality Analysis Reporting System (FARS) for 2010 through 2014 (see Table A-14 in Appendix A) show that the functional classes and roadway types considered in the analysis experienced an average of 21,248 fatalities per year or 64 percent of the average of 32,887 fatalities per year that occurred on all U.S. roads during that period. This indicates that the infrastructure improvement estimates presented above address roadways that represent a substantial and important part of the traffic safety challenge in the U.S., but not all of it. On the rest of the roadway system, which includes many more miles of roads and streets and lower traffic volumes than those already studied, the remaining 36 percent of fatalities (and serious injuries) will require very substantial additional investments in infrastructure improvement to address.

The needs for some countermeasures including adding passing lanes on rural two-lane highways and implementing striping and delineation improvements appear to be underestimated by the methodology used. Additional improvements of these types may be needed.

It has been noted above that infrastructure investments are only part of the investment needed to reduce traffic fatalities and serious injuries. Other elements of a coordinated crash reduction program – including alcohol and speed enforcement, seat belt programs, vehicle technology improvements, and emergency medical services improvements will also be needed. Forecasts of vehicle technology improvements, including connected and automated vehicles, indicate a potential for major reductions in traffic crashes. However, current forecasts may be overoptimistic, especially without accompanying infrastructure investment programs. In particular, even as automated vehicle technologies advance, the U.S. road and street system may be operating for many years with a challenging mix of automated and driven vehicles. Furthermore, effective operation of automated vehicles may be more dependent on superior road infrastructure – good geometric design, reduced vehicle-vehicle, vehicle-pedestrian, and vehicle-bicycle conflict points, and easily detected pavement markings – than many forecasters currently realize. Whatever the future holds, the needs for infrastructure improvements to reduce crashes will likely continue to grow unless addressed with larger investments than are being made at present.

Section 6.
Role of usRAP Star Ratings in Managing Infrastructure Improvement Programs

Star ratings determined using usRAP and iRAP protocols are being increasingly used as a tool to guide design of highway improvement projects. A minimum three-star rating has been suggested as a goal for highway improvement projects. The Three Star Coalition, of which both AAA and the AAA Foundation for Traffic Safety are members, has been formed to promote the use of minimum three-star ratings for design projects. In particular, the World Bank and regional development banks are being encouraged to apply minimum three-star ratings in the design road projects that they fund in low- and middle-income countries. The impetus for minimum three-star ratings comes from some past projects that have been designed without regard for safety principles, resulting in increased crashes due to factors such as roadside objects close to the roadway, sharp curves, lack of pedestrian and bicycle facilities, and inattention to speed management.

Research data suggest that a minimum three-star rating can be a useful guide for design, particularly for projects on major roads with higher traffic volumes. It is very logical for funding agencies to apply a minimum three-star rating to guide design of individual projects where no benefit-cost analysis has been performed. Thus, it is very appropriate that the minimum three-star ratings continue to be applied to design of appropriate projects in low- and middle-income countries if the design decision was not based on benefit-cost analysis. However, there has not been previous consideration of how the concept of minimum three-star ratings should be applied in safety management of a road network as a whole.

Road networks, administered by individual highway agencies or road authorities, consist of roads with diverse functional classifications, traffic volumes, and operating speeds. Review of usRAP safer roads investment plans suggests that minimum three-star ratings are not necessarily appropriate for all roads. For some roads, particularly roads with lower traffic volumes, improvement to a three-star rating may not be cost-effective. Improvement of such roads to a three-star rating should provide some limited benefit, but the same funds could be used to improve a higher volume road and obtain much greater benefits. Given the realities of limited funding levels, it is desirable to direct the funds available for safety improvement toward projects where they will do the most good.

Safer roads investment plans developed with the ViDA software can serve to direct resources toward the most productive projects. Often, such projects will improve roads to a three-star rating or higher. However, some projects may cost-effectively improve a one- or two-star to two stars, and some one- and two-star roads may have no cost-effective improvements.

Tables 44 and 45 presents the distribution of star ratings, before and after recommended improvements, for all roads that were considered in previous usRAP studies using the ViDA Version 3.0 software. This includes nearly 5,400 mi of roads of all types in three states: Kansas, Utah, and Wisconsin. Table 44 shows that the vehicle-occupant star ratings for the existing roadways in the star rating range of three stars and above include 60 percent of all roadways in the network studied. After implementation of the improvements recommended by the ViDA software the percentage of roadways with vehicle-occupant star ratings in the range of three stars and above would increase to 73 percent of the road network, as indicated in Table 45. However, Table 45 indicates that even after all improvements with benefit-cost ratios that exceed 1.0 are implemented, 27 percent of the road network would remain with vehicle-occupant star ratings of two stars or less. Analyses with the usRAP data have indicated that there is no simple traffic volume level above which improvements to a three-star rating are always desirable.

The minimum three-star rating appears to be an appropriate criterion for design guidance for projects where no economic analysis is performed. Where a benefit-cost analysis is performed (e.g., with the ViDA software), it appears most appropriate to let the benefit-cost analysis results indicate what type of improvement project is most appropriate. Depending upon the characteristics of the site, including traffic volumes, the resulting design may be rated below, at, or above the three-star guideline.

As we move Toward Zero Deaths on our roadway system, there will likely come a time when improvement projects with benefit-cost ratios less than 1.0 will need to be considered. Thus, some day it may be desirable to implement projects that achieve three-star designs, even at locations where we know this is not cost-effective. However, at present, there are plenty of opportunities for projects with benefit-cost ratios of 1.0, or even substantially higher, and such projects should certainly have priority as safety improvement investments over projects with benefit-cost ratios less than 1.0. In other words, our long-term goals for crash reduction are best served by investing in projects that are likely to provide the greatest benefits.

Section 7.
Conclusions and Recommendations

The conclusions of the research are as follows:

1. Highway infrastructure investments have an important role in reducing crashes and moving the U.S. highway system Toward Zero Deaths. Highway infrastructure improvements have the potential to reduce both the likelihood and consequences of crashes caused not only by the roadway environment but also by driver error. Improvements to highway infrastructure features, including the roadway, roadside, and traffic control devices, can constrain driver behavior even without the need for a conscious decision by drivers to behave differently. In addition, infrastructure improvements may provide the most certain approach to reducing fatalities and serious injuries because many have been widely implemented, providing years of performance data and allowing researchers to quantify their typical or average effects on safety.

2. The safer roads investment plans that have been developed in previous usRAP studies for approximately 12,000 mi of road can be scaled up to make nationwide estimates of highway infrastructure improvement needs. The resulting nationwide estimates include roadway types and functional classes of roads that experience approximately 64 percent of traffic fatalities in the United States. Thus, the nationwide estimates are conservative since they address most, but not all, relevant roadways.

3. Considering all cost-effective infrastructure investments (i.e., those for which the benefits exceed the costs), current infrastructure improvement needs in the U.S. for the roadway types and functional classes listed above would cost $146 billion to address. If all of these needs were addressed, the present value of the 20-year safety benefits would be $348 billion, with a benefit-cost ratio of 2.4. In other words, benefits of $2.40 could be achieved for every $1.00 spent on infrastructure improvement. Addressing these needs could reduce 63,700 fatalities and more than 350,000 serious injuries over 20 years.

4. Given the limitations on the funds available for infrastructure investments for safety improvement, most highway agencies have preferred to focus on investments with the greatest return. As we demand higher benefit-cost ratios from our investments, both the funds needed and the benefits derived from the investment programs become smaller. If we focused only on investments with benefit-cost ratios of at least 5.0, the infrastructure improvement program would be only $16 billion (i.e., just 9 percent of the $146 billion in needs noted above), but the benefits of the improvement program would be cut almost in half. Thus, a smaller improvement program would be more efficient, but would accomplish only about half as much in reducing fatalities and serious injuries. If the United States is to truly move Toward Zero Deaths, greater investments, not just the most cost-effective investments, will be needed.

5. The highway infrastructure improvements considered in the safer roads investment plans include:
    - Adding passing lanes
    - Widening lanes
    - Widening shoulders
    - Widening the cross section to include a median
    - Adding a center two-way left-turn lane
    - Adding median barrier
    - Improving the roadside by clearing roadside objects, improving sideslopes, or installing barriers

- Installing centerline or shoulder rumble strips
- Adding a bicycle lane or path
- Adding pedestrian facilities (refuge island, marked crossings)
- Improving delineation
- Adding intersection left-turn lanes
- Converting an intersection to a roundabout
- Providing grade separation at an intersection
- Signalizing an intersection
- Updating rail crossings

6. The highway infrastructure investments that are included to the greatest extent in the safer roads investment plans and provide the greatest total benefits include:
   - Intersection improvements (30 percent of overall benefits)
   - Roadside improvements (20 percent of overall benefits)
   - Pedestrian facilities (20 percent of overall benefits)
   - Median barriers (14 percent of overall benefits)
   - Rumble strips (9 percent of overall benefits)
   - Shoulder paving and widening (3 percent of overall benefits)

   Because it has not been possible to consider all infrastructure improvement types in this study, the proportions of specific improvement types in the overall program, discussed on page 34, may be overestimated. But, for example, even if roadside or pedestrian facility improvements ultimately constitute less than 20 percent of overall infrastructure improvement needs, such improvements should still have a substantial role in future safety improvement programs.

7. Current investments in highway infrastructure improvements in the U.S. are substantially lower than the identified needs. There are no comprehensive data on how much U.S. highway agencies currently spend on traffic safety improvements. FHWA provides approximately $2 billion annually to state and local agencies in the Highway Safety Improvement Program (HSIP). State and local governments also invest funds of their own in safety improvement projects, although no national estimates of state and local government expenditures on traffic safety are available. In addition, general highway improvement programs make many improvements that benefit safety as well as meeting other objectives. However, even if, as a nation, we are spending $4 or $5 billion on infrastructure improvements for safety, this is only a small portion of the identified needs.

8. Highway infrastructure improvements can serve an important role in moving Toward Zero Deaths, but infrastructure improvement programs must begin to address a much greater portion of the identified needs. The $146 billion in identified needs do not necessarily all need to be addressed in the first year of an investment program, but these needed investments should not be deferred too long because new needs develop each year. If we continue to underinvest in infrastructure improvement, the backlog of unaddressed needs will grow rather than shrink.

The study results clearly lead to a recommendation that a substantial increase is needed in highway infrastructure improvements to reduce fatalities and serious injuries. If the identified needs are addressed, this would reduce 16 percent of fatalities and 12 percent of serious injuries on the road types studied. Thus, highway infrastructure improvements can be an important part of moving Toward Zero Deaths in the U.S. Other elements of a coordinated crash reduction program—including alcohol and speed enforcement, seat belt programs, vehicle technology improvements, and emergency medical services improvements—will also be needed. The increase in infrastructure investments will complement other safety programs, such as those oriented toward improving driver behavior.

The estimates of infrastructure investment needs developed in this report can be improved as the available usRAP study results grow in future years. It is recommended that research using the approach presented in this report be repeated periodically to update the infrastructure improvement needs estimates.

Section 8.
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Appendix A.
Development of National Estimates for Infrastructure Improvement Needs

This appendix summarizes the development of national estimates for infrastructure improvement needs to reduce crash frequency and severity. The objective of this effort is to use the results of previous U.S. Road Assessment Program (usRAP) studies as a representative sample of infrastructure improvement needs on roads and streets in the U.S. and to scale up the estimates from that sample to the national road and street network. The steps in the analysis process include:

- Review and summarize the results of previous usRAP studies.
- Scale up the fatality estimates from previous usRAP studies to national fatality estimates and compare them to data from the NHTSA Fatality Analysis Reporting System (FARS).
- Make any appropriate adjustments to better match the sealed-up usRAP data to FARS data.
- Scale up the infrastructure investment programs from previous usRAP studies to estimate the size and composition of needed national infrastructure investment programs to reduce crash frequency and severity.

These steps in the analysis process are summarized in this appendix.

A.1 Roadways Evaluated in Previous usRAP Studies

Table A-1 identifies the highway agencies that have participated in past usRAP studies to develop safer roads investment plans, together with the road mileage included in the safer roads investment plan for each agency. Earlier studies were performed with the usRAP Tools software that utilizes Version 2.2 of the safer roads investment plan algorithm. Later studies used the ViDA software that utilizes Version 3.0 of the safer roads investment plan algorithm. Both of these software packages were developed for usRAP by its international partner, the International Road Assessment Program (iRAP).

Table A-1 is limited to roadways from previous usRAP studies of the following roadway types:

- Rural two-lane undivided roads
- Rural four-lane undivided roads
- Rural four-lane divided roads
- Rural four-lane freeways
- Rural six-or-more-lane freeways
- Urban two-lane undivided streets
- Urban four-lane undivided streets
- Urban six-or-more-lane undivided streets
- Urban one-way streets
- Urban four-lane divided roads or streets
- Urban six-or-more-lane divided roads or streets
- Urban four-lane freeways
- Urban six-lane freeways
- Urban eight-or-more-lane freeways

Rural nonfreeways with six or more lanes, rural and urban roadways with center two-way left-turn lanes, and other roadway types with special features that do not fit within the cross-section categories described above have been omitted from the analysis because they could not be identified explicitly in the FHWA Highway Safety Performance Monitoring (HPMS) database. The roadway types omitted from the analysis are generally less common than those included.

Table A-1 shows that safer roads investment plans have been developed for 11,916 mi of roadways. For both undivided and divided highways, this total is based on the centerline mileage of the roadways. The table indicates that 7,118 mi of roadways (60 percent of the total roadway length) were evaluated with the usRAP Tools software (Version 2.2) and 4,798 mi of roadway (40 percent of the total roadway length) were evaluated with the ViDA software.

The usRAP Tools software was developed in 2008, as an outgrowth of the iRAP Tools software, with the capability to produce both star ratings and safer roads investment plans. All usRAP studies performed with usRAP Tools used Version 2.2 of the software.
An improved software package, known as ViDA, was developed by iRAP and first released in 2013. The changes in ViDA included an updated graphical user interface, additional input variables, improved algorithms for developing star ratings and safer roads investment plans, consideration of additional countermeasures, and increased computational efficiency using parallel processing. usRAP studies initiated in 2013 and later have used the ViDA software.

Table A-2 summarizes the distribution of the selected road types represented in the past usRAP studies.

Table A-3 summarizes the distribution of roadway mileage for specific combinations of road type and traffic volume level, as represented by ranges of annual average daily traffic volume (AADT). The table shows that on the study network, as on the U.S. roadway network as a whole, different roadway types have distinct ranges of traffic volumes. No roadway type covers the full range of potential traffic volume. The analysis estimated infrastructure improvement needs for the specific combinations of road type and traffic volume shown in Table A-3.

A.2 Predicted Fatalities for Roadways Included in Previous usRAP Studies

Table 4 shows the predicted fatalities and serious injuries per year for the 12,690-mi usRAP study network as a whole. These predictions are based on the crash prediction models incorporated in the usRAP Tools and ViDA software with calibration based on the observed safety performance of the roads on the study network).

A.3 Countermeasures Considered in Previous usRAP Studies

Countermeasures to include in the estimates of potential infrastructure investment needs has been made, based on experiences in previous usRAP studies. The usRAP Tools and ViDA software consider potential needs for up to 70 countermeasures. These two versions of the software include slightly different lists of countermeasures. The infrastructure improvement needs estimates include as many countermeasures as appropriate, with a few countermeasures omitted for specific reasons:

- Countermeasures that are not used (or not widely used) in the United States, such as motorcycle lanes, have been omitted.
- Countermeasures that are included in one version of the software, but not in the other, have been included based only on the usRAP studies performed with that version of the software.
- Countermeasures that are rarely triggered by the software for U.S. conditions have been omitted, since such countermeasures are either not needed as much in the U.S. or their needs are underestimated by the existing software.
- Countermeasures for which the analysis logic is suited to identify only a limited set of sites, but not all sites of potential need, have been omitted to avoid knowingly underestimating the need for that countermeasure. In particular, some countermeasures have been added to the usRAP Tools or

ViDA software to flag the need for certain countermeasures when that need is obvious, but the software clearly lacks the data to identify all locations where that countermeasure is needed. Examples are street lighting, skid resistance improvements, one-way networks, combining adjacent driveways, and school crossing upgrades. It would be desirable to include such improvements in the nationwide estimates, but the existing usRAP software logic is likely to underestimate the need for these improvements, so it appears better to omit them than suggest an inappropriately small need.

- Countermeasures applicable primarily or only to unpaved roads have been omitted. Countermeasures related to road resurfacing have been omitted because their safety effectiveness measures are not well documented and the purpose of the research is to encourage explicit safety investments, not routine pavement maintenance.

Closely related countermeasures have been merged into a single countermeasure, where appropriate. For example, the usRAP Tools and ViDA software often treat the application of the same countermeasures on the two sides of the road (left and right) as two separate countermeasures. Such cases have been merged into a single combined countermeasure for purposes of this research. usRAP Tools and ViDA use as many as six different median countermeasure names representing different widths of median. usRAP Tools and ViDA also utilize separate countermeasure names for the same countermeasure applied at three- and four-leg intersections or at signalized and unsignalized intersections. For all such instances, the separate countermeasure names have been merged into a single combined countermeasure.

Table A-5 lists the countermeasure categories and the specific countermeasures in each category that we believe are appropriate to include in the infrastructure improvement needs estimate.

A.4 Assumptions Made in Determining Countermeasure Benefits and Costs

The benefit-cost analyses performed in usRAP studies require assumptions about the following parameters used in determining benefits and costs:

- Crash costs
- Unit construction costs for countermeasures
- Discount rate (minimum attractive rate of return)
- Minimum benefit-cost ratio
- Calibration data

This section of the technical memorandum summarizes the assumptions used in conducting benefit-cost analyses to formulate infrastructure investment plans for this research. Differing assumptions for these parameters may have been made in individual usRAP studies in the past, to suit the preferences of individual highway agencies, but these assumptions have been standardized, as appropriate for this research.

Crash Costs

Highway agency assumptions concerning crash costs (i.e., the benefits of reducing crashes of specific severity levels) vary widely between states. Current state highway agency estimates of fatality costs range from approximately $1 to 9 million, and previous usRAP studies have used each agency's preferred value of crash costs. For the current research, a standardized value of crash costs was desirable so that results from various states are not over- or under-emphasized based on each state's preferred crash costs.

Most state highway agencies prefer crash cost values based on estimates of total societal costs for crashes. Typical state estimates of the "total societal costs" of a fatality are in the range from $3 to 5 million. By contrast, the USDOT recommends crash costs based on people's "willingness to pay" to avoid a fatality (USDOT, 2015). The currently recommended USDOT values, based on the "willingness to pay" method, is an average fatality cost of $9.4 million, and a range of potential fatality costs from $5.2 to 13.0 million. USDOT guidance is that benefit-cost analyses should use the intermediate value of $9.4 million or should conduct sensitivity analyses with the low and high values of $5.2 and $13.0 million. FHWA is required by USDOT policy to use these "willingness to pay" values in its own internal benefit-cost studies, but does not require states to use them. And, as noted above, states generally prefer the "total societal cost" approach to the "willingness to pay" approach.

The AASHTO *Highway Safety Manual* (HSM) in Chapter 7 recommends the following values of crash costs by severity levels for use in benefit-cost analyses:

- Fatality (K) $4,008,900
- Disabling Injury (A) 216,000
- Evident Injury (B) 79,000
- Possible Injury (C) 44,900
- Property Damage Only (O) 7,400

These values are currently used by several state highway agencies because they appear in the HSM and, therefore, have credibility. The HSM indicates that these values were drawn from an FHWA report (Council et al., 2005); the FHWA report, in turn, states that these values are based on 2001 data for "total societal costs" of crashes. However, the 2005 FHWA report also includes a procedure for updating the crash cost estimates to future years based on two U.S. Department of Labor statistics: the Consumer Price Index (CPI) and the Employment Cost Index (ECI) (U.S. Department of Labor, CPI web site, EPI web site). When this updating procedure is applied to the 2001 estimates based on CPI and ECI values for 2015 (the latest year available), the resulting crash costs are:

- Fatality (K) $5,722,300
- Disabling Injury (A) 302,900
- Evident Injury (B) 110,700
- Possible Injury (C) 62,400
- Property Damage Only (O) 10,100

The fatality and disabling injury values given above ($5,722,300 and $302,900, respectively) were used as standardized values for application in the current research. The reasons for recommending these values are: (a) they are based on the "total societal cost" approach preferred by states; (b) they are based on HSM recommendations, updated to current conditions; and (c) they are reasonably consistent with current values used by highway agencies. Results from all previous usRAP studies have been recomputed using these standardized crash values.

Unit Construction Costs

Unit construction costs clearly vary from agency to agency, and region to region, across the United States, and there is no single source of nationally representative data. In each usRAP study, unit construction costs for countermeasures have been obtained from, or more often at least reviewed and approved by, individual highway agencies. We reviewed the construction cost estimates from various highway agencies and chose a single set of unit construction costs for infrastructure improvements for use in this research. These recommended values of unit construction costs are presented in Appendix B.

Discount Rate (Minimum Attractive Rate of Return)

Every benefit-cost analysis uses a discount rate to convert expenditures over time to their present value. The discount rate is equivalent to the minimum rate of return that is considered an attractive investment. The U.S. government (USDOT, 2015) recommends the use of discount rates in the range from 3 to 7 percent in benefit-cost analyses of Federal investments, with 4 percent as a representative intermediate value, and we consider that 4 percent is an appropriate standard value for all analyses in the current research.

Minimum Benefit-Cost Ratio

In each usRAP study, the participating highway agency has been given the opportunity to select a minimum benefit-cost ratio that all countermeasures must meet. Highway safety investments often provide benefit-cost ratios substantially greater than 1.0. The current research has considered minimum benefit-cost ratios in the range from 1.0 to 5.0. As the minimum benefit-cost ratio is increased, infrastructure improvement programs become lost costly, but more cost-effective. The consideration of a range of minimum benefit-cost ratios allows a sensitivity analysis to compare these alternatives.

Calibration Data

Each usRAP evaluation has been calibrated with actual crash data for the study network in question. The calibration data include network-specific data for the number of fatal and serious injury crashes involving pedestrians, bicycles, motorcycles, and all other vehicles, and network-specific data for the ratio of serious injury to fatal crashes. In general, we have retained these individual study calibrations in the research, because this will make the overall results representative of average conditions. Furthermore, this is the only viable approach, because there are no suitable data available to calibrate the collective study results.

A.5 Countermeasure Benefits and Costs

Tables A-6 through A-10 present the results of benefit-cost analyses for the roadway networks from past usRAP studies, for the selected countermeasures of interest (see Table 5), with a minimum benefit-cost ratios from 1.0 to 5.0. Tables A-6 through A-10 represent network-wide infrastructure improvement programs for the road network considered in each past usRAP study. The countermeasures assessed with the usRAP Tools Version 2.2 software alone represent a total road network on 7,118 mi. The countermeasures assessed with the ViDA Version 3.0 software alone represent a total road network on 4,798 mi. The countermeasures assessed with both software packages alone represent a combined total road network on 11,916 mi.

A.6 HPMS Estimates for Nationwide Road Mileage for Specific Road Types

The FHWA Highway Performance Monitoring System (HPMS) database for 2014 was used to make national estimates of mileage for the road types shown in Tables A-2 and A-3. Table A-11 shows these nationwide HPMS mileage estimates. The HPMS estimates were for roads and streets in all 50 states plus the District of Columbia. Unpaved roads and roads functionally classified as local roads were excluded.

Table A-11 indicates that there are an estimated total of 1,083,187 mi of roads and streets in the U.S. for the road types described above. The mileage estimates from HPMS in Table A-11 are categorized by road type and AADT level. For urban nonfreeways, the mileage estimates are also categorized by functional class, including principal arterials, minor arterials, major collectors, and minor collectors.

The HPMS data are far from perfect for developing nationwide estimates of road mileage. The data needed to identify and eliminate unpaved roads and local roads were not complete and estimates had to be made based on the available data. A key concern in Table A-11 is that there is substantial road mileage with unknown AADT levels. Several alternative methods for handling the missing AADT data were considered, and it was decided that the best approach was to distribute the mileage with missing AADT levels in proportion to the mileage with known AADT levels with each road type. There was also road mileage with unknown functional class for each of the urban nonfreeway road types. This mileage with unknown functional class was substantial only for urban two-lane undivided streets. The mileage with unknown function class is indicated separately in Table 8 and is included in the urban and combined mileage totals.

Preliminary comparisons of FARS fatality counts with scaled-up usRAP fatality counts were made (see discussion below). The comparisons suggested that the safety performance of the urban nonfreeways in the previous usRAP studies was more representative of urban principal arterials that all urban collectors and arterials combined. To test this premise, a modified HPMS mileage estimate, shown in Table A-12, was prepared. Table A-12 excludes mileage for urban minor arterials, major collectors, and minor collectors. In Table A-12, the road mileage with unknown AADT levels has been distributed among the mileage by AADT level for each roadway type in proportion to the mileage with known AADT levels. Road mileage with unknown functional class was also excluded from the mileage estimates shown in Table A-12 on the assumption that such roads were unlikely to be principal arterials.

A.7 Comparison of Scaled-Up usRAP Fatality Estimates to FARS Data

The next step in the analysis process was to compare the scaled-up usRAP fatality estimates to fatality estimates for the same roadway types from FARS data. If the scaled-up estimates and the FARS estimates are in reasonable agreement, this confirms that the scaling-up process is accurate. If the scaled-up estimates do not agree with the FARS estimates, adjustments to the scaling up process may be needed.

Table A-13 presents the fatality counts from FARS for each of the road types for the five year period from 2010 to 2014. The fatality counts from FARS in the table include all crashes that occurred on paved roads of the types shown in Table A-2 for the following functional classes: rural collectors, minor arterials, principal arterials, and freeways; and urban minor arterials, principal arterials, and freeways. The FARS data in Table A-13 indicate that the rural road types and functional classes of interest experienced an average of 13,396 fatalities per year, while the urban road types and functional classes of interest experienced an average of 9,045 fatalities per year, for a total of 22,441 fatalities per year. Table A-13 also presents the HPMS road length estimates from Table A-11 for each road type for the following functional classes: rural collectors, arterials, and freeways; and urban arterials and freeways. Table A-13 indicates based on HPMS data that there were an estimated total of 1,083,187 road miles for the road types and functional classes.

Table A-13 also shows the road lengths from previous usRAP studies by road type (a total of 11,916 mi based on Table A-2) and the total fatalities per year for the road networks from previous usRAP studies by road type (407.5 fatalities per year based on Table A-4).

Because no AADT level data are available in FARS, the scaling-up of the usRAP study data for this comparison was done within road type categories without considering AADT levels. For example, within the rural two-lane undivided (R2U) road-type category, the scaling was computed as:

$$National\ fatalities\ per\ year\ on\ R2U\ roads =$$
$$usRAP\ study\ fatalities\ per\ year\ on\ R2U\ roads \times \frac{HPMS\ mileage\ on\ R2U\ roads}{usRAP\ study\ mileage\ on\ R2U\ roads} =$$
$$119.6 \times \frac{556{,}913}{7{,}491} = 8{,}892\ nationwide\ fatalities\ per\ year\ on\ 2U\ roads$$

Each of the scaled-up fatality counts per year for HPMS roads entries in Table A-13 was computed in similar fashion from data in the other columns of the table.

Table A-13 shows reasonably good agreement between the FARS fatality counts and scaled-up usRAP study fatality counts for rural roads – the total fatality counts are within 10 percent of one another (13,396 fatalities per year from FARS vs. 12,115 fatalities per year from the scaled-up usRAP study counts). Given the relatively small sample size of usRAP data and the uncertainties in HPMS mileage estimates, it is not reasonable to expect closer agreement than this. By contrast, the scaled-up usRAP fatality counts in Table A-13 overestimate the FARS fatality counts by 250 percent (9,045 fatalities per year from FARS vs. 31,864 fatalities per year from the scaled-up usRAP study counts). As a result, for urban and rural roads combined, the fatality counts based on usRAP study results overpredict the FARS fatality counts by 96 percent.

Based on the results in Table A-13, the scaling-up for rural roads was not changed, but it was decided that it was unrealistic to expect that the usRAP study roads for urban areas were representative of both minor arterials and principal arterials. Table A-14 shows the analysis for Table A-13 repeated with the FARS fatality counts and HPMS mileage for urban roads limited to just principal arterials and freeways. The table still shows less than desirable agreement between the FARS fatality counts and scaled-up usRAP study fatality counts for urban arterial. However, with this change, the comparison of total fatalities for urban and rural areas combined agree within just over 20 percent. This agreement is likely as close as can be expected given the relatively small sample size of usRAP data and the uncertainties in HPMS mileage estimates. Agreement may improve in future years as the size and diversity of the available sample of usRAP study roads expands.

During the period from 2010 to 2014, all U.S. roads of the types and functional classes represented in Table A-14 experienced an average of 32,887 fatalities per year, so the road types and functional classes addressed in the current study experience approximately 65 percent of total U.S. fatalities.

A.8 Scaled-Up Infrastructure Investment Needs from usRAP Study Results to National Needs

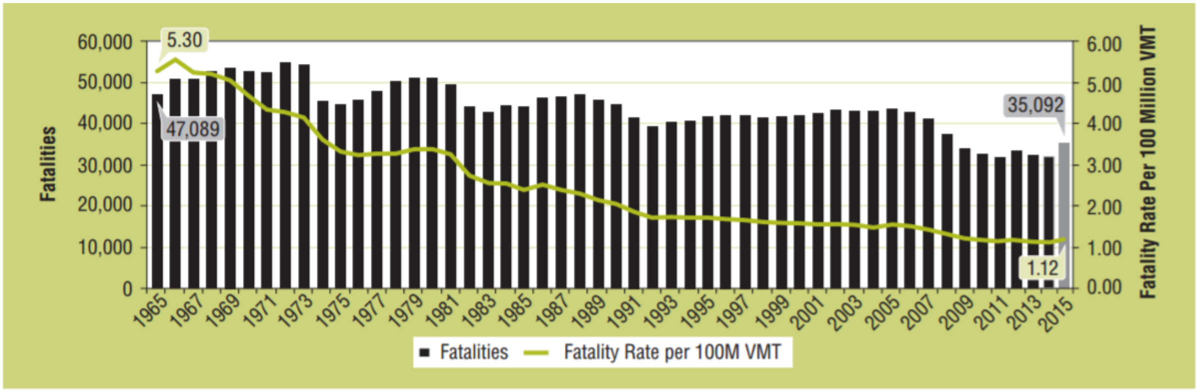
The final step in the analysis was to scale up the infrastructure investment programs for the usRAP study road networks (see Tables A-6 to A-10) to represent infrastructure investment needs for a comparable nationwide roadway network. The road lengths for the usRAP study networks by road type and AADT level have been shown in Table A-3. Table A-12 shows the nationwide length of comparable roads estimated from HPMS by road type and AADT level. Nationwide infrastructure investment needs can be estimated by scaling up the infrastructure investment programs summarized in Tables A-6 through A-10 by the ratio of the road mileages in Table A-12 to the comparable mileage for the same road type and AADT level in Table A-3. Where data for a road type and AADT level combination are included in Table A-12, but not in Table A-3, no estimate can be made. This is a limitation of the study that may be overcome in the future as the mileage of completed usRAP studies expands.

Table A-15 summarizes the nationwide infrastructure needs estimated by this method for minimum benefit-cost ratios from 1.0 to 5.0. Tables A-16 through A-20 summarize the infrastructure improvement needs for minimum benefit-cost ratios from 1.0 to 5.0, respectively, for specific countermeasure or infrastructure improvement types. As in the preceding tables, these tables represent an 825,000-mi road network consisting of paved roads for the road types and AADT levels shown in Table A-3 in the functional classes of collectors, minor arterials, principal arterials, and freeways for rural roads and principal arterials and freeways for urban roads and streets.

Appendix B. Unit Construction Costs Used in usRAP Studies

Table B-1 summarizes the unit construction costs used in developing the infrastructure improvement program costs in usRAP studies presented in Section 4 and Appendix A of this report. The table identifies the countermeasure category, countermeasure name, unit of cost, countermeasure service life, and construction cost per unit. Construction costs are shown separately for rural and urban areas. Construction costs are shown separately for low, medium, and high cost sites based on the upgrade cost level codes assigned to each site in the usRAP data coding process.

Figures



Sources: 1965–1974: National Center for Health Statistics, HEW, and State Accident Summaries (Adjusted to 30-Day Traffic Deaths by NHTSA); FARS 1975-2014 Final File, 2015 Annual Report File (ARF); Vehicle Miles Traveled (VMT): FHWA.

Figure 1. Number of fatalities and fatality rate per 100 million vehicle-miles traveled in the United States from 1965 to 2015 (NHTSA, 2016)

Figure 2. Roadside slope for Case Study 1 before improvement

SOURCE: Nevada Department of Transportation

Figure 3. Roadside slope for Case Study 1 after improvement

SOURCE: Nevada Department of Transportation

Figure 4. Transition from composite shoulder to unpaved shoulder at one end of the project in Case Study 2
SOURCE: Iowa Department of Transportation

Figure 5. Typical section along the Case Study 2 corridor after construction of 2-ft paved shoulder
SOURCE: Iowa Department of Transportation

Figure 6. Example of centerline rumble strip installed on an undivided highway in Kentucky
SOURCE: Kentucky Department of Transportation

Figure 7. Freeway segment for Case Study 4 before the installation of continuous shoulder rumble strips (existing intermittent rumble strips are outlined in red)

SOURCE: Utah Department of Transportation

Figure 8. Freeway segment for Case Study 4 after the installation of continuous shoulder rumble strips (indicated by black arrows) showing existing intermittent rumble strips (outlined in red)

SOURCE: Utah Department of Transportation

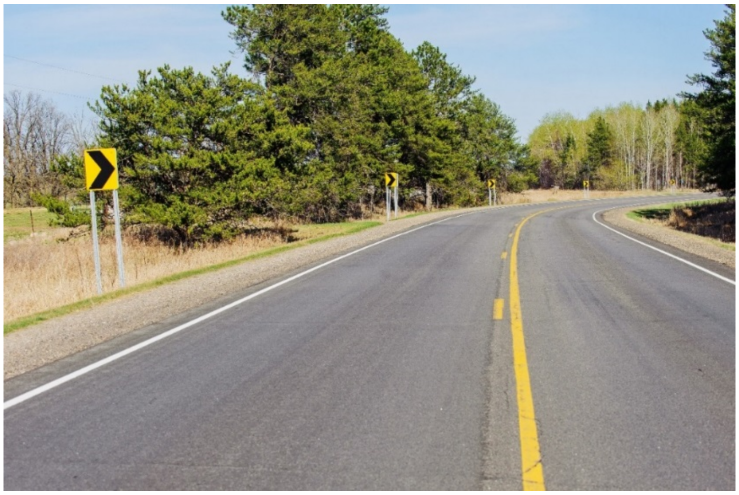


Figure 9. Curve Chevrons Installed in Minnesota at a Typical Site for Case Study 5

SOURCE: Minnesota Department of Transportation

Figure 10. Rural two-lane highway site for Case Study 6 prior to passing lane installation
SOURCE: Missouri Department of Transportation

Figure 11. Rural two-lane highway site for Case Study 6 after passing lane installation
SOURCE: Missouri Department of Transportation

Figure 12. Median cable barrier placed in the center of a Missouri freeway typical of the site for Case Study 7
SOURCE: Missouri Department of Transportation

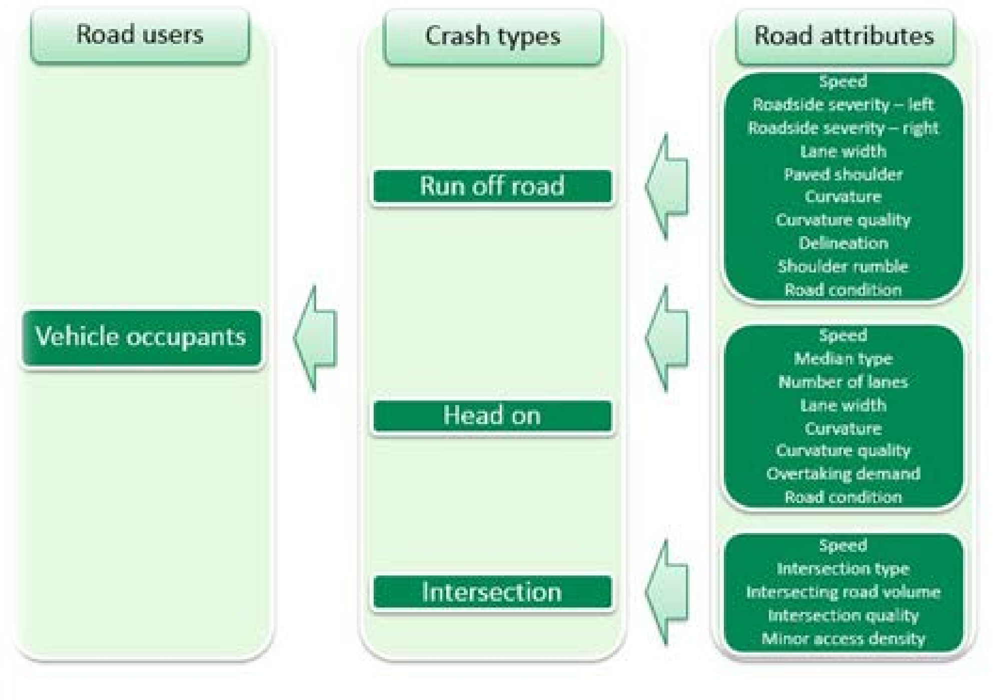


Figure 13. Example of Scoring System for Vehicle-Occupant Star Ratings

SOURCE: International Road Assessment Programme

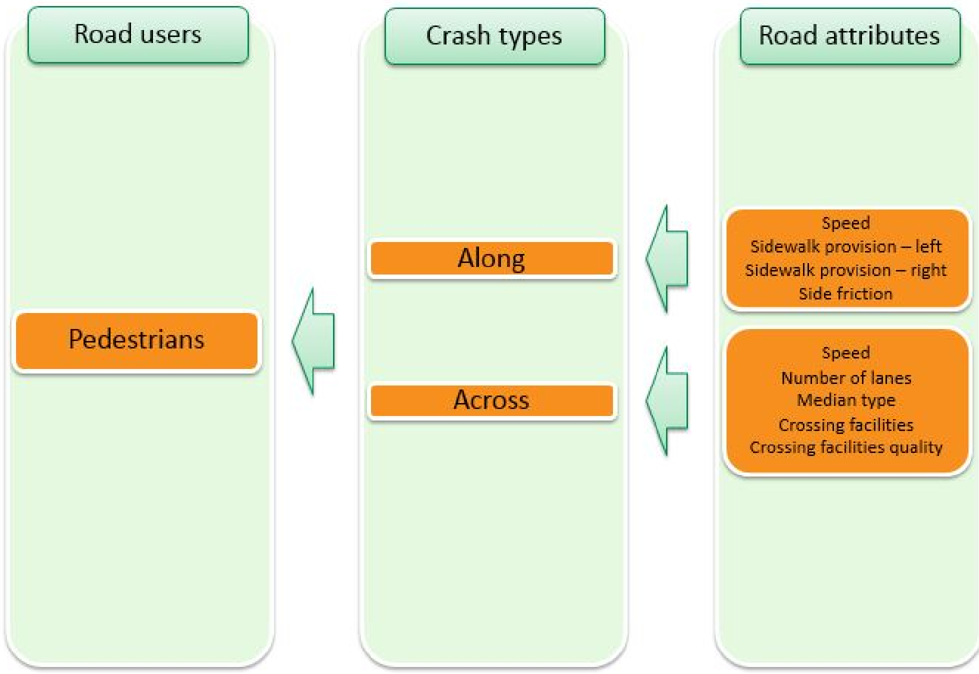


Figure 14. Example of Scoring System for Pedestrian Star Ratings

SOURCE: International Road Assessment Programme

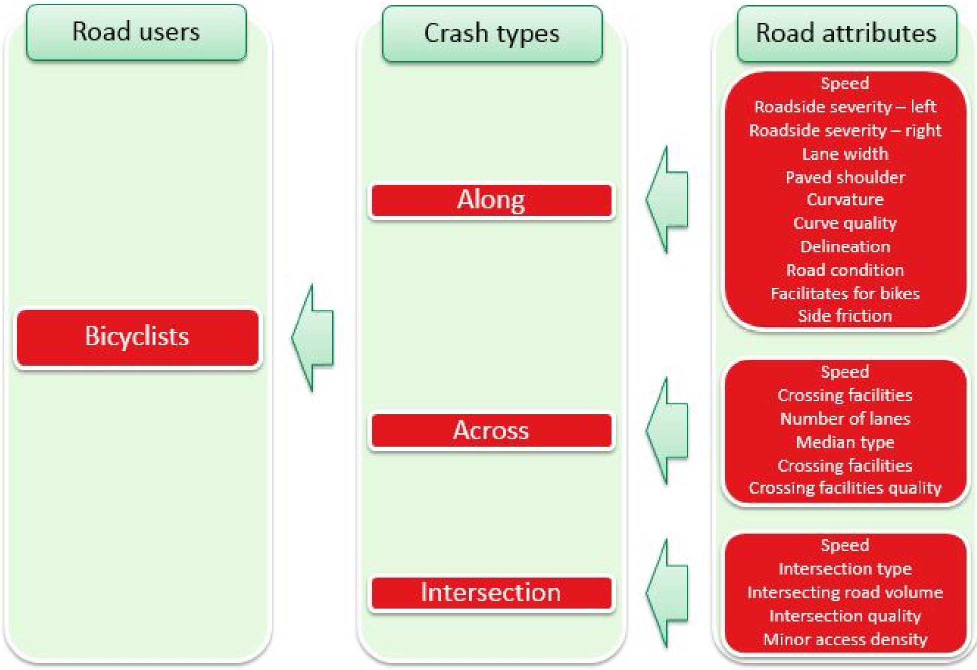


Figure 15. Example of Scoring System for Bicyclist Star Ratings

SOURCE: International Road Assessment Programme

Safer Roads Investment Plan

Currency: $ USD - Analysis Period: Multiple

Total FSIs Saved	Total PV of Safety Benefits	Estimated Cost	Cost per FSI saved	Program BCR
29	14,721,078	7,362,507	256,422	2

Countermeasure	Length / Sites	FSIs saved	PV of safety benefit	Estimated Cost	Cost per FSI saved	Program BCR
Roadside barriers - right side	14.80 km	10	4,951,398	2,944,500	304,896	2
Roadside barriers - left side	15.10 km	10	5,038,855	3,043,950	309,724	2
Clear roadside hazards - left side	11.00 km	3	1,297,757	111,540	44,066	12
Clear roadside hazards - right side	10.70 km	2	1,206,609	102,180	43,418	12
Improve delineation	9.60 km	1	691,293	342,886	254,306	2
Shoulder paving right side (> 3 ft)	5.80 km	1	532,012	351,050	338,311	2
Shoulder paving left (> 3 ft)	3.10 km	1	327,244	191,750	300,423	2
Bicycle lane (on-road)	3.50 km	0	71,094	43,680	315,004	2
Improve curve delineation	0.60 km	0	188,562	10,715	29,135	18
Lane widening (up to 1.5 ft)	0.70 km	0	181,437	120,373	340,149	2
Delineation and signing (intersection)	1 sites	0	20,542	17,859	445,737	1
Sideslope improvement - right side	0.50 km	0	86,434	29,250	173,504	3
Sideslope improvement - left side	0.50 km	0	89,299	29,250	167,938	3
Shoulder rumble strips	0.30 km	0	38,542	23,525	312,941	2

Figure 16. Example Summary Table for a usRAP Safer Roads Investment Plan

SOURCE: International Road Assessment Programme

Tables

Table 1. OECD countries ranked by traffic fatalities per 100,000 population (WHO, 2015; OECD, 2015)

Country	Traffic fatalities per 100,000 population	Traffic fatalities per 100 million vehicle-miles of travel	Country	Traffic fatalities per 100,000 population	Traffic fatalities per 100 million vehicle-miles of travel
Sweden	2.8	0.56	New Zealand	6.0	1.08
United Kingdom	2.9	0.58	Czech Republic	6.1	2.24
Switzerland	3.3	0.69	Italy	6.1	--
Netherlands	3.4	0.72	Slovenia	6.4	1.22
Denmark	3.5	0.64	Slovakia	6.6	--
Israel	3.6	0.85	Belgium	6.7	1.17
Spain	3.7	1.26	Estonia	7.0	--
Norway	3.8	0.71	Hungary	7.7	--
Ireland	4.1	0.63	Portugal	7.8	--
Germany	4.3	0.79	Luxembourg	8.7	--
Iceland	4.6	0.76	Turkey	8.9	--
Japan	4.7	1.29	Greece	9.1	--
Finland	4.8	0.77	Poland	10.3	--
France	5.1	0.93	South Korea	10.4	2.93
Australia	5.4	0.84	United States	10.6	1.14
Austria	5.4	0.93	Mexico	12.3	--
Canada	6.0	1.00	Chile	12.4	--

Table 2. Typical Percentage Reduction in Crashes of All Severity Levels for Lane Width Improvements on Higher Volume Roads (adapted from AASHTO, 2010; AASHTO, 2014)

Lane width (ft)		Percentage reduction in crashes by highway type			
Existing	Improved	Rural two-lane	Rural multilane, undivided	Rural multilane, divided	Rural and urban freeways
9	10	8.9	3.7	4.4	--
9	11	20.1	8.3	9.8	--
9	12	22.3	9.3	11.1	--
10	11	12.2	4.8	5.6	1.9[a]
10	12	14.7	5.8	7.0	5.4[a]
11	12	2.8	1.1	1.5	3.7

[a] Existing condition equal to 10.5 ft rather than 10 ft

Table 3. Typical Percentage Reduction in Crashes of All Severity Levels for Shoulder Width Improvements on Higher Volume Roads (adapted from AASHTO, 2010; AASHTO, 2014)

Shoulder width (ft)		Percentage reduction in crashes by highway type				
Existing	Improved	Rural two-lane	Rural multilane, undivided	Rural multilane, divided (right)	Rural and urban freeways (right)	Rural and urban freeways (left)
0	2	8.9	4.8	4.2	--[a]	--
0	4	15.6	8.3	7.6	--[a]	--
0	6	22.3	11.9	11.9	--[a]	--
0	8	28.1	15.0	15.2	--[a]	--
2	4	7.3	3.7	3.5	--[a]	3.4
2	6	14.7	7.4	7.9	--[a]	6.6
2	8	21.1	10.7	11.5	--[a]	9.8
4	6	7.9	3.9	4.6	--[a]	3.4
4	8	14.8	7.3	8.3	--[a]	6.7
6	8	7.4	3.5	3.8	--[a]	3.4

[a] No comparable data for freeways, because the crash reduction estimate in the *Highway Safety Manual* applies to single-vehicle crashes only, not to total crashes

Table 4. Typical Percentage Reduction in Crashes of All Severity Levels for Shoulder Type Improvements on Higher Volume Roads (adapted from AASHTO, 2010)

Shoulder type		Percentage reduction in crashes by highway type	
Existing	**Improved**	**Rural two-lane**	**Rural multilane, undivided**
Turf	Gravel	3.3	1.6
Turf	Paved	4.4	2.1
Composite	Paved	2.2	1.1
Gravel	Paved	1.1	0.5

Table 5. Typical Percentage Reduction in Crashes of All Severity Levels as Median Width is Increased on Roadway with ADT of 10,000 veh/day (adapted from AASHTO, 2010)

Median width (ft)		Percentage reduction in crashes by highway type		
Existing	**Improved**	**Rural multilane**	**Urban and suburban arterial**	**Rural and urban freeways**
No median (4U)	Median (4D)	43.2	35.2	--[a]
10	20	1.9	2.0	--[a]
10	30	3.8	3.0	--[a]
10	50	6.7	5.0	--[a]
20	30	2.0	1.0	--[a]
20	50	4.9	3.0	--[a]
30	50	3.0	2.0	--[a]

[a] the effect of median width on freeways depends on several other factors and cannot be summarized easily

Table 6. Expected Percentage Reduction in Fatal and Injury Crashes for Specific Delineation Treatments by Highway Type (adapted from Potts et al., 2011)

Delineation treatment	Percentage reduction in fatal and injury crashes by highway type					
	Rural two-lane	Rural multilane, undivided	Rural multilane, divided	Urban multilane	Rural freeways	Urban freeways
Wider markings with resurfacing	--	--	25	8	9	4
Wider markings and edge line and rumble strips with resurfacing	--	--	26	14	24	10
Wider markings and shoulder and rumble strips with resurfacing	--	--	25	--	23	20
Wider markings with shoulder and edge line rumble strips and resurfacing	38	--	--	--	38	--
Wider markings only	--	--	--	--	22	--

Table 7. Typical Percentage Reduction in Crashes of All Severity Levels as Roadside Hazard Rating is Improved for Rural Two-Lane Highways (adapted from AASHTO, 2010)

Existing RHR	Improved RHR	Percentage reduction in crashes
7	5	12.5
7	3	23.4
7	1	33.0
5	3	12.5
5	1	23.4
3	1	12.5

Table 8. Typical Percentage Reduction in Crashes for All Crash Severity Levels as Sideslope is Flattened for Rural Multilane Undivided Highways (adapted from AASHTO, 2010)

Existing sideslope	Improved sideslope	Percentage reduction in crashes
1:2 or steeper	1:3	2.5
1:2 or steeper	1:5	7.6
1:2 or steeper	1:7 or flatter	15.3
1:3	1:5	5.2
1:3	1:7 or flatter	13.0
1:5	1:7 or flatter	8.3

Table 9. Typical Percentage Reduction in Total Crashes from Decrease in Roadside Fixed Object Density for Specific Urban and Suburban Arterial Cross Sections, Assuming a 15-ft Offset to Fixed Objects (adapted from AASHTO, 2010)

Fixed object density per mile		Percentage reduction in crashes by cross section of urban or suburban arterial				
Existing	**Improved**	**2U**	**3T**	**4U**	**4D**	**5T**
150	100	13.0	23.8	25.4	24.9	12.8
150	50	26.0	17.6	18.8	18.4	9.5
150	25	32.5	22.0	23.5	23.0	11.9
150	0	35.2	23.8	25.4	24.9	12.8
100	50	14.9	9.7	10.4	10.1	5.0
100	25	22.4	14.5	15.5	15.2	7.5
100	0	25.5	16.5	17.7	17.3	8.5
50	25	8.8	5.3	5.8	5.6	2.6
50	0	12.4	7.5	8.2	8.0	3.7
25	0	4.0	2.3	2.5	2.5	1.1

NOTE: 2U = two-lane undivided; 3T = three-lane with center two-way left-turn lane; 4U = four-lane undivided; 4D = four-lane divided; 5T = five-lane with center two-way left-turn lane

Table 10. Typical Percentage Reduction in Total Crashes from Increase in Distance to Fixed Objects for Specific Urban and Suburban Arterial Cross Sections, Assuming a Fixed Object Density of 50 objects per mi (adapted from AASHTO, 2010)

Distance to fixed objects		Percentage reduction in crashes by cross section of urban or suburban arterial				
Existing	**Improved**	**2U**	**3T**	**4U**	**4D**	**5T**
2	5	18.0	12.4	13.2	12.9	6.8
2	10	26.3	18.1	19.3	18.9	9.9
2	20	31.8	21.9	23.3	22.8	12.0
2	30	34.1	23.5	25.0	24.5	12.9
5	10	10.2	6.6	7.0	6.9	3.4
5	20	16.8	10.8	11.6	11.4	5.6
5	30	19.7	12.7	13.6	13.3	6.5
10	20	7.4	4.6	4.9	4.8	2.3
10	30	10.6	6.6	7.1	6.9	3.3
20	30	3.5	2.1	2.3	2.2	1.0

NOTE: 2U = two-lane undivided; 3T = three-lane with center two-way left-turn lane; 4U = four-lane undivided; 4D = four-lane divided; 5T = five-lane with center two-way left-turn lane

Table 11. Typical Percentage Reduction in Total Crashes When Left- or Right-Turn Lanes Are Added at Urban or Suburban Arterial Intersections (adapted from AASHTO, 2010)

Turns lanes added	Percentage reduction in crashes by urban/suburban arterial intersection type			
	3-leg minor-road stop control	3-leg signal	4-leg minor-road stop control	4-leg signal
Left-turn lane (1 approach)	33	7	27	10
Left-turn lane (2 approaches)	55	14	47	19
Left-turn lane (3 approaches)	--	20	--	27
Left-turn lane (4 approaches)	--	--	--	34
Right-turn lane (1 approach)	14	4	14	4
Right-turn lane (2 approaches)	26	8	26	8
Right-turn lane (3 approaches)	--	--	--	12
Right-turn lane (4 approaches)	--	--	--	15

Table 12. Typical Percentage Reduction in Total Crashes When Left- or Right Turn Lanes Are Added to Rural Highway Intersections (adapted from AASHTO, 2010)

Turns lanes added	Percentage reduction in crashes by rural highway intersection type				
	Two lane			Multilane	
	3-leg minor-road stop control	4-leg minor-road stop control	4-leg signalized	3-leg minor-road stop control	4-leg minor-road stop control
Left-turn lane (1 approach)	44	28	18	44	28
Left-turn lane (2 approaches)	69	48	33	--	48
Left-turn lane (3 approaches)	--	--	45	--	--
Left-turn lane (4 approaches)	--	--	55	--	--
Right-turn lane (1 approach)	14	14	4	14	14
Right-turn lane (2 approaches)	26	26	8	--	26
Right-turn lane (3 approaches)	--	--	12	--	--
Right-turn lane (4 approaches)	--	--	15	--	--

Table 13. Typical Percentage Reduction in Total Crashes When Protected or Permissive/Protected Left-Turn Phasing is Added at an Urban or Suburban Arterial Intersection (adapted from AASHTO, 2010)

Left-turn phasing	Percentage reduction in crashes by urban/suburban arterial intersection type	
	3-leg signalized	4-leg signalized
Permissive/protected (1 approach)	1	1
Permissive/protected (2 approaches)	2	2
Permissive/protected (3 approaches)	3	3
Permissive/protected (4 approaches)	--	4
Protected (1 approach)	6	6
Protected (2 approaches)	8	8
Protected (3 approaches)	12	12
Protected (4 approaches)	--	15

Table 14. Percentage Reduction in Pedestrian Crash Frequency for Varying Types of Pedestrian Crossing Facilities (iRAP, 2014)

Type of Pedestrian Crossing Facility	Percent reduction in fatal and serious injury pedestrian crashes
Grade separated type of pedestrian facility with pedestrian fencing	100.0
Grade separated facility	94.0
Signalized crossing with refuge island	85.0
Signalized crossing without refuge island	81.0
Unsignalized raised crossing with a refuge island	63.0
Unsignalized raised crossing without a refuge island	52.0
Unsignalized crossing with a refuge island	43.0
Unsignalized crossing without a refuge island	28.0
Refuge island only	24.0

NOTE: Percentage reductions are in comparison to having no pedestrian crossing for the same pedestrian flow crossing the road.

Table 15. Percentage Reduction in Crash Pedestrian Frequency for Various Types of Sidewalk or Shoulder Facilities (iRAP, 2014a)

Type of Sidewalk or Shoulder	Percent reduction in fatal and serious injury pedestrian crashes
Sidewalk with physical barrier separating it from the road	100.0
Sidewalk more than 10 ft from the road	99.6
Sidewalk 3 to 10 ft from the road	99.5
Sidewalk adjacent to road	99.5
Paved shoulder at least 7.8 ft wide	30.0
Paved shoulder 3 to 8 pt wide	25.0
Paved shoulder less than 3 ft wide	10.0

NOTE: Percentage reductions are in comparison to having no sidewalk or shoulder for the same bicycle flow along the road.

Table 16. Percentage Reduction in Bicycle Crash Frequency for Varying Types of Bicycle or Shoulder Facilities (iRAP, 2014b)

Type of Bicycle Facility or Shoulder	Percent reduction in fatal and serious injury bicycle crashes
Segregated bicycle path with barrier	100.0
Segregated bicycle path without barrier	99.5
Dedicated bicycle lane on roadway	40.0
Paved shoulder more than 7.8 ft wide	20.0
Wide curb lane (at least 14 ft wide)	15.0
Paved shoulder 3 to 7.8 ft wide	15.0
Paved shoulder less than 3 ft wide	10.0
Signed shared roadway	5.0

NOTE: Percentage reductions are in comparison to having no bicycle facility or shoulder for the same bicycle flow along the road.

Table 17. Roadway attributes for the roadside slope improvement in Case Study 1

Roadway Attribute	Description/value
Roadway type	Rural two-lane highway
Project length (mi)	10
Traffic volume (AADT) (veh/day) (before)	5,600
Traffic volume (AADT) (veh/day) (after)	5,200
Access control	Partial
Lane width (ft)	12
Median type (before)	Centerline only
Median type (after)	Centerline and centerline rumble strips
Left shoulder type	Paved with rumble strips
Left shoulder width (ft)	3
Right shoulder type	Paved with rumble strips
Right shoulder width (ft)	3
Roadside slope (before)	1:2 to 1:3
Roadside slope (after)	1:6
Speed limit (mph)	65
Land use	Undeveloped

SOURCE: Nevada Department of Transportation

Table 18. Crash frequencies and rates before and after the roadside slope improvement for Case Study 1

Measure	Before period (3 years)		After period (3 years)		Percent change	
	Crash frequency	Crash rate[a]	Crash frequency	Crash rate[a]	Crash frequency	Crash rate[a]
Total crashes	58	94.6	26	45.7	-55%	-52%
Fatal and injury crashes	26	42.4	6	10.5	-77%	-75%
PDO crashes	32	52.2	20	35.1	-38%	-33%

[a] per 100 million vehicle-miles of travel

NOTE: Before period 09/04/2005 to 09/04/2008 (3 years); after period 09/04/2008 – 09/04/2011 (3 years).

SOURCE: Nevada Department of Transportation

Table 19. Roadway attributes for the shoulder paving improvement site in Case Study 2

Roadway attribute	Description/value
Roadway type	Rural two-lane undivided highway
Segment length (mi)	4.3
Traffic volume (AADT) (veh/day) (before)	3,900 (min 3,100; max 5,500)
Traffic volume (AADT) (veh/day) (after)	3,200 (min 2,700; max 4,400)
Speed limit (mph)	55
Lane width	11 ft
Shoulder width (ft) (before)	6-7 ft gravel
Shoulder width (ft) (after)	2 ft paved + 4-5 ft gravel

SOURCE: Iowa Department of Transportation

Table 20. **Crash frequencies and rates before and after shoulder paving for Case Study 2**

Crash type	Crash severity level	Before period (5 years)		After period (5 years)		Percent change	
		Crash frequency	Crash rate[a]	Crash frequency	Crash rate[a]	Crash frequency	Crash rate[a]
All	All	98	318.41	47	186.29	-52.04	-41.49
	Fatalities and all injuries	49	159.21	16.00	63.42	-67.35	-60.17
	Fatalities and serious injuries	5	16.25	0	0	-100	-100
SVROR	All	32	103.97	7	27.75	-78.13	-73.31
	Fatalities and all injuries	26	84.48	6	23.78	-76.92	-71.85
	Fatalities and serious injuries	4	13.00	0	0	-100	-100

[a] per 100 million vehicle-miles of travel
NOTE: Before period: 2004-2008; After period: 2010-2014
SOURCE: Iowa Department of Transportation

Table 21. Crash frequencies and rates for the same time periods as Case Study 2 on comparable rural two-lane highways

Crash type	Crash severity level	Before period (5 years)		After period (5 years)		Percent change	
		Crash frequency	Crash rate[a]	Crash frequency	Crash rate[a]	Crash frequency	Crash rate[a]
All	All	719	234.08	461	164.47	-35.88	-29.74
	Fatalities and all injuries	322	104.83	182	64.93	-43.48	-38.06
	Fatalities and serious injuries	24	7.81	22	7.85	-8.33	0.45
SVROR	All	198	64.46	124	44.24	-37.37	-31.37
	Fatalities and all injuries	158	51.44	85	30.32	-46.20	-41.05
	Fatalities and serious injuries	12	3.91	11	3.92	-8.33	0.45

[a] per 100 million vehicle-miles of travel
NOTE: Before period: 2004-2008; After period: 2010-2014
SOURCE: Iowa Department of Transportation

Table 22. Roadway characteristics for centerline rumble strip installation in Case Study 3

Roadway attribute	Description/value
Total number of segments	34
Roadway type	Rural two-lane undivided highway
Segment length (mi)	Total: 109 mi (min: 0.3 mi; max: 7.3 mi; avg: 3.2 mi)
Traffic volume (AADT) (veh/day) (before)	5,000
Traffic volume (AADT) (veh/day) (after)	5,000
Median type (before)	Centerline only
Median type (after)	Centerline and centerline rumble strips
Lane width (ft)	12
Shoulder type	None
Shoulder width (ft)	0
Speed limit (mph)	55

SOURCE: Kentucky Transportation Cabinet

Table 23. Crash frequencies and crash rates before and after installation of centerline rumble strips for all Case Study 3 sites combined

Crash severity level	Before period (4 years)		After period (4 years)		Percent change	
	Crash frequency	Crash rate[a]	Crash frequency	Crash rate[a]	Crash frequency	Crash rate[a]
Total crashes	1264	167.8	1238	164.4	-2%	-2%
Fatal crashes	23	3.1	12	1.6	-48%	-48%
Serious injury crashes	47	6.2	47	6.2	0%	0%
Minor injury crashes	113	15.0	98	13.0	-13%	-13%
Possible injury crashes	176	23.4	162	21.5	-8%	-8%
PDO crashes	905	120.2	919	122.0	2%	2%

[a] per 100 million vehicle-miles of travel

NOTE: Before period: 2007-2010; After period: 2012-2015

SOURCE: Kentucky Transportation Cabinet

Table 24. Roadway attributes for the shoulder rumble strip improvement site in Case Study 4

Roadway attribute	Description/value
Roadway type	Rural four-lane divided freeway
Segment length (mi)	12.1
Average traffic volume (AADT) (veh/day) (before)	6,900
Average traffic volume (AADT) (veh/day) (after)	7,100
Lane width (ft)	12
Shoulder width (ft) (outside/inside)	10/4
Speed limit (mph)	75

SOURCE: Utah Department of Transportation

Table 25. Crash frequencies and rates before and after shoulder rumble strip installation for Case Study 4

Crash type	Crash severity level	Before Period (3 years)		After Period (3 years)		Percent Change	
		Crash frequency	Crash rate[a]	Crash frequency	Crash rate[a]	Crash frequency	Crash rate[a]
All	All	59	64.65	32	34.04	-45.69	-47.35
Road Departure	All	42	45.95	12	12.73	-71.43	-72.30
	Fatal	1	1.09	0	0.00	-100	-100
	Serious injury	3	3.28	1	0.95	-70.00	-70.92
	Evident injury	10	10.94	0	0.00	-100	-100
	Possible injury	5	5.47	2	2.12	-60.00	-61.23
	Property damage only	23	25.16	9	9.54	-60.87	-62.07

[a] per 100 million vehicle-miles of travel

NOTE: Before period: 2008-2010; After period: 2012-2014

SOURCE: Utah Department of Transportation

Table 26. Roadway characteristics for countermeasure installation sites for Case Study 5

Characteristic	Value
Total number of curves	54
Roadway type	Rural two-lane undivided highway
Segment length	Average length of approximately 1,000 ft
Average traffic volume (AADT) (veh/day) (before)	1,200
Average traffic volume (AADT) (veh/day) (after)	1,200
Median type	Centerline only
Lane width	12 ft
Shoulder Type	None
Shoulder width	0
Speed limit (mph)	55

SOURCE: Minnesota Department of Transportation

Table 27. Crash Data Before and After Chevron Sign Installation for Horizontal Curves in Case Study 5

Crash severity level	Before period		Crashes After Treatment		Percent change
	Crash frequency	Crash frequency per year	Crash frequency	Crash frequency per year	
Total crashes	65	0.79	5	0.06	-92%

SOURCE: Minnesota Department of Transportation

Table 28. Roadway attributes for the passing lane improvement site in Case Study 5

Roadway attribute	Description/value
Roadway type (before)	Two-lane undivided road
Roadway type (after)	Two-lane undivided road with alternating passing lanes
Segment length (mi)	11.47
Median type (before)	Centerline only
Average traffic volume (AADT) (veh/day) (before)	7,400
Average traffic volume (AADT) (veh/day) (after)	6,600
Median type (after)	Centerline and centerline rumble strips
Number of through travel lanes	2
Lane width (ft)	Through lanes: 12; Passing lane: 11
Shoulder type	Paved
Left shoulder width (ft)	8 ft before/8 ft after
Right shoulder width (ft)	8 ft before/2 ft after
Speed limit (mph)	65

SOURCE: Missouri Department of Transportation

Table 29. Crash frequencies and rates before and after passing lane installation for Case Study 6

Crash severity level	Before period (5 years)		After period (5 years)		Percent change	
	Crash frequency	Crash rate	Crash frequency	Crash rate	Crash frequency	Crash rate
Total crashes	163	105.8	144	104.1	-12%	-2%
Fatal crashes	5	3.2	4	2.9	-20%	-11%
Disabling injury crashes	11	7.1	9	6.5	-18%	-9%
Minor injury crashes	40	26.0	27	19.5	-33%	-25%
PDO crashes	107	69.4	104	75.2	-3%	8%

[a] per 100 million vehicle-miles of travel
NOTE: Before period: 2003-2007; After period: 2009-2013
SOURCE: Missouri Department of Transportation

Table 30. Roadway characteristics for cable median barrier installation site for Case Study 7

Roadway attribute	Description/value
Roadway type	Rural four-lane divided freeway
Segment length (mi)	42
Number of interchanges	10
Median type	Depressed grassy median
Median width (ft)	45
Lane width (ft)	12
Shoulder width (ft):	
NB outside	10 ft
NB inside (median)	4 ft
SB outside	10 ft
SB inside (median)	10 ft
Speed limit (mph)	70

SOURCE: Missouri Department of Transportation

Table 31. Median barrier installation characteristics for Case Study 7

Characteristic	Description/Value
Median barrier type	High-tension cable barrier
Barrier location	Outside edge of southbound inside shoulder
Post spacing (ft)	20

SOURCE: Missouri Department of Transportation

Table 32. Yearly weighted AADT and MVMT for 42-mi roadway section in Case Study 7

Year	Direction 1 AADT	Direction 2 AADT	Combined AADT	100 Million Vehicle Miles Traveled (MVMT)
2003	10,883	10,709	21,593	3.30
2004	11,229	11,012	22,241	3.40
2005	10,914	12,113	23,027	3.52
2006	10,947	12,153	23,101	3.53
2007	10,894	12,070	22,964	3.51
2008	10,201	10,294	20,496	2.35*
2009	10,237	10,330	20,568	3.14
2010	10,522	10,620	21,142	3.23
2011	10,876	10,922	21,799	3.33
2012	10,876	10,922	21,799	3.33
2013	11,168	11,193	22,362	3.41
2014	10,830	11,500	22,330	3.41

NOTE: MVMT for 2008 includes only the time period from January 1 through September 30. October 1 through December 31 were considered the construction period and excluded.
SOURCE: Missouri Department of Transportation

Table 33. Crash reduction after installation of median cable barrier for Case Study 7

Measure	Before period		After period		Percent change	
	Crash frequency	Crash rate[a]	Crash frequency	Crash rate[a]	Crash frequency	Crash rate[a]
Total crashes	1,641	83.8	1,705	85.9	3.9	2.5
Fatal crashes	25	1.3	12	0.6	-52.0	-52.6
Disabling injury crashes	76	3.9	49	2.5	-35.5	-36.4
Minor injury crashes	301	15.4	236	11.9	-21.6	-22.6
PDO crashes	1,239	63.2	1,408	70.9	13.6	12.2
Total cross-median crashes	62	3.2	6	0.3	-90.3	-90.4
Fatal and severe cross-median crashes	9	0.5	0	0.0	-100.0	-100.0
Fatal and all injury cross-median crashes	26	1.3	1	0.1	-96.2	-96.2
Total cable median crashes	N/A	N/A	36	1.8	N/A	N/A
Fatal and serious injury cable barrier crashes	N/A	N/A	3	0.2	N/A	N/A
Fatal and all injury cable barrier crashes	N/A	N/A	11	0.6	N/A	N/A
Combined total cross-median and cable barrier crashes	62	3.2	42	2.1	-32.3	-33.1
Combined F&S cross-median and cable barrier crashes	9	0.5	3	0.2	-66.7	-67.1
Combined F&I cross-median and cable barrier crashes	26	1.3	12	0.6	-53.8	-54.5

[a] per 100 million vehicle-miles of travel

SOURCE: Missouri Department of Transportation

Table 34. Key Roadway Attributes Considered in usRAP Scoring System for Star Ratings and Crash Prediction

- Area type (rural/urban)
- Land use
- Number of lanes for through traffic
- One-way vs. two-way operation
- Roadway width/lane width
- Shoulder type and width
- Horizontal alignment (especially curve radius)
- Vertical alignment (especially grades)
- Delineation
- Road surface condition
- Roadside features (type of object/distance from traveled way)
- Presence/absence of centerline and shoulder rumble strips
- Access point density
- Medians (divided/undivided and type of median)
- Intersection type (number of legs/traffic control/left-turn lanes)
- Pedestrian facilities
- Bicycle facilities
- Quality of curve
- Quality of intersection
- Quality of pedestrian crossing
- Traffic volume (AADT)
- Motorcycle percentage
- Pedestrian flow crossing road
- Pedestrian flow along road
- Bicycle flow along road
- Intersecting road volume
- Speed limit
- 85th percentile traffic speed (if available)
- Mean traffic speed (if available)

NOTE: The total number of fatalities per year predicted for the road network can be adjusted to match the total fatalities per year in the calibration data set. The ratio of serious injuries to fatalities can be adjusted to match the corresponding ratio in the calibration data set.

Table 35. Distribution of Road Mileage from Past usRAP Studies by Road Type

Road Type	Total Roadway Length (mi)
RURAL ROADS	
Rural two-lane undivided roads	7,491
Rural four-lane undivided roads	252
Rural four-lane divided roads	537
Rural four-lane freeways	772
Rural six-or-more-lane freeways	116
RURAL Subtotal	9,168
URBAN ROADS AND STREETS	
Urban two-lane undivided streets	1,180
Urban four-lane undivided streets	588
Urban six-or-more-lane undivided streets	85
Urban one-way streets	41
Urban four-lane divided roads or streets	466
Urban six-or-more-lane divided roads or streets	123
Urban four-lane freeways	115
Urban six-lane freeways	115
Urban eight-or-more-lane freeways	35
URBAN Subtotal	2,748
COMBINED TOTAL	11,916

SOURCE: Data assembled from past usRAP studies.

Table 36. Roadway Mileage from Past usRAP Studies by Road Type and AADT

	Roadway miles by AADT level (veh/day)										
Road Type	**0-400**	**400-1,000**	**1,000-2,000**	**2,000-5,000**	**5,000-10,000**	**10,000-25,000**	**25,000-50,000**	**50,000-100,000**	**100,000-200,000**	**over 200,000**	**Total**
RURAL ROADS											
Rural two-lane undivided roads	1,331	1,666	1,382	2,039	876	194	3	-	-	-	7,491
Rural four-lane undivided roads	-	2	13	55	94	74	14	-	-	-	252
Rural four-lane divided roads	-	-	2	17	260	235	23	-	-	-	537
Rural four-lane freeways	-	-	-	6	74	330	327	35	-	-	772
Rural six-or-more-lane freeways	-	-	-	-	-	3	39	74	-	-	116
RURAL Suntotal	1,331	1,668	1,397	2,117	1,304	836	406	109	-	-	9,168
URBAN ROADS AND STREETS											
Urban two-lane undivided streets	25	37	94	360	403	252	9	-	-	-	1,180
Urban four-lane undivided streets	1	-	3	27	126	313	116	2	-	-	588
Urban six-or-more-lane undivided streets	-	-	-	4	8	23	50	-	-	-	85
Urban one-way streets	1	-	4	8	8	12	6	2	-	-	41
Urban four-lane divided roads or streets	-	-	2	11	49	240	138	26	-	-	466
Urban six-or-more-lane divided roads or streets	-	-	-	1	3	40	71	8	-	-	123
Urban four-lane freeways	-	-	-	5	-	22	50	37	1	-	115
Urban six-lane freeways	-	-	-	-	-	-	13	47	53	2	115
Urban eight-or-more-lane freeways	-	-	-	-	-	-	1	2	28	4	35
URBAN Subtotal	27	37	103	416	597	902	454	124	82	6	2,748
COMBINED TOTAL	1,358	1,705	1,500	2,533	1,901	1,738	860	233	82	6	11,916

SOURCE: Data assembled from past usRAP studies.

Table 37. Countermeasures from usRAP Software Recommended for Inclusion in the Infrastructure Improvement Plans

Countermeasure Category	Countermeasure name
Add lanes	Add passing lane
Add lanes and median	Widen to divided highway
Add median treatment	Add center two-way left-turn lane
Add median barrier	Add median barrier to existing median
Bicycle facilities	Add bicycle lane Add bicycle path
Delineation	Improve delineation Improve curve delineation
Intersections	Add left-turn lanes Add roundabout Improve intersection delineation and signing Provide grade separation Signalize intersection Update rail crossing
Lane widening	Widen lanes
Parking improvements	Parking improvements
Pedestrian facilities	Add refuge island Install signalized crossing Install unsignalized crossing Provide sidewalk
Roadside improvements	Clear roadside objects Improve sideslopes Install roadside barriers
Rumble strips	Centerline rumble strip Shoulder rumble strips
Shoulder widening	Widen shoulders

Table 38. Summary of Countermeasure Programs from Past usRAP Studies for Minimum Benefit-Cost Ratio Equal to 1.0

Countermeasure category/Countermeasure name	Model used		Recommended infrastructure improvement program					Notes	Reduced No. of injuries (20 years)		
	usRAP Tools Ver 2.2	ViDA Ver 3.0	Length of Improved roadway (mi)	No. of improved sites	Crash reduction benefits (million)	Improvement cost (million)	Benefit-cost ratio		Fatal	Serious Injury	Combined
ADD LANES											
Add passing lane	X	X	115		413	75	5.5		62	827	889
ADD LANES AND MEDIAN											
Widen to divided highway	X	X	45		229	105	2.2		41	302	343
ADD MEDIAN TREATMENT											
Add center two-way left-turn lane		X	14		12	8	1.5	a	2	13	15
ADD MEDIAN BARRIER											
Add median barrier to existing median		X	87		300	67	4.5	a	60	313	373
BICYCLE FACILITIES											
Add bicycle lane		X	126		8	5	1.6	a	2	9	11
Add bicycle path		X	65		45	29	1.6	a	9	51	60
DELINEATION											
Improve delineation	X	X	111		22	9	2.4		3	31	34
Improve curve delineation	X		10		0.6	0.3	2.0	b	0.1	1	1.1
INTERSECTIONS											
Add left-turn lanes	X	X		1,699	489	166	2.9		80	675	755
Add roundabout	X			390	1,010	504	2.0	b	179	1,532	1,711
Improve intersection delineation and signing		X		241	21	5	4.2	b	3	39	42
Provide grade separation	X	X		14	203	134	1.5		37	280	317
Signalize intersection	X	X		924	566	164	3.5		97	910	1,007
Update rail crossing	X			18	24	2	14.1		5	30	35
LANE WIDENING											
Widen lanes		X	37		31	10	3.1	b	5	62	67
PARKING IMPROVEMENTS											
Improve parking		X	20		8	1	8.0	a	1	7	8
PEDESTRIAN FACILITIES											
Add refuge island		X		45	2	1	2.0	a	0.3	2	2.3
Install signalized crossing		X		128	15	11	1.4	a	3	16	19
Install unsignalized crossing		X		32	70	5	14.0	a	10	148	158
Provide sidewalk		X	570		483	232	2.1	a	82	484	566
ROADSIDE IMPROVEMENTS											
Clear roadside objects		X	1,047		215	27	8.0	a	39	195	234
Improve sideslopes	X	X	224		72	25	2.9		13	104	117
Install roadside barriers	X	X	2,579		2,244	965	2.3		397	3,026	3,423
RUMBLE STRIPS											
Centerline rumble strip	X	X	70		18	6	3.0		4	20	24
Shoulder rumble strips		X	487		171	84	2.0	a	35	172	207
SHOULDER WIDENING											
Widen shoulders	X	X	2,146		1,663	395	4.2		258	3,056	3,314
COMBINED TOTALS					8,335	3,036	2.7		1,426	12,303	13,729

NOTE: [a] used Version 3.0 results only to take advantage of improved Version 3.0 logic for this countermeasure
[b] used Version 2.2 results only because many sites evaluated in version 3.0 had incomplete data that limited consideration of this countermeasure
SOURCE: Data assembled from past usRAP studies.

Table 39. Summary of Infrastructure Improvement Programs from Past usRAP Studies

Safety program measure	Minimum benefit-cost ratio				
	1.0	2.0	3.0	4.0	5.0
Present value of 20-year expenditures on infrastructure improvements ($ million)	3,036	1,380	785	518	133
Present value of 20-year safety benefits ($ million)	8,335	6,577	5,486	4,741	1,544
Benefit-cost ratio	2.7	4.8	7.0	9.2	11.6
Fatalities reduced over 20 years	1,426	1,115	925	796	265
Serious injuries reduced over 20 years	12,303	9,737	8,108	6,960	1,496
Fatalities and serious injuries reduced over 20 years	13,729	10,852	9,033	7,756	1,761

SOURCE: Data assembled from past usRAP studies.

Table 40. Summary of Nationwide Road Mileage from HPMS for Collector and Arterial Roads and Streets and Freeways (with Unknowns Distributed)

Roadway type (with functional class for urban nonfreeways)	Roadway miles by AADT level (veh/day)										
	0 - 400	401 - 1,000	1,001 - 2,000	2,001 - 5,000	5,001 - 10,000	10,001 - 25,000	25,001 - 50,000	50,001 - 100,000	100,001 - 200,000	More than 200,000	Total
RURAL ROADS											
Rural two-lane undivided roads	225,114	118,957	91,332	91,723	25,926	3,778	75	2	6	0	556,913
Rural four-lane undivided roads	173	210	903	6,679	12,117	7,657	328	0	0	0	28,068
Rural four-lane divided roads	345	468	1,197	5,365	10,973	10,768	910	55	19	0	30,101
Rural four-lane freeways	447	495	726	2,860	9,275	23,534	13,428	906	5	0	51,677
Rural six-or-more-lane freeways	0	0	0	0	22	99	1,325	1,067	179	0	2,692
RURAL SUBTOTAL[a]	**226,080**	**120,130**	**94,158**	**106,627**	**58,313**	**45,837**	**16,067**	**2,030**	**208**	**0**	**669,451**
URBAN ROADS AND STREETS											
Urban two-lane undivided streets	751	498	1,348	5,278	12,703	20,914	3,544	303	0	0	45,338
Urban four-lane undivided streets	0	31	41	1,039	4,335	18,325	7,859	363	0	0	31,992
Urban six-or-more-lane undivided streets	19	4	1	43	399	1,102	905	40	0	0	2,512
Urban one-way streets	282	204	274	526	825	1,259	271	5	0	0	3,648
Urban four-lane divided roads or streets	56	16	12	309	1,794	10,090	6,152	463	0	0	18,892
Urban six-or-more-lane divided roads or streets	11	11	2	21	43	881	3,366	1,248	44	0	5,626
Urban four-lane freeways	65	104	201	958	2,554	7,768	10,079	5,813	500	9	28,052
Urban six-lane freeways	0	0	0	5	32	269	1,666	6,321	4,101	94	12,488
Urban eight-or-more-lane freeways	1	0	0	0	4	32	82	957	4,102	1,709	6,887
URBAN SUBTOTAL[b]	1,184	867	1,878	8,180	22,688	60,639	33,924	15,514	8,748	1,811	**155,434**
COMBINED TOTAL[c]	**227,264**	**120,998**	**96,036**	**114,808**	**81,000**	**106,476**	**49,991**	**17,544**	**8,956**	**1,811**	**824,885**

[a] includes collectors, arterials, and freeways

[b] includes principal arterials and freeways only

[c] includes rural collectors and arterials, urban nonfreeway principal arterials, and urban freeways only

SOURCE: Data assembled from past usRAP studies.

Table 41. Summary of Nationwide Infrastructure Improvement Needs to Reduce Fatalities and Serious Injuries for Minimum Benefit-Cost Ratio Equal to 1.0

Countermeasure category/Countermeasure name	Model used		Recommended infrastructure improvement program					Notes	No. of injuries reduced (20 years)		
	usRAP Tools Ver 2.2	ViDA Ver 3.0	Length of Improved roadway (mi)	No. of improved sites	Crash reduction benefits (million)	Improvement cost (million)	Benefit-cost ratio		Fatal	Serious Injury	Combined
ADD LANES											
Add passing lane	X	X	832		1,089	640	1.7		182	1,516	1,698
ADD LANES AND MEDIAN											
Widen to divided highway	X	X	863		4,414	2,328	1.9		721	4,190	4,911
ADD MEDIAN TREATMENT											
Add center two-way left-turn lane		X	1,827		1,347	936	1.4	a	241	1,375	1,616
ADD MEDIAN BARRIER											
Add median barrier to existing median		X	15,993		47,754	11,506	4.2	a	9,677	48,497	58,174
BICYCLE FACILITIES											
Add bicycle lane		X	15,572		1,039	542	1.9	a	198	1,128	1,326
Add bicycle path		X	8,842		5,724	3,786	1.5	a	1,122	6,611	7,733
DELINEATION											
Improve delineation	X	X	1,125		365	107	3.4		35	361	396
Improve curve delineation	X		4,291		247	124	2.0	b	48	290	338
INTERSECTIONS											
Add left-turn lanes	X	X		993	4,980	2,305	2.2		619	4,401	5,020
Add roundabout	X			23,374	62,350	31,788	2.0	b	10,811	98,759	109,570
Improve intersection delineation and signing		X		30,109	2,312	594	3.9	b	349	4,644	4,993
Provide grade separation	X	X		71	1,261	1,083	1.2		249	1,416	1,665
Signalize intersection	X	X		924	566	164	3.5		98	910	1,008
Update rail crossing	X			943	1,288	93	13.8		252	1,489	1,741
LANE WIDENING											
Widen lanes		X	1,661		1,485	492	3.0	b	226	2,951	3,177
PARKING IMPROVEMENTS											
Improve parking		X	1,876		962	96	7.9	a	76	662	738
PEDESTRIAN FACILITIES											
Add refuge island		X		9,552	351	284	1.2	a	70	356	426
Install signalized crossing		X		15,252	1,414	1,116	1.3	a	277	1,472	1,749
Install unsignalized crossing		X		2,458	5,724	348	16.4	a	831	12,111	12,942
Provide sidewalk		X	101,159		92,226	41,302	2.2	a	16,644	49,075	65,719
ROADSIDE IMPROVEMENTS											
Clear roadside objects		X	127,885		26,101	3,317	7.9	a	4,701	23,759	28,460
Improve sideslopes	X	X	9,930		2,085	1,193	1.7		435	1,917	2,352
Install roadside barriers	X	X	58,677		43,851	24,238	1.8		8,225	43,299	51,524
RUMBLE STRIPS											
Centerline rumble strip	X	X	2,998		737	284	2.6		122	716	838
Shoulder rumble strips		X	75,574		29,458	13,313	2.2	a	5,913	30,782	36,695
SHOULDER WIDENING											
Widen shoulders	X	X	27,321		9,505	4,544	2.1		1,563	10,875	12,438
COMBINED TOTALS					348,435	146,523	2.4		63,685	353,562	417,247

NOTE: [a] used Version 3.0 results only to take advantage of improved Version 3.0 logic for this countermeasure
[b] used Version 2.2 results only because many sites evaluated in version 3.0 had incomplete data that limited consideration of this countermeasure

SOURCE: Analysis results from applying the methodology presented in Appendix A.

Table 42. Summary of Nationwide Infrastructure Improvement Needs by Countermeasure Category for Minimum Benefit-Cost Ratio Equal to 1.0

Countermeasure category	Recommended infrastructure improvement program			No. of injuries reduced (20 years)		
	Crash reduction benefits (million)	Improvement cost (million)	Benefit-cost ratio	Fatal	Serious Injury	Combined
Add lanes	1,089	640	1.7	182	1,516	1,698
Add lanes and median	4,414	2,328	1.9	721	4,190	4,911
Add median treatment	1,347	936	1.4	241	1,375	1,616
Add median barrier	47,754	11,506	4.2	9,677	48,497	58,174
Bicycle facilities	6,723	4,328	2.6	1,320	7,739	9,059
Delineation	612	231	2.6	83	651	734
Intersections	72,767	36,027	2.0	12,378	111,619	123,997
Lane widening	1,485	492	3.0	226	2,951	3,177
Parking improvements	962	96	7.9	76	662	738
Pedestrian facilities	99,715	43,050	2.3	17,882	63,014	80,836
Roadside improvements	72,037	28,748	2.5	13,361	68,975	82,336
Rumble strips	30,195	13,597	2.2	6,035	31,498	37,533
Shoulder widening	9,505	4,544	2.1	1,563	10,875	12,438
COMBINED TOTALS	348,435	146,523	2.4	63,685	353,562	417,247

SOURCE: Summary of data presented in Table 41.

Table 43. Forecast Nationwide Infrastructure Improvement Needs for a Range of Minimum Benefit-Cost Ratios

Safety program measure	Minimum benefit-cost ratio				
	1.0	2.0	3.0	4.0	5.0
Present value of 20-year expenditures ($ million)	146,500	64,400	36,800	24,800	16,600
Crash cost savings per year ($ million)	25,600	20,700	18,400	16,700	14,400
Present value of 20-year safety benefits ($ million)	348,400	281,700	250,500	226,800	196,400
Benefit-cost ratio	2.4	4.4	6.8	9.1	11.8
Expected fatalities over 20 years	394,860	394,860	394,860	394,860	394,860
Expected serious injuries over 20 years	3,323,680	3,323,680	3,323,680	3,323,680	3,323,680
Expected fatalities and serious injuries over 20 years	3,718,540	3,718,540	3,718,540	3,718,540	3,718,540
Fatalities reduced over 20 years	63,700	51,100	44,800	40,100	34,300
Serious injuries reduced over 20 years	353,500	315,900	277,000	246,900	194,800
Fatalities and serious injuries reduced over 20 years	417,200	367,000	321,800	287,000	229,100
Percentage reduction in fatalities	16.1	12.9	11.3	10.2	8.7
Percentage reduction in serious injuries	10.6	9.5	8.3	7.4	5.9
Percentage reduction in fatalities and serious injuries	11.2	9.9	8.7	7.7	6.2

SOURCE: Adapted from results presented in Tables A-16 to A-20 in Appendix A.

Table 44. Distribution of Star Ratings Before Improvement of Road Networks from Past usRAP Studies

Star Rating	Vehicle occupant		Motorcyclist		Pedestrian		Bicyclist	
	Length (mi)	Percent	Length (mi)	Percent	Length (mi)	Percent	Length (mi)	Percent
5 Stars	259.6	5%	146.2	3%	126.2	2%	83.2	2%
4 Stars	681.1	13%	267.9	5%	174.6	3%	54.6	1%
3 Stars	2253.4	42%	2168.3	40%	248.5	5%	328.3	6%
2 Stars	1252.5	23%	1595.5	30%	202.1	4%	916.4	17%
1 Star	937.5	17%	1206.2	22%	725.0	13%	773.3	14%
Not applicable	2.0	0%	2.0	0%	3909.8	73%	3230.2	60%
Totals	**5,386.1**	**100%**	**5,386.1**	**100%**	**5,386.1**	**100%**	**5,386.1**	**100%**

NOTE: Includes all roadways in past usRAP studies using ViDA Version 3.0.

SOURCE: Data assembled from past usRAP studies

Table 45. Distribution of Star Ratings After Improvement of Road Networks from Past usRAP Studies

Star Rating	Vehicle occupant		Motorcyclist		Pedestrian		Bicyclist	
	Length (mi)	Percent	Length (mi)	Percent	Length (mi)	Percent	Length (mi)	Percent
5 Stars	477.6	9%	192.7	4%	164.2	3%	160.3	3%
4 Stars	988.4	18%	450.3	8%	402.4	7%	84.0	2%
3 Stars	2426.8	46%	2655.9	50%	322.6	6%	451.0	8%
2 Stars	929.6	17%	1308.9	24%	238.2	4%	964.9	18%
1 Star	561.6	10%	776.2	14%	349.0	6%	495.6	9%
Not applicable	2.0	0%	2.0	0%	3909.8	74%	3230.2	60%
Totals	**5,386.1**	**100%**	**5,386.1**	**100%**	**5,386.1**	**100%**	**5,386.1**	**100%**

NOTE: Includes all roadways in past usRAP studies using ViDA Version 3.0. Reflects the effects of all improvements recommended by the ViDA software with a minimum benefit-cost ratio of 1.0.

SOURCE: Data assembled from past usRAP studies.

Table A-1. Roadway Mileage Included in Past usRAP Studies by Highway Agency

State/Agency	Roadway Length (mi)		
	usRAP Tools Version 2.2	ViDA Version 3.0	TOTAL
ALABAMA			
Mobile County[a]	778	-	778
ILLINOIS			
Boone County	96	-	96
Champaign County	239	-	239
DuPage County	270	-	270
Kane County	258	-	258
Lake County	280	-	280
McHenry County	218	-	218
Vermilion County	120	-	120
Will County	251	-	251
Winnebago County	303	-	303
IOWA			
Selected State Highways	1,462	-	1,462
Buchanan County	197	-	197
Dallas County	156	-	156
KANSAS			
Selected State Highways	-	27	27
Selected County Roads	-	6	6
KENTUCKY			
Selected State Highways	256	-	256
MICHIGAN			
Genesee County	494	-	494
Sault Tribe[b]	251	-	251
UTAH			
State Highways[c]		4,438	4,438
WASHINGTON			
Selected State Highways	1,489	-	1,489
WISCONSIN			
City of Milwaukee	-	327	327
TOTAL	7,118	4,798	11,916

NOTE: For county agencies, only roads under county jurisdiction are included, unless otherwise specified. For city agencies, only roads under city jurisdiction are included, unless otherwise specified. Only the road types shown in Table A-2 are included in this table.

[a] Includes state highways, county roads and city streets in Mobile County

[b] Includes public roads in northern Michigan used frequently by members of the Sault Tribe of Chippewa Indians

[c] Includes all state highways in Utah except Interstate freeways

SOURCE: Data assembled from past usRAP studies.

Table A-2. Distribution of Road Mileage from Past usRAP Studies by Road Type

Road Type	Total Roadway Length (mi)
RURAL ROADS	
Rural two-lane undivided roads	7,491
Rural four-lane undivided roads	252
Rural four-lane divided roads	537
Rural four-lane freeways	772
Rural six-or-more-lane freeways	116
RURAL Subtotal	9,168
URBAN ROADS AND STREETS	
Urban two-lane undivided streets	1,180
Urban four-lane undivided streets	588
Urban six-or-more-lane undivided streets	85
Urban one-way streets	41
Urban four-lane divided roads or streets	466
Urban six-or-more-lane divided roads or streets	123
Urban four-lane freeways	115
Urban six-lane freeways	115
Urban eight-or-more-lane freeways	35
URBAN Subtotal	2,748
COMBINED TOTAL	11,916

SOURCE: Data assembled from past usRAP studies.

Table A-3. Roadway Mileage from Past usRAP Studies by Road Type and AADT

	Roadway miles by AADT level (veh/day)										
Road Type	**0-400**	**400-1,000**	**1,000-2,000**	**2,000-5,000**	**5,000-10,000**	**10,000-25,000**	**25,000-50,000**	**50,000-100,000**	**100,000-200,000**	**over 200,000**	**Total**
RURAL ROADS											
Rural two-lane undivided roads	1,331	1,666	1,382	2,039	876	194	3	-	-	-	7,491
Rural four-lane undivided roads	-	2	13	55	94	74	14	-	-	-	252
Rural four-lane divided roads	-	-	2	17	260	235	23	-	-	-	537
Rural four-lane freeways	-	-	-	6	74	330	327	35	-	-	772
Rural six-or-more-lane freeways	-	-	-	-	-	3	39	74	-	-	116
RURAL Subtotal	1,331	1,668	1,397	2,117	1,304	836	406	109	-	-	9,168
URBAN ROADS AND STREETS											
Urban two-lane undivided streets	25	37	94	360	403	252	9	-	-	-	1,180
Urban four-lane undivided streets	1	-	3	27	126	313	116	2	-	-	588
Urban six-or-more-lane undivided streets	-	-	-	4	8	23	50	-	-	-	85
Urban one-way streets	1	-	4	8	8	12	6	2	-	-	41
Urban four-lane divided roads or streets	-	-	2	11	49	240	138	26	-	-	466
Urban six-or-more-lane divided roads or streets	-	-	-	1	3	40	71	8	-	-	123
Urban four-lane freeways	-	-	-	5	-	22	50	37	1	-	115
Urban six-lane freeways	-	-	-	-	-	-	13	47	53	2	115
Urban eight-or-more-lane freeways	-	-	-	-	-	-	1	2	28	4	35
URBAN Subtotal	27	37	103	416	597	902	454	124	82	6	2,748
COMBINED TOTAL	1,358	1,705	1,500	2,533	1,901	1,738	860	233	82	6	11,916

SOURCE: Data assembled from past usRAP studies.

Table A-4. Predicted Fatalities and Serious Injuries Per Year

Road Type	Predicted number of injured persons per year		
	Fatality	Serious Injury	Total
RURAL ROADS			
Rural two-lane undivided roads	119.6	1,109.3	1,228.9
Rural four-lane undivided roads	11.4	103.8	115.2
Rural four-lane divided roads	12.6	87.1	99.7
Rural four-lane freeways	16.4	89.9	106.3
Rural six-or-more-lane freeways	6.7	53.3	60.0
RURAL Subtotal	166.7	1,443.4	1,610.1
URBAN ROADS AND STREETS			
Urban two-lane undivided streets	64.0	640.4	704.4
Urban four-lane undivided streets	73.7	621.3	695.0
Urban six-or-more-lane undivided streets	20.1	152.8	172.9
Urban one-way streets	9.2	114.9	124.1
Urban four-lane divided roads or streets	34.4	296.4	330.8
Urban six-or-more-lane divided roads or streets	16.3	101.7	118.0
Urban four-lane freeways	4.6	21.7	26.3
Urban six-lane freeways	12.6	69.2	81.8
Urban eight-or-more-lane freeways	5.9	37.4	43.3
URBAN Subtotal	240.8	2,055.8	2,296.6
COMBINED TOTAL	407.5	3,499.2	3,906.7

SOURCE: Data assembled from past usRAP studies.

Table A-5. Countermeasures from usRAP Software Recommended for Inclusion in the Infrastructure Improvement Plans

Countermeasure Category	Countermeasure name
Add lanes	Add passing lane
Add lanes and median	Widen to divided highway
Add median treatment	Add center two-way left-turn lane
Add median barrier	Add median barrier to existing median
Bicycle facilities	Add bicycle lane
	Add bicycle path
Delineation	Improve delineation
	Improve curve delineation
Intersections	Add left-turn lanes
	Add roundabout
	Improve intersection delineation and signing
	Provide grade separation
	Signalize intersection
	Update rail crossing
Lane widening	Widen lanes
Parking improvements	Parking improvements
Pedestrian facilities	Add refuge island
	Install signalized crossing
	Install unsignalized crossing
	Provide sidewalk
Roadside improvements	Clear roadside objects
	Improve sideslopes
	Install roadside barriers
Rumble strips	Centerline rumble strip
	Shoulder rumble strips
Shoulder widening	Widen shoulders

Table A-6. Summary of Countermeasure Programs from Past usRAP Studies for Minimum Benefit-Cost Ratio Equal to 1.0

Countermeasure category/Countermeasure name	Model used		Recommended infrastructure improvement program					Notes	Reduced No. of injuries (20 years)		
	usRAP Tools Ver 2.2	ViDA Ver 3.0	Length of Improved roadway (mi)	No. of improved sites	Crash reduction benefits (million)	Improvement cost (million)	Benefit-cost ratio		Fatal	Serious Injury	Combined
ADD LANES											
Add passing lane	X	X	115		413	75	5.5		62	827	889
ADD LANES AND MEDIAN											
Widen to divided highway	X	X	45		229	105	2.2		41	302	343
ADD MEDIAN TREATMENT											
Add center two-way left-turn lane		X	14		12	8	1.5	a	2	13	15
ADD MEDIAN BARRIER											
Add median barrier to existing median		X	87		300	67	4.5	a	60	313	373
BICYCLE FACILITIES											
Add bicycle lane		X	126		8	5	1.6	a	2	9	11
Add bicycle path		X	65		45	29	1.6	a	9	51	60
DELINEATION											
Improve delineation	X	X	111		22	9	2.4		3	31	34
Improve curve delineation	X		10		0.6	0.3	2.0	b	0.1	1	1.1
INTERSECTIONS											
Add left-turn lanes	X	X		1,699	489	166	2.9		80	675	755
Add roundabout	X			390	1,010	504	2.0	b	179	1,532	1,711
Improve intersection delineation and signing		X		241	21	5	4.2	b	3	39	42
Provide grade separation	X	X		14	203	134	1.5		37	280	317
Signalize intersection	X	X		924	566	164	3.5		97	910	1,007
Update rail crossing	X			18	24	2	14.1		5	30	35
LANE WIDENING											
Widen lanes		X	37		31	10	3.1	b	5	62	67
PARKING IMPROVEMENTS											
Improve parking		X	20		8	1	8.0	a	1	7	8
PEDESTRIAN FACILITIES											
Add refuge island		X		45	2	1	2.0	a	0.3	2	2.3
Install signalized crossing		X		128	15	11	1.4	a	3	16	19
Install unsignalized crossing		X		32	70	5	14.0	a	10	148	158
Provide sidewalk		X	570		483	232	2.1	a	82	484	566
ROADSIDE IMPROVEMENTS											
Clear roadside objects		X	1,047		215	27	8.0	a	39	195	234
Improve sideslopes	X	X	224		72	25	2.9		13	104	117
Install roadside barriers	X	X	2,579		2,244	965	2.3		397	3,026	3,423
RUMBLE STRIPS											
Centerline rumble strip	X	X	70		18	6	3.0		4	20	24
Shoulder rumble strips		X	487		171	84	2.0	a	35	172	207
SHOULDER WIDENING											
Widen shoulders	X	X	2,146		1,663	395	4.2		258	3,056	3,314
COMBINED TOTALS					8,335	3,036	2.7		1,426	12,303	13,729

NOTE: [a] used Version 3.0 results only to take advantage of improved Version 3.0 logic for this countermeasure
[b] used Version 2.2 results only because many sites evaluated in version 3.0 had incomplete data that limited consideration of this countermeasure

SOURCE: Data assembled from past usRAP studies.

Table A-7. Summary of Countermeasure Programs from Past usRAP Studies for Minimum Benefit-Cost Ratio Equal to 2.0

Countermeasure category/Countermeasure name	Model used		Recommended infrastructure improvement program					Notes	Reduced No. of injuries (20 years)		
	usRAP Tools Ver 2.2	ViDA Ver 3.0	Length of Improved roadway (mi)	No. of improved sites	Crash reduction benefits (million)	Improvement cost (million)	Benefit-cost ratio		Fatal	Serious Injury	Combined
ADD LANES											
Add passing lane	X	X	84		384	53	7.2		57	777	834
ADD LANES AND MEDIAN											
Widen to divided highway	X	X	17		133	42	3.2		23	183	206
ADD MEDIAN TREATMENT											
Add center two-way left-turn lane		X	3		5	2	2.5	a	1	5	6
ADD MEDIAN BARRIER											
Add median barrier to existing median		X	55		265	44	6.0	a	53	279	332
BICYCLE FACILITIES											
Add bicycle lane		X	96		12	3	4.0	a	2	13	15
Add bicycle path		X	20		21	9	2.3	a	4	24	28
DELINEATION											
Improve delineation	X	X	44		15	4	3.8		2	19	21
Improve curve delineation	X		16		2.6	0.5	4.0	b	0.3	2	2.3
INTERSECTIONS											
Add left-turn lanes	X	X		778	429	76	5.6		72	593	665
Add roundabout	X			145	569	177	3.2	b	101	866	967
Improve intersection delineation and signing		X		175	25	4	6.3	b	4	49	53
Provide grade separation	X	X		1	41	8	5.1		7	69	76
Signalize intersection	X	X		480	524	87	6.0		94	770	864
Update rail crossing	X			17	24	2	12.0		5	30	35
LANE WIDENING											
Widen lanes		X	15		23	4	5.8	b	4	43	47
PARKING IMPROVEMENTS											
Improve parking		X	16		7	1	7.0	a	1	7	8
PEDESTRIAN FACILITIES											
Add refuge island		X		25	1	0.4	2.5	a	0.2	0.9	1.1
Install signalized crossing		X		59	6	2	3.0	a	1	7	8
Install unsignalized crossing		X		37	73	5	14.6	a	11	150	161
Provide sidewalk		X	246		342	97	3.5	a	53	337	390
ROADSIDE IMPROVEMENTS											
Clear roadside objects		X	1,424		462	35	13.2	a	84	437	521
Improve sideslopes	X	X	188		86	20	4.3		16	114	130
Install roadside barriers	X	X	1,208		1,595	453	3.5		279	2,175	2,474
RUMBLE STRIPS											
Centerline rumble strip	X	X	42		16	4	4.0		3	17	20
Shoulder rumble strips		X	177		107	33	3.2	a	21	111	132
SHOULDER WIDENING											
Widen shoulders	X	X	1,117		1,411	215	6.6		216	2,660	2,876
				COMBINED TOTALS	6,577	1,380	4.8		1,115	9,737	10,852

NOTE: [a] used Version 3.0 results only to take advantage of improved Version 3.0 logic for this countermeasure

[b] used Version 2.2 results only because many sites evaluated in version 3.0 had incomplete data that limited consideration of this countermeasure

SOURCE: Data assembled from past usRAP studies.

Table A-8. Summary of Countermeasure Programs from Past usRAP Studies for Minimum Benefit-Cost Ratio Equal to 3.0

Countermeasure category/Countermeasure name	Model used		Recommended infrastructure improvement program					Notes	Reduced No. of injuries (20 years)		
	usRAP Tools Ver 2.2	ViDA Ver 3.0	Length of Improved roadway (mi)	No. of improved sites	Crash reduction benefits (million)	Improvement cost (million)	Benefit-cost ratio		Fatal	Serious Injury	Combined
ADD LANES											
Add passing lane	X	X	74		367	46	8.0		55	471	796
ADD LANES AND MEDIAN											
Widen to divided highway	X	X	6		73	16	4.6		13	101	114
ADD MEDIAN TREATMENT											
Add center two-way left-turn lane		X	1		2	0.6	3.3	a	0.4	2	2.4
ADD MEDIAN BARRIER											
Add median barrier to existing median		X	40		233	32	7.3	a	47	245	292
BICYCLE FACILITIES											
Add bicycle lane		X	70		12	2	6.0	a	2	14	16
Add bicycle path		X	7		9	2	4.5	a	2	10	12
DELINEATION											
Improve delineation	X	X	25		11	2	5.5		1	14	15
Improve curve delineation	X		14		2	0.4	5.0	b	0.4	2	2.4
INTERSECTIONS											
Add left-turn lanes	X	X		530	404	53	2.6		6.9	560	629
Add roundabout	X			57	304	66	4.6	b	53	474	527
Improve intersection delineation and signing		X		138	23	3	2.7	b	3	45	48
Provide grade separation	X	X		1	41	8	5.1		7	69	76
Signalize intersection	X	X		32	473	59	8.0		86	669	755
Update rail crossing	X			14	23	1.3	17.7		4	30	34
LANE WIDENING											
Widen lanes		X	8		19	2	3.1	b	3	35	38
PARKING IMPROVEMENTS											
Improve parking		X	15		8	1	8.0	a	1	7	8
PEDESTRIAN FACILITIES											
Add refuge island		X		45	1.4	0.2	7.0	a	0.1	1.1	2.2
Install signalized crossing		X		128	5	1	5.0	a	1	5	6
Install unsignalized crossing		X		32	71	5	14.2	a	11	149	160
Provide sidewalk		X	150		275	58	4.7	a	41	272	313
ROADSIDE IMPROVEMENTS											
Clear roadside objects		X	1,578		664	37	17.9	a	117	629	746
Improve sideslopes	X	X	134		83	14	5.9		1316	106	122
Install roadside barriers	X	X	581		1,081	220	4.9		191	1,510	1,701
RUMBLE STRIPS											
Centerline rumble strip	X	X	23		12	2	6.0		2	13	15
Shoulder rumble strips		X	74		64	14	4.6	a	12	68	80
SHOULDER WIDENING											
Widen shoulders	X	X	667		1,225	139	8.8		187	2,341	2,528
COMBINED TOTALS					5,486	785	7.0		925	8,108	9,033

NOTE: [a] used Version 3.0 results only to take advantage of improved Version 3.0 logic for this countermeasure
[b] used Version 2.2 results only because many sites evaluated in version 3.0 had incomplete data that limited consideration of this countermeasure

SOURCE: Data assembled from past usRAP studies.

Table A-9. Summary of Countermeasure Programs from Past usRAP Studies for Minimum Benefit-Cost Ratio Equal to 4.0

Countermeasure category/Countermeasure name	Model used		Recommended infrastructure improvement program					Notes	Reduced No. of injuries (20 years)		
	usRAP Tools Ver 2.2	ViDA Ver 3.0	Length of Improved roadway (mi)	No. of improved sites	Crash reduction benefits (million)	Improvement cost (million)	Benefit-cost ratio		Fatal	Serious Injury	Combined
ADD LANES											
Add passing lane	X	X	62		340	39	8.7		51	686	737
ADD LANES AND MEDIAN											
Widen to divided highway	X	X	1		30	3	10.0		5	43	48
ADD MEDIAN TREATMENT											
Add center two-way left-turn lane		X	0.2		0.5	0.1	5.0	a	0.1	0.5	0.6
ADD MEDIAN BARRIER											
Add median barrier to existing median		X	28		196	23	8.5	a	39	205	244
BICYCLE FACILITIES											
Add bicycle lane		X	44		10	2	5.0	a	2	12	14
Add bicycle path		X	2		3	0.7	4.3	a	0.6	4	4.6
DELINEATION											
Improve delineation	X	X	17		8	1.4	5.7		1	11	12
Improve curve delineation	X		9		2	0.3	6.7	b	0.3	2	2.3
INTERSECTIONS											
Add left-turn lanes	X	X		406	328	40	9.5		65	522	587
Add roundabout	X			30	191	34	5.6	b	34	297	331
Improve intersection delineation and signing		X		114	22	2	11.0	b	3	45	48
Provide grade separation	X	X		1	41	8	5.1		7	69	76
Signalize intersection	X	X		234	422	43	9.8		78	585	663
Update rail crossing	X			14	23	1.3	17.7		4	30	34
LANE WIDENING											
Widen lanes		X	8		18	2	9.0	b	3	34	37
PARKING IMPROVEMENTS											
Improve parking		X	14		7	0.6	11.7	a	1	6	7
PEDESTRIAN FACILITIES											
Add refuge island		X		9	1.2	0.1	12.0	a	0.1	1	1.1
Install signalized crossing		X		34	4	0.6	6.7	a	1	4	5
Install unsignalized crossing		X		30	71	4	17.8	a	10	147	157
Provide sidewalk		X	98		221	37	6.0	a	30	213	243
ROADSIDE IMPROVEMENTS											
Clear roadside objects		X	1,577		768	36	21.5	a	134	733	867
Improve sideslopes	X	X	90		72	10	7.2		13	93	106
Install roadside barriers	X	X	311		760	120	6.3		136	1,054	1,190
RUMBLE STRIPS											
Centerline rumble strip	X	X	16		9	1.3	6.9		2	10	12
Shoulder rumble strips		X	43		48	8	6.0	a	9	50	59
SHOULDER WIDENING											
Widen shoulders	X	X	460		1,092	100	1.0		166	2,105	2,271
COMBINED TOTALS					4,741	518	9.2		796	6,960	7,756

NOTE: [a] used Version 3.0 results only to take advantage of improved Version 3.0 logic for this countermeasure
[b] used Version 2.2 results only because many sites evaluated in version 3.0 had incomplete data that limited consideration of this countermeasure
SOURCE: Data assembled from past usRAP studies.

Table A-10. Summary of Countermeasure Programs from Past usRAP Studies for Minimum Benefit-Cost Ratio Equal to 5.0

Countermeasure category/Countermeasure name	Model used		Recommended infrastructure improvement program					Notes	Reduced No. of injuries (20 years)		
	usRAP Tools Ver 2.2	ViDA Ver 3.0	Length of Improved roadway (mi)	No. of improved sites	Crash reduction benefits (million)	Improvement cost (million)	Benefit-cost ratio		Fatal	Serious Injury	Combined
ADD LANES											
Add passing lane	X	X	0.1		0.5	0.1	5		62	827	889
ADD LANES AND MEDIAN											
Widen to divided highway	X	X	0.2		6	0.8	2.5		41	302	343
ADD MEDIAN TREATMENT											
Add center two-way left-turn lane		X	0.2		0.5	0.1	5.0	a	2	13	15
ADD MEDIAN BARRIER											
Add median barrier to existing median		X	23		176	19	9.4	a	60	313	373
BICYCLE FACILITIES											
Add bicycle lane		X	34		9	1.2	7.5	a	2	9	11
Add bicycle path		X	0.8		2	0.3	6.7	a	9	51	60
DELINEATION											
Improve delineation	X	X	5		4	0.5	8.0		0.3	3	3.3
Improve curve delineation	X		0		-	-	-	b	-	-	-
INTERSECTIONS											
Add left-turn lanes	X	X		37	37	4	9.3		4	33	37
Add roundabout	X			0	-	-	-	-	-	-	-
Improve intersection delineation and signing		X		0	-	-	-	-	-	-	-
Provide grade separation	X	X		0	-	-	-		-	-	-
Signalize intersection	X	X		0	-	-	-		-	-	-
Update rail crossing	X			0	-	-	-		-	-	-
LANE WIDENING											
Widen lanes		X	0		-	-	-	-	-	-	-
PARKING IMPROVEMENTS											
Improve parking		X	12		7	0.5	14.0	a	1	6	7
PEDESTRIAN FACILITIES											
Add refuge island		X		6	1	0.1	10.0	a	0.1	0.8	0.9
Install signalized crossing		X		32	4	0.5	8.0	a	1	4	5
Install unsignalized crossing		X		0	-	-	-	-	-	-	-
Provide sidewalk		X	69		179	26	6.9	a	23	169	192
ROADSIDE IMPROVEMENTS											
Clear roadside objects		X	1,524		821	35	23.4	a	143	787	930
Improve sideslopes	X	X	49		36	5	7.2		8	31	39
Install roadside barriers	X	X	63		189	29	6.5		37	191	228
RUMBLE STRIPS											
Centerline rumble strip	X	X	5		4	0.4	10.0		1	4	5
Shoulder rumble strips		X	24		32	5	6.4	a	6	34	39
SHOULDER WIDENING											
Widen shoulders	X	X	36		36	5	7.2		4	32	36
				COMBINED TOTALS	1,544	133	11.6		265	1,496	1,761

NOTE: [a] used Version 3.0 results only to take advantage of improved Version 3.0 logic for this countermeasure

[b] used Version 2.2 results only because many sites evaluated in version 3.0 had incomplete data that limited consideration of this countermeasure

SOURCE: Data assembled from past usRAP studies.

Table A-11. Summary of Nationwide Road Mileage from HPMS for Collector and Arterial Roads and Streets and Freeways

Roadway type (with functional class for urban nonfreeways)	Roadway miles by AADT level (veh/day) 0 - 400	401 - 1,000	1,001 - 2,000	2,001 - 5,000	5,001 - 10,000	10,001 - 25,000	25,001 - 50,000	50,001 - 100,000	100,001 - 200,000	More than 200,000	Unknown AADT	Total
RURAL ROADS												
Rural two-lane undivided roads	**183,249**	**96,834**	**74,347**	**74,665**	**21,104**	**3,076**	**61**	**2**	**5**	**0**	**103,570**	**556,913**
Rural four-lane undivided roads	**173**	**210**	**902**	**6,672**	**12,104**	**7,649**	**328**	**0**	**0**	**0**	**30**	**28,068**
Rural four-lane divided roads	**345**	**468**	**1,197**	**5,363**	**10,969**	**10,765**	**910**	**55**	**19**	**0**	**11**	**30,101**
Rural four-lane freeways	**430**	**476**	**698**	**2,750**	**8,919**	**22,632**	**12,913**	**872**	**4**	**0**	**1,981**	**51,677**
Rural six-or-more-lane freeways	**0**	**0**	**0**	**0**	**22**	**99**	**1,325**	**1,067**	**179**	**0**	**0**	**2,692**
RURAL SUBTOTAL[a]	**184,197**	**97,988**	**77,144**	**89,451**	**53,119**	**44,220**	**15,538**	**1,995**	**207**	**0**	**105,592**	**669,451**
URBAN ROADS AND STREETS												
Urban two-lane undivided streets	**48,035**	**77,135**	**87,369**	**198,223**	**158,964**	**89,897**	**7,228**	**389**	**3**	**3**	**340,394**	**1,007,640**
Principal Arterial	746	495	1,339	5,245	12,621	20,780	3,521	301	0	0	290	45,338
Minor Arterial	5,722	8,284	14,847	50,273	67,955	47,943	2,947	38	0	0	312	198,322
Major Collector	29,679	55,094	61,202	127,557	69,639	18,916	419	27	0	0	281	362,813
Minor Collector	6,702	8,509	6,314	9,474	5,009	434	16	2	0	0	19	36,479
Unknown functional class	5,186	4,753	3,666	5,675	3,739	1,825	324	21	3	3	339,492	364,688
Urban four-lane undivided streets	**826**	**441**	**1,097**	**6,851**	**19,563**	**49,279**	**13,589**	**516**	**9**	**0**	**699**	**92,868**
Principal Arterial	0	31	40	1,037	4,326	18,287	7,843	362	0	0	65	31,992
Minor Arterial	291	156	287	2,714	9,045	25,444	5,252	66	0	0	25	43,279
Major Collector	415	222	696	2,723	5,495	5,028	245	4	0	0	3	14,831
Minor Collector	99	12	52	238	473	245	11	0	0	0	0	1,130
Unknown functional class	20	20	22	139	224	275	239	84	8	0	606	1,637
Urban six-or-more-lane undivided streets	**24**	**5**	**26**	**114**	**512**	**2,648**	**4,146**	**875**	**39**	**0**	**6**	**8,397**
Principal Arterial	19	4	1	43	399	1,102	905	40	0	0	0	2,512
Minor Arterial	0	0	1	23	12	113	99	1	0	0	1	250
Major Collector	0	0	0	0	0	0	0	0	0	0	0	0
Minor Collector	0	0	0	0	0	0	0	0	0	0	0	0
Unknown functional class	6	1	24	48	101	1,433	3,143	835	39	0	5	5,635
Urban one-way streets	**913**	**1,062**	**1,525**	**3,878**	**4,274**	**4,148**	**522**	**6**	**1**	**0**	**680**	**17,008**
Principal Arterial	278	202	270	519	814	1,242	267	5	0	0	51	3,648
Minor Arterial	57	165	176	752	1,236	1,853	63	0	0	0	27	4,329
Major Collector	199	226	239	804	776	266	2	0	0	0	10	2,521
Minor Collector	3	2	17	50	11	2	0	0	0	0	1	86
Unknown functional class	376	467	823	1,754	1,437	786	190	0	1	0	591	6,424
Urban four-lane divided roads or streets	**246**	**102**	**200**	**1,385**	**5,063**	**18,852**	**8,862**	**646**	**8**	**0**	**32**	**35,397**
Principal Arterial	56	16	12	309	1,794	10,090	6,152	463	0	0	0	18,892
Minor Arterial	35	27	50	646	1,697	6,075	2,091	49	0	0	0	10,671
Major Collector	155	51	117	338	1,358	1,924	184	0	0	0	0	4,126
Minor Collector	0	0	10	73	70	245	0	0	0	0	0	398
Unknown functional class	0	9	11	19	145	517	435	135	8	0	32	1,311
Urban six-or-more-lane divided roads or	**19**	**13**	**16**	**53**	**268**	**1,523**	**4,019**	**1,355**	**63**	**0**	**4**	**7,332**
Principal Arterial	11	11	2	21	43	881	3,366	1,248	44	0	0	5,626
Minor Arterial	8	2	14	30	222	538	585	51	0	0	0	1,450
Major Collector	0	0	0	2	3	97	23	0	0	0	0	127
Minor Collector	0	0	0	0	0	0	0	0	0	0	0	0
Unknown functional class	0	0	0	0	0	7	44	55	19	0	4	130
Urban four-lane freeways	**63**	**102**	**196**	**936**	**2,496**	**7,590**	**9,848**	**5,680**	**489**	**8**	**643**	**28,052**
Urban six-lane freeways	**0**	**0**	**0**	**5**	**32**	**269**	**1,665**	**6,319**	**4,100**	**94**	**4**	**12,488**
Urban eight-or-more-lane freeways	**1**	**0**	**0**	**0**	**4**	**32**	**82**	**957**	**4,102**	**1,709**	**0**	**6,887**
URBAN SUBTOTAL[b]	**1,174**	**859**	**1,861**	**8,115**	**22,528**	**60,273**	**33,650**	**15,376**	**8,735**	**1,811**	**1,052**	**155,434**
COMBINED TOTAL[c]	**185,371**	**98,847**	**79,005**	**97,566**	**75,646**	**104,493**	**49,188**	**17,371**	**8,942**	**1,811**	**106,644**	**824,885**

[a] includes collectors, arterials, and freeways
[b] includes principal arterials and freeways only
[c] includes rural collectors and arterials, urban nonfreeway principal arterials, and urban freeways only
SOURCE: Data assembled from past usRAP studies

Table A-12. Summary of Nationwide Road Mileage from HPMS for Collector and Arterial Roads and Streets and Freeways (with Unknowns Distributed)

Roadway type (with functional class for urban nonfreeways)	Roadway miles by AADT level (veh/day)										
	0 - 400	401 - 1,000	1,001 - 2,000	2,001 - 5,000	5,001 - 10,000	10,001 - 25,000	25,001 - 50,000	50,001 - 100,000	100,001 - 200,000	More than 200,000	Total
RURAL ROADS											
Rural two-lane undivided roads	225,114	118,957	91,332	91,723	25,926	3,778	75	2	6	0	556,913
Rural four-lane undivided roads	173	210	903	6,679	12,117	7,657	328	0	0	0	28,068
Rural four-lane divided roads	345	468	1,197	5,365	10,973	10,768	910	55	19	0	30,101
Rural four-lane freeways	447	495	726	2,860	9,275	23,534	13,428	906	5	0	51,677
Rural six-or-more-lane freeways	0	0	0	0	22	99	1,325	1,067	179	0	2,692
RURAL SUBTOTAL[a]	**226,080**	**120,130**	**94,158**	**106,627**	**58,313**	**45,837**	**16,067**	**2,030**	**208**	**0**	**669,451**
URBAN ROADS AND STREETS											
Urban two-lane undivided streets	751	498	1,348	5,278	12,703	20,914	3,544	303	0	0	45,338
Urban four-lane undivided streets	0	31	41	1,039	4,335	18,325	7,859	363	0	0	31,992
Urban six-or-more-lane undivided streets	19	4	1	43	399	1,102	905	40	0	0	2,512
Urban one-way streets	282	204	274	526	825	1,259	271	5	0	0	3,648
Urban four-lane divided roads or streets	56	16	12	309	1,794	10,090	6,152	463	0	0	18,892
Urban six-or-more-lane divided roads or streets	11	11	2	21	43	881	3,366	1,248	44	0	5,626
Urban four-lane freeways	65	104	201	958	2,554	7,768	10,079	5,813	500	9	28,052
Urban six-lane freeways	0	0	0	5	32	269	1,666	6,321	4,101	94	12,488
Urban eight-or-more-lane freeways	1	0	0	0	4	32	82	957	4,102	1,709	6,887
URBAN SUBTOTAL[b]	1,184	867	1,878	8,180	22,688	60,639	33,924	15,514	8,748	1,811	**155,434**
COMBINED TOTAL[c]	**227,264**	**120,998**	**96,036**	**114,808**	**81,000**	**106,476**	**49,991**	**17,544**	**8,956**	**1,811**	**824,885**

[a] includes collectors, arterials, and freeways

[b] includes principal arterials and freeways only

[c] includes rural collectors and arterials, urban nonfreeway principal arterials, and urban freeways only

SOURCE: Based on HPMS data for 2014.

Table A-13. Comparison of FARS Fatality Counts to Counts Scaled Up Based on HPMS Road Lengths (Rural Collectors, Minor Arterials, Principal Arterials, and Freeways; Urban Minor Arterials, Principal Arterials, and Freeways)

Road type	FARS fatality counts							HPMS road length (mi)	Past usRAP Studies		Scaled-up fatalities per year for HPMS roads	Scaled-up fatalities based on HPMS roads compared to FARS
	2010	2011	2012	2013	2014	Total	Total/year		Road length (mi)	Fatalities per year		
RURAL ROADS												
Rural two-lane undivided roads	9,424	9,541	10,075	9,310	9,207	47,557	9,511	556,913	7,491	120	8,892	
Rural four-lane undivided roads	335	285	320	302	282	1,524	305	28,068	252	11.4	1,270	
Rural four-lane divided roads	1,700	1,460	1,579	1,618	1,439	7,796	1,559	30,101	537	12.5	701	
Rural four-lane freeways	1,961	1,811	1,689	1,752	1,657	8,870	1,774	51,677	772	16.4	1,098	
Rural six-or-more-lane freeways	212	257	267	300	197	1,233	247	2,692	116	6.7	155	
RURAL Subtotal	13,632	13,354	13,930	13,282	12,782	66,980	13,396	669,451	9,168	166.6	12,115	
URBAN ROADS AND STREETS												
Urban two-lane undivided streets	2,461	2,279	2,428	2,258	2,231	11,657	2,331	243,660	1,180	64.0	13,215	
Urban four-lane undivided streets	1,097	1,080	1,113	999	1,022	5,311	1,062	75,271	588	73.7	9,434	
Urban six-or-more-lane undivided streets	45	46	70	80	151	392	78	2,762	85	20.1	653	
Urban one-way streets	175	168	199	213	216	971	194	7,977	41	9.2	1,790	
Urban four-lane divided roads or streets	1,501	1,523	1,500	1,764	1,367	7,655	1,531	29,563	466	34.4	2,182	
Urban six-or-more-lane divided roads or streets	1,323	1,245	1,274	1,254	1,750	6,846	1,369	7,076	123	16.3	938	
Urban four-lane freeways	754	786	880	818	763	4,001	800	28,052	115	4.6	1,122	
Urban six-lane freeways	717	772	770	737	887	3,883	777	12,488	115	12.6	1,368	
Urban eight-or-more-lane freeways	905	931	834	896	942	4,508	902	6,887	35	5.9	1,161	
Urban Subtotal	8,978	8,830	9,068	9,019	9,329	45,224	9,045	413,736	2,748	240.8	31,864	
COMBINED TOTAL	22,610	22,184	22,998	22,301	22,111	112,204	22,441	1,083,187	11,916	407.4	43,980	96.0% overestimate

SOURCE: Based on FARS data for 2010 to 2014, HPMS data for 2014, and past usRAP studies.

Table A-14. Comparison of FARS Fatality Counts to Counts Scaled Up Based on HPMS Road Lengths (Rural Collectors, Minor Arterials, Principal Arterials, and Freeways; Urban Principal Arterials and Freeways)

Road type	FARS fatality counts 2010	2011	2012	2013	2014	Total	Total/year	HPMS road length (mi)	Past usRAP Studies Road length (mi)	Fatalities per year	Scaled-up fatalities per year for HPMS roads	Scaled-up fatalities based on HPMS roads compared to FARS
RURAL ROADS												
Rural two-lane undivided roads	9,424	9,541	10,075	9,310	9,207	47,557	9,511	556,913	7,491	119.6	8,892	
Rural four-lane undivided roads	335	285	320	302	282	1,524	305	28,068	252	11.4	1,270	
Rural four-lane divided roads	1,700	1,460	1,579	1,618	1,439	7,796	1,559	30,101	537	12.6	706	
Rural four-lane freeways	1,961	1,811	1,689	1,752	1,657	8,870	1,774	51,677	772	16.4	1,098	
Rural six-or-more-lane freeways	212	257	267	300	197	1,233	247	2,692	116	6.7	155	
RURAL Subtotal	13,632	13,354	13,930	13,282	12,782	66,980	13,396	669,451	9,168	166.7	12,121	
URBAN ROADS AND STREETS												
Urban two-lane undivided streets	1,018	898	7,647	885	865	11,313	2,263	45,338	1,180	64.0	2,459	
Urban four-lane undivided streets	660	679	653	557	605	3,154	631	31,992	588	73.7	4,010	
Urban six-or-more-lane undivided streets	35	39	60	65	121	320	64	2,512	85	20.1	594	
Urban one-way streets	149	130	174	175	178	806	161	3,648	41	9.2	819	
Urban four-lane divided roads or streets	1,123	1,142	1,065	1,316	1,026	5,672	1,134	18,892	466	34.4	1,395	
Urban six-or-more-lane divided roads or stree	1,082	1,018	1,033	1,048	1,423	5,604	1,121	5,626	123	16.3	746	
Urban four-lane freeways	754	786	880	818	763	4,001	800	28,052	115	4.6	1,122	
Urban six-lane freeways	717	772	770	737	887	3,883	777	12,488	115	12.6	1,368	
Urban eight-or-more-lane freeways	905	931	834	896	942	4,508	902	6,887	35	5.9	1,161	
Urban Subtotal	6,443	6,395	13,116	6,497	6,810	39,261	7,852	155,435	2,748	240.8	13,673	
COMBINED TOTAL	20,075	19,749	27,046	19,779	19,592	106,241	21,248	824,886	11,916	407.5	25,794	21.4% overestimate

SOURCE: Based on FARS data for 2010 to 2014, HPMS data for 2014, and past usRAP studies.

Table A-15. Forecast Nationwide Infrastructure Improvement Needs for a Range of Minimum Benefit-Cost Ratios

Safety program measure	Minimum benefit-cost ratio 1.0	2.0	3.0	4.0	5.0
Initial expenditure to meet current needs ($ million)	134,100	57,800	32,700	21,900	14,800
Total expenditure over 20 years to meet current needs ($ million)	152,500	67,500	38,800	26,200	17,400
Present value of 20-year expenditures ($ million)	146,500	64,400	36,800	24,800	16,600
Crash cost savings per year ($ million)	25,600	20,700	18,400	16,700	14,400
Present value of 20-year safety benefits ($ million)	348,400	281,700	250,500	226,800	196,400
Benefit-cost ratio	2.4	4.4	6.8	9.1	11.8
Expected fatalities over 20 years	394,860	394,860	394,860	394,860	394,860
Expected serious injuries over 20 years	3,323,680	3,323,680	3,323,680	3,323,680	3,323,680
Expected fatalities and serious injuries over 20 years	3,718,540	3,718,540	3,718,540	3,718,540	3,718,540
Fatalities reduced over 20 years	63,700	51,100	44,800	40,100	34,300
Serious injuries reduced over 20 years	353,500	315,900	277,000	246,900	194,800
Fatalities and serious injuries reduced over 20 years	417,200	367,000	321,800	287,000	229,100
Percentage reduction in fatalities	16.1	12.9	11.3	10.2	8.7
Percentage reduction in serious injuries	10.6	9.5	8.3	7.4	5.9
Percentage reduction in fatalities and serious injuries	11.2	9.9	8.7	7.7	6.2

NOTE: Based on usRAP study improvement programs shown in Tables A-6 through A-10 scaled up to national needs based on the ratio of the road mileages in Table A-12 to those in Table A-3. These national needs represent the road types shown in Tables A-2 and A-3 for paved roads functionally classified as collectors, minor arterials, principal arterials, and freeways in rural areas and as principal arterials and freeways in urban areas.

SOURCE: Adapted from results presented in Tables A-16 to A-20.

Table A-16. Summary of Nationwide Infrastructure Improvement Needs to Reduce Fatalities and Serious Injuries for Minimum Benefit-Cost Ratio Equal to 1.0

Countermeasure category/Countermeasure name	Model used		Recommended infrastructure improvement program					Notes	No. of injuries reduced (20 years)		
	usRAP Tools Ver 2.2	ViDA Ver 3.0	Length of Improved roadway (mi)	No. of improved sites	Crash reduction benefits (million)	Improvement cost (million)	Benefit-cost ratio		Fatal	Serious Injury	Combined
ADD LANES											
Add passing lane	X	X	832		1,089	640	1.7		182	1,516	1,698
ADD LANES AND MEDIAN											
Widen to divided highway	X	X	863		4,414	2,328	1.9		721	4,190	4,911
ADD MEDIAN TREATMENT											
Add center two-way left-turn lane		X	1,827		1,347	936	1.4	a	241	1,375	1,616
ADD MEDIAN BARRIER											
Add median barrier to existing median		X	15,993		47,754	11,506	4.2	a	9,677	48,497	58,174
BICYCLE FACILITIES											
Add bicycle lane		X	15,572		1,039	542	1.9	a	198	1,128	1,326
Add bicycle path		X	8,842		5,724	3,786	1.5	a	1,122	6,611	7,733
DELINEATION											
Improve delineation	X	X	1,125		365	107	3.4		35	361	396
Improve curve delineation	X		4,291		247	124	2.0	b	48	290	338
INTERSECTIONS											
Add left-turn lanes	X	X		993	4,980	2,305	2.2		619	4,401	5,020
Add roundabout	X			23,374	62,350	31,788	2.0	b	10,811	98,759	109,570
Improve intersection delineation and signing		X		30,109	2,312	594	3.9	b	349	4,644	4,993
Provide grade separation	X	X		71	1,261	1,083	1.2		249	1,416	1,665
Signalize intersection	X	X		924	566	164	3.5		98	910	1,008
Update rail crossing	X			943	1,288	93	13.8		252	1,489	1,741
LANE WIDENING											
Widen lanes		X	1,661		1,485	492	3.0	b	226	2,951	3,177
PARKING IMPROVEMENTS											
Improve parking		X	1,876		962	96	7.9	a	76	662	738
PEDESTRIAN FACILITIES											
Add refuge island		X		9,552	351	284	1.2	a	70	356	426
Install signalized crossing		X		15,252	1,414	1,116	1.3	a	277	1,472	1,749
Install unsignalized crossing		X		2,458	5,724	348	16.4	a	831	12,111	12,942
Provide sidewalk		X	101,159		92,226	41,302	2.2	a	16,644	49,075	65,719
ROADSIDE IMPROVEMENTS											
Clear roadside objects		X	127,885		26,101	3,317	7.9	a	4,701	23,759	28,460
Improve sideslopes	X	X	9,930		2,085	1,193	1.7		435	1,917	2,352
Install roadside barriers	X	X	58,677		43,851	24,238	1.8		8,225	43,299	51,524
RUMBLE STRIPS											
Centerline rumble strip	X	X	2,998		737	284	2.6		122	716	838
Shoulder rumble strips		X	75,574		29,458	13,313	2.2	a	5,913	30,782	36,695
SHOULDER WIDENING											
Widen shoulders	X	X	27,321		9,505	4,544	2.1		1,563	10,875	12,438
COMBINED TOTALS					348,435	146,523	2.4		63,685	353,562	417,247

NOTE: [a] used Version 3.0 results only to take advantage of improved Version 3.0 logic for this countermeasure
[b] used Version 2.2 results only because many sites evaluated in version 3.0 had incomplete data that limited consideration of this countermeasure

SOURCE: Analysis results from applying the methodology presented in this appendix.

Table A-17. Summary of Nationwide Infrastructure Improvement Needs to Reduce Fatalities and Serious Injuries for Minimum Benefit-Cost Ratio Equal to 2.0

Countermeasure category/Countermeasure name	Model used		Recommended infrastructure improvement program					Notes	No. of injuries reduced (20 years)		
	usRAP Tools Ver 2.2	ViDA Ver 3.0	Length of Improved roadway (mi)	No. of improved sites	Crash reduction benefits ($ million)	Improvement cost ($ million)	Benefit-cost ratio		Fatal	Serious Injury	Combined
ADD LANES											
Add passing lane	X	X	188		585	122	4.8		89	993	1,082
ADD LANES AND MEDIAN											
Widen to divided highway	X	X	321		2,334	854	2.7		327	2,054	2,381
ADD MEDIAN TREATMENT											
Add center two-way left-turn lane		X	203		309	123	2.5	a	62	332	394
ADD MEDIAN BARRIER											
Add median barrier to existing median		X	9,862		41,956	7,646	5.5	a	8,481	43,230	51,711
BICYCLE FACILITIES											
Add bicycle lane		X	11,470		1,368	409	3.3	a	262	1,522	1,784
Add bicycle path		X	2,689		2,636	1,063	2.5	a	516	3,057	3,573
DELINEATION											
Improve delineation	X	X	674		310	69	4.5		28	286	314
Improve curve delineation	X		7,570		749	217	3.5	b	145	884	1,029
INTERSECTIONS											
Add left-turn lanes	X	X		6,314	2,943	660	4.5		346	2,748	3,094
Add roundabout	X			7,627	31,186	10,001	3.1	b	5,456	48,470	53,926
Improve intersection delineation and signing		X		22,327	3,128	436	7.2	b	452	6,648	7,100
Provide grade separation	X	X		1	41	8	5.1		7	68	75
Signalize intersection	X	X		480	524	87	6.0		94	770	864
Update rail crossing	X			892	1,282	88	14.5		251	1,480	1,731
LANE WIDENING											
Widen lanes		X	583		1,003	164	6.1	b	157	1,910	2,067
PARKING IMPROVEMENTS											
Improve parking		X	1,659		751	79	9.5	a	73	650	723
PEDESTRIAN FACILITIES											
Add refuge island		X		4,219	158	63	2.5	a	28	126	154
Install signalized crossing		X		7,654	560	182	3.1	a	113	577	690
Install unsignalized crossing		X		2,667	5,933	374	15.9	a	877	12,267	13,144
Provide sidewalk		X	48,900		68,946	19,497	3.5	a	11,944	73,047	84,991
ROADSIDE IMPROVEMENTS											
Clear roadside objects		X	175,083		57,955	4,278	13.5	a	10,811	55,509	66,320
Improve sideslopes	X	X	7,753		2,813	858	3.3		590	2,502	3,092
Install roadside barriers	X	X	22,387		27,429	9,328	2.9		4,953	27,105	32,058
RUMBLE STRIPS											
Centerline rumble strip	X	X	1,629		630	152	4.1		104	601	705
Shoulder rumble strips		X	30,948		19,955	5,786	3.4	a	3,952	21,650	25,302
SHOULDER WIDENING											
Widen shoulders	X	X	11,152		6,165	1,832	3.4		963	7,371	8,284
				COMBINED TOTALS	281,651	64,378	4.4		51,087	315,857	366,944

NOTE: [a] used Version 3.0 results only to take advantage of improved Version 3.0 logic for this countermeasure
[b] used Version 2.2 results only because many sites evaluated in version 3.0 had incomplete data that limited consideration of this countermeasure

SOURCE: Analysis results from applying the methodology presented in this appendix.

Table A-18. Summary of Nationwide Infrastructure Improvement Needs to Reduce Fatalities and Serious Injuries for Minimum Benefit-Cost Ratio Equal to 3.0

Countermeasure category/Countermeasure name	Model used		Recommended infrastructure improvement program					Notes	No. of injuries reduced (20 years)		
	usRAP Tools Ver 2.2	ViDA Ver 3.0	Length of Improved roadway (mi)	No. of improved sites	Crash reduction benefits (million)	Improvement cost (million)	Benefit-cost ratio		Fatal	Serious Injury	Combined
ADD LANES											
Add passing lane	X	X	208		702	144	4.9		98	1,067	1,165
ADD LANES AND MEDIAN											
Widen to divided highway	X	X	95		954	244	3.9		155	771	926
ADD MEDIAN TREATMENT											
Add center two-way left-turn lane		X	56		126	39	3.2	a	26	129	155
ADD MEDIAN BARRIER											
Add median barrier to existing median		X	7,336		36,678	5,762	6.4	a	7,408	37,911	45,319
BICYCLE FACILITIES											
Add bicycle lane		X	9,062		1,590	320	5.0	a	303	1,811	2,114
Add bicycle path		X	1,000		1,251	321	3.9	a	243	1,480	1,723
DELINEATION											
Improve delineation	X	X	396		254	44	5.8		22	222	390
Improve curve delineation	X		6,383		837	183	4.6	b	163	989	1,152
INTERSECTIONS											
Add left-turn lanes	X	X		3,522	2,273	366	6.2		267	2,169	2,436
Add roundabout	X			3,008	16,049	3,743	4.3	b	2,671	538	30,210
Improve intersection delineation and signing		X		17,825	2,911	342	8.5	b	419	6,223	6,642
Provide grade separation	X	X		1	41	8	5.1		7	69	76
Signalize intersection	X	X		321	473	59	8.0		86	669	755
Update rail crossing	X			778	1,254	78	16.1		245	1,447	2,447
LANE WIDENING											
Widen lanes		X	338		846	96	8.8	b	132	1,608	1,740
PARKING IMPROVEMENTS											
1		X	1,566		802	71	11.3	a	76	689	765
PEDESTRIAN FACILITIES											
Add refuge island		X		1,338	177	21	8.4	a	14	147	161
Install signalized crossing		X		5,441	466	106	4.4	a	94	478	572
Install unsignalized crossing		X		2,398	5,852	340	17.2	a	862	12,163	13,025
Provide sidewalk		X	29,868		55,467	11,864	4.7	a	9,358	59,060	68,410
ROADSIDE IMPROVEMENTS											
Clear roadside objects		X	195,079		84,659	4,614	18.3	a	15,265	81,354	96,619
Improve sideslopes	X	X	5,025		2,567	546	4.7		540	2,213	2,753
Install roadside barriers	X	X	9,425		16,953	4,053	4.2		3,121	17,157	20,278
RUMBLE STRIPS											
Centerline rumble strip	X	X	797		438	76	5.8		75	429	504
Shoulder rumble strips		X	13,353		12,779	2,546	5.0	a	2,508	14,063	16,571
SHOULDER WIDENING											
Widen shoulders	X	X	4,906		4,126	823	5.0		612	5,151	5,763
				COMBINED TOTALS	250,523	36,806	6.8		44,775	277,013	321,788

NOTE: [a] used Version 3.0 results only to take advantage of improved Version 3.0 logic for this countermeasure
[b] used Version 2.2 results only because many sites evaluated in version 3.0 had incomplete data that limited consideration of this countermeasure

SOURCE: Analysis results from applying the methodology presented in this appendix.

Table A-19. Summary of Nationwide Infrastructure Improvement Needs to Reduce Fatalities and Serious Injuries for Minimum Benefit-Cost Ratio Equal to 4.0

Countermeasure category/Countermeasure name	Model used		Recommended infrastructure improvement program					Notes	No. of injuries reduced (20 years)		
	usRAP Tools Ver 2.2	ViDA Ver 3.0	Length of Improved roadway (mi)	No. of improved sites	Crash reduction benefits (million)	Improvement cost (million)	Benefit-cost ratio		Fatal	Serious Injury	Combined
ADD LANES											
Add passing lane	X	X	114		460	65	7.1		75	828	903
ADD LANES AND MEDIAN											
Widen to divided highway	X	X	16		502	71	7.1		110	368	478
ADD MEDIAN TREATMENT											
Add center two-way left-turn lane		X	5		12	3	4.0	a	2	12	14
ADD MEDIAN BARRIER											
3,876		X	4,950		29,175	3,876	7.5	a	5,903	29,884	35,787
BICYCLE FACILITIES											
Add bicycle lane		X	5,581		1,307	203	6.4	a	248	1,496	1,744
Add bicycle path		X	347		614	114	4.3	a	120	727	847
DELINEATION											
Improve delineation	X	X	310		213	30	7.1		19	188	207
Improve curve delineation	X		4,043		700	116	6.0	b	136	828	964
INTERSECTIONS											
Add left-turn lanes	X	X		2,263	1,835	230	8.0		213	1,774	1,987
Add roundabout	X			1,157	7,834	1,405	5.6	b	1,255	14,353	15,578
Improve intersection delineation and signing		X		15,780	2,969	298	10.0	b	423	6,445	6,868
Provide grade separation	X	X		1	41	8	5.1		7	69	76
Signalize intersection	X	X		234	422	43	9.8		78	585	663
Update rail crossing	X			778	1,253	78	16.1		246	1,448	1,694
LANE WIDENING											
Widen lanes		X	313		825	89	9.3	b	129	1,563	1,692
PARKING IMPROVEMENTS											
1		X	1,451		786	65	12.1	a	73	673	746
PEDESTRIAN FACILITIES											
Add refuge island		X		1,087	162	17	9.5	a	13	134	147
Install signalized crossing		X		4,392	445	75	5.9	a	89	451	540
Install unsignalized crossing		X		2,175	5,754	313	18.4	a	847	11,955	12,802
Provide sidewalk		X	21,513		47,249	8,495	5.6	a	7,661	52,127	57,788
ROADSIDE IMPROVEMENTS											
Clear roadside objects		X	194,275		96,946	4,488	21.6	a	17,360	93,743	111,103
Improve sideslopes	X	X	3,135		2,096	338	6.2		439	1,811	2,250
Install roadside barriers	X	X	4,791		11,446	2,112	5.4		2,141	11,615	13,756
RUMBLE STRIPS											
Centerline rumble strip	X	X	501		328	47	7.0		55	319	379
Shoulder rumble strips		X	9,129		10,410	1,775	5.9	a	2,031	11,528	13,599
SHOULDER WIDENING											
Widen shoulders	X	X	2,611		3,039	442	6.9		424	3,929	4,353
				COMBINED TOTALS	226,819	24,797	9.1		40,100	246,893	286,993

NOTE: [a] used Version 3.0 results only to take advantage of improved Version 3.0 logic for this countermeasure
[b] used Version 2.2 results only because many sites evaluated in version 3.0 had incomplete data that limited consideration of this countermeasure

SOURCE: Analysis results from applying the methodology presented in this appendix.

Table A-20. Summary of Nationwide Infrastructure Improvement Needs to Reduce Fatalities and Serious Injuries for Minimum Benefit-Cost Ratio Equal to 5.0

Countermeasure category/Countermeasure name	Model used		Recommended infrastructure improvement program					Notes	No. of injuries reduced (20 years)		
	usRAP Tools Ver 2.2	ViDA Ver 3.0	Length of Improved roadway (mi)	No. of improved sites	Crash reduction benefits (million)	Improvement cost (million)	Benefit-cost ratio		Fatal	Serious Injury	Combined
ADD LANES											
Add passing lane	X	X	1		0.5	0.1	5.0		0.1	0.6	0.7
ADD LANES AND MEDIAN											
Widen to divided highway	X	X	15		477	69	6.9		105	329	434
ADD MEDIAN TREATMENT											
Add center two-way left-turn lane		X	5		15	3	5.0	a	2	12	14
ADD MEDIAN BARRIER											
Add median barrier to existing median		X	3,871		24,883	3,025	8.2	a	5,059	25,321	30,380
BICYCLE FACILITIES											
Add bicycle lane		X	3,530		951	124	7.7	a	178	1,081	1,259
Add bicycle path		X	244		435	68	6.4	a	85	515	600
DELINEATION											
Improve delineation	X	X	257		189	24	7.9		16	164	180
Improve curve delineation	X		0		-	-	-	b	-	-	-
INTERSECTIONS											
Add left-turn lanes	X	X		1,550	1,329	156	8.7		135	1,145	1,280
Add roundabout	X			0	-	-	-	-	-	-	-
Improve intersection delineation and signing		X		0	-	-	-	-	-	-	-
Provide grade separation	X	X		0	-	-	-		-	-	-
Signalize intersection	X	X		0	-	-	-		-	-	-
Update rail crossing	X			0	-	-	-		-	-	-
LANE WIDENING											
Widen lanes		X	0		-	-	-	-	-	-	-
PARKING IMPROVEMENTS											
1		X	1,165		728	51	14.2	a	66	617	683
PEDESTRIAN FACILITIES											
Add refuge island		X		835	145	13	11.2	a	12	120	132
Install signalized crossing		X		4,051	421	69	6.1	a	86	431	517
Install unsignalized crossing		X		0	-	-	-	a	-	-	-
Provide sidewalk		X	14,405		36,509	5,682	6.4	a	5,666	43,880	43,880
ROADSIDE IMPROVEMENTS											
Clear roadside objects		X	192,725		111,083	4,396	25.2	a	19,248	107,032	126,280
Improve sideslopes	X	X	2,432		1,784	260	6.9		375	1,494	1,869
Install roadside barriers	X	X	2,757		7,998	1,245	6.4		1,547	7,926	9,473
RUMBLE STRIPS											
Centerline rumble strip	X	X	272		230	25	9.2		37	219	256
Shoulder rumble strips		X	5,927		7,766	1,165	6.7	a	1,498	8,819	10,317
SHOULDER WIDENING											
Widen shoulders	X	X	1,446		1,484	219	6.8		177	1,347	1,524
COMBINED TOTALS					196,431	16,597	11.8		34,295	194,786	229,081

NOTE: [a] used Version 3.0 results only to take advantage of improved Version 3.0 logic for this countermeasure
[b] used Version 2.2 results only because many sites evaluated in version 3.0 had incomplete data that limited consideration of this countermeasure

SOURCE: Analysis results from applying the methodology presented in this appendix.

Table B-1. Unit Countermeasure Costs Used in usRAP Analyses to Develop Infrastructure Improvement Programs for This Research

Countermeasure category	Countermeasure name	Unit of cost	Service Life (years)	Unit Construction Cost ($) by Area Type and Upgrade Cost Category					
				Rural			Urban		
				Low	Medium	High	Low	Medium	High
Add lanes	Add passing lane	per mi	20	627,510	1,255,020	1,882,530	897,822	1,795,644	2,693,466
Add lanes and median	Widen to divided highway - > 65-ft median	per roadway-mi[a]	20	2,635,542	5,271,084	7,906,626	3,591,288	7,182,576	10,773,864
Add lanes and median	Widen to divided highway - 15- to 30-ft median	per roadway-mi[a]	20	1,882,530	3,765,060	5,647,590	2,693,466	5,386,932	8,080,398
Add lanes and median	Widen to divided highway - 3- to 15-ft median	per roadway-mi[a]	20	1,506,024	3,012,048	4,518,072	2,244,555	4,489,110	6,733,665
Add lanes and median	Widen to divided highway - 30 to 65-ft median	per roadway-mi[a]	20	2,259,036	4,518,072	6,777,108	3,142,377	6,284,754	9,427,131
Add lanes and median	Widen to divided highway with median barrier	per roadway-mi[a]	20	1,506,024	3,012,048	4,518,072	2,244,555	4,489,110	6,733,665
Add median barrier	Add median barrier to existing median	per mi	10	313,755	407,882	502,008	374,093	486,320	598,548
Add median treatment	Add center two-way left-turn lane	per mi	10	188,253	282,380	376,506	224,456	336,683	448,911
Bicycle facilities	Add bicycle lane	per mi	20	18,825	25,100	31,376	29,927	37,409	44,891
Bicycle facilities	Add bicycle path	per mi	20	188,253	251,004	376,506	374,093	448,911	598,548
Delineation	Improve curve delineation	per roadway-mi[a]	5	9,413	9,413	9,413	14,964	14,964	14,964
Delineation	Improve delineation	per lane-mi	5	9,413	9,413	9,413	14,964	14,964	14,964
Intersections	Add left-turn lane (signalized four leg)	per intersection	10	50,000	62,500	75,000	60,000	75,000	90,000
Intersections	Add left-turn lane (signalized three-leg)	per intersection	10	50,000	62,500	75,000	60,000	75,000	90,000
Intersections	Add left-turn lane (unsignalized four leg)	per intersection	10	50,000	62,500	75,000	60,000	75,000	90,000
Intersections	Add left-turn lane (unsignalized three-leg)	per intersection	10	50,000	62,500	75,000	60,000	75,000	90,000
Intersections	Add roundabout	per intersection	20	1,060,000	1,300,000	1,800,000	2,000,000	2,500,000	3,000,000
Intersections	Improve intersection delineation and signing	per intersection	5	5,850	5,850	5,850	9,300	9,300	9,300
Intersections	Provide grade separation (intersection)	per intersection	20	7,800,000	11,700,000	15,600,000	11,160,000	16,740,000	22,320,000
Intersections	Signalize intersection (Four-leg)	per intersection	20	200,000	220,000	240,000	200,000	220,000	240,000
Intersections	Signalize intersection (three-leg)	per intersection	20	130,000	150,000	170,000	130,000	150,000	170,000
Intersections	Update rail crossing	per site	20	78,000	109,200	140,400	93,000	130,200	167,400
Lane widening	Widen lanes (> 1.5 ft)	per lane-mi	10	96,862	140,627	210,779	140,627	209,492	314,238
Lane widening	Widen lanes (up to 1.5 ft)	per lane-mi	10	69,187	100,402	150,602	100,402	149,637	224,456
Parking Improvements	Parking improvements	per roadway-mi[a]	20	31,376	62,751	94,127	37,409	74,819	112,228
Pedestrian facilities	Add refuge island	per site	10	7,800	23,400	39,000	9,300	27,900	46,500
Pedestrian facilities	Install signalized crossing	per site	20	130,000	150,000	170,000	130,000	150,000	170,000
Pedestrian facilities	Install unsignalized crossing	per site	10	74,400	93,000	111,600	74,400	93,000	111,600
Pedestrian facilities	Provide sidewalk (> 10 ft from road)	per mi	20	244,568	305,710	429,603	350,762	437,648	613,029
Pedestrian facilities	Provide sidewalk (adjacent to road)	per mi	20	230,087	289,620	403,859	329,845	413,513	613,029
Roadside improvements	Clear roadside objects	per mi per side of road	20	12,550	25,100	37,651	14,964	29,927	44,891
Roadside improvements	Improve sideslopes	per mi per side of road	20	94,127	188,253	282,380	149,637	299,274	448,911
Roadside improvements	Install roadside barriers	per mi per side of road	20	313,755	407,882	502,008	374,093	486,320	598,548
Rumble strips	Centerline rumble strip	per mi	10	37,651	50,201	62,751	44,891	59,855	74,819
Rumble strips	Shoulder rumble strips	per roadway-mi[a]	10	75,301	100,402	125,502	89,782	119,710	149,637
Shoulder widening	Widen shoulders (< 3 ft)	per mi per side of road	20	62,751	94,127	125,502	90,989	224,456	181,978
Shoulder widening	Widen shoulders (> 3 ft)	per mi per side of road	20	94,931	142,397	189,862	137,570	206,515	275,300

[a] per mi for each directional roadway on divided highways
SOURCE: Data assembled from past usRAP studies.