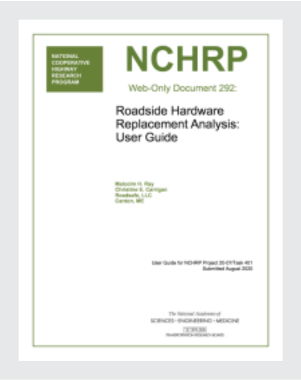

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Roadside Hardware Replacement Analysis: User Guide

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User Guide for NCHRP Project 20-07/Task 401
Submitted August 2020

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ACRONYMS

AASHTO	American Association of State Highway and Transportation Officials
FHWA	Federal Highway Administration
MASH	Manual for Assessing Safety Hardware
MMUCC	Model Minimum Uniform Crash Criteria

NOMENCLATURE

AADT	Average daily traffic in vehicles/day.
$AADT_o$	The measured average annual daily traffic in vehicles/day.
ABCA	Annual benefit of fatal and serious injury crashes avoided in dollars.
CL	Confidence level.
$CREH_J$	Police-reported crash rate for existing hardware type j in units of crashes/MVMP for continuous roadside hardware or crashes/MVP for discreet roadside hardware.
CRH_J	Cost of replacing hardware type j in dollars.
EEH_J	Existing hardware type j exposure in units of MVMP for continuous roadside hardware or MVP for discreet roadside hardware.
$FCSA_J$	Annual number of fatal and serious injury crashes avoided.
G	Traffic volume growth as a decimal.
IIR	Internal rate of return as a percent.
m	Number of types of hardware considered for replacement.
MVMP	Million vehicle miles passing continuous hardware type j.
MVP	Million vehicles passing discreet hardware type j.
NC_j	Number of crashes of all severity involving hardware type j.
$NFSC_j$	Number of fatal and serious injury crashes involving hardware type j.
QEH_J	Quantity of existing hardware type j in the same area used for collecting crash data in ft for continuous hardware and each for discreet hardware.
QEH_J	Quantity of existing hardware type j in ft for continuous hardware and each for discreet hardware.
REH_J	Fatal and serious injury crash risk for existing hardware type j.
RRH_J	Fatal and serious injury crash risk for replacement hardware type j.
RRR_J	Relative risk reduction for replacing existing hardware type j with upgraded hardware.
TCRH	Total hardware replacement cost in dollars.
$UCIH_J$	Unit cost of installing replacement hardware type j in dollars.
$UCRH_J$	Unit cost of removing existing hardware type j in dollars.
VSL	Value of statistical life in dollars.
YCD	Years of available police-reported crash data.
YD	Number of years between the observed AADT and the design year in years.
YL	Project life in years.

1 BACKGROUND

On December 21, 2015, the Federal Highway Administration (FHWA) and the American Association of State Highway and Transportation Officials (AASHTO) jointly agreed on a plan to implement the new crash test and evaluation procedures in the AASHTO Manual for Assessing Roadside Hardware (MASH) (*1*). In subsequent years the FHWA and AASHTO have issued several memoranda providing clarification about the dates, roles and responsibilities for accomplishing the transition (*2*). While the implementation plan provides specific dates for when new hardware installations should comply with the MASH crash testing requirements, the plan urges states and other highway agencies to "upgrade existing highway safety hardware to comply with the 2015[1] edition of MASH either when it becomes damaged beyond repair, or when an individual agency's policies require an upgrade to the safety hardware" (*1*). While the implementation plan encourages agencies to upgrade existing safety hardware to MASH 2016 it does not provide any specific guidance on how to establish priorities or policy on how such upgrading should occur. This user guide presents a method that highway agencies can use to establish these priorities for individual projects or as policy guidelines.

The AASHO-FHWA agreement classifies roadside hardware projects into three categories:

- Roadside hardware used in new construction is subject to specific dates for each type of hardware. Construction projects let after the appropriate date for each type hardware must satisfy the MASH 2016 criteria. The 2018 AASHTO "Green Book" defines new construction as projects "that construct roads on new alignments where no existing roadway is present" (*3*). Roadside hardware used in reconstruction projects are also considered "new" hardware since reconstruction projects are "those that utilize an existing roadway alignment… but involve a change in the basic roadway type" (*3*).
- Existing hardware is already installed in the field and not part of a new construction or reconstruction project. For example, roadside hardware on re-surfacing projects may still be in serviceable condition but not evaluated according to MASH. Highway agencies are encouraged to upgrade existing non-MASH hardware but there is no specified process for prioritizing that work.
- Highway agencies are encouraged to replace existing non-MASH hardware that is "damaged beyond repair" with MASH evaluated hardware (*2*). There is no specific definition of "damaged beyond repair" and no specific policy for prioritizing this work either.

This guide deals with the second two categories of hardware – existing still serviceable hardware and damaged hardware. Today, the majority of any highway agency's roadside hardware has not been evaluated according to MASH but is probably in reasonably good repair and functional and would likely remain functional for a considerable period of time. For example, a highway agency may have installed a 27-inch tall w-beam guardrail on a particular pavement overlay project just prior to the 2015 FHWA memorandum. The guardrail is relatively new and in good repair today but 27-inch w-beam guardrail is not MASH compliant. Crash tests have shown that 31-inch tall w-beam guardrail passes the MASH criteria (*4*). Should the agency immediately replace the recently installed

[1] While the implementation plan refers to the 2015 edition of MASH, the 2nd Edition did not actually appear until 2016.

27-inch guardrail with 31-inch guardrail? Waiting until the 27-inch guardrail is "damaged beyond repair" may mean the guardrail stays in service for decades (*1*). Is that acceptable? The recently installed non-MASH 27-inch guardrail probably also has Report 350 guardrail terminals and guardrail-bridge rail transitions that are also in good repair since they were only recently installed. When should they be upgraded to MASH 2016? Is the priority for upgrading the terminals the same as upgrading the w-beam guardrail? These are the types of questions that highway agencies face in developing a "process to replace existing highway safety hardware" (*1*).

Establishing priorities for upgrading roadside hardware is not a new activity in roadside design. A similar situation occurred when NCHRP Report 350 appeared in the 1990s (*5*). After NCHRP Report 350 was published, the FHWA incorporated it as one of the guides and references for design standards for highways in 23 CFR Part 625 (*6*). In 1998 AASHTO and the FHWA negotiated an implementation agreement with specific dates for each type of roadside hardware much like the MASH implementation agreement (*7*). The 1998 AASHTO-FHWA agreement also categorized hardware into three groups: hardware used in new construction, hardware used on 3R project, and systemwide replacements. There were specific dates for upgrading each type of hardware for each of the three categories. For example, systemwide replacement was not required for most hardware meaning pre-Report 350 hardware that was in place in the field could remain until the roadway was reconstructed or a 3R project was programed. The exception to this were Category III work zone devices which had to be replaced systemwide by 1 October 2002. What was meant by "3R" projects was explained in note 3 of the memo. New construction was defined as "a new installation of a feature … where none exists" (*7*). Upgrading the hardware for an existing feature that had to be "moved, reconstructed, or extended" in a reconstruction project was recommended although agencies, as in the MASH implementation agreement, were encouraged to develop policies to address these situations (*7*).

The need, therefore, to establish priorities for upgrading existing hardware to hardware that meets newer crash testing guidelines occurs periodically in roadside safety and a method for more systematically implementing priorities for upgrading is a recurring need. In the past, policies have been developed primarily using engineering judgement rather than a systematic assessment of the effectiveness and economics of upgrading existing hardware.

The purpose of this user manual is to present a method that the highway agencies can use to prioritize upgrading existing roadside hardware to new crash test requirements. The roadside hardware covered by MASH 2016 includes guardrails, median barriers, bridge railings, transitions, guardrail terminals, crash cushions, breakaway sign supports, luminaire supports and work zone hardware. Upgrading all of these types of devices to MASH 2016 is a large undertaking that will take many years and significant funding to accomplish. Since everything cannot be accomplished at once, user agencies need a means for developing hardware upgrade policies that implement MASH 2016 hardware in a systematic, staged, and prioritized manner. This manual presents a systematic data-driven method that user agencies can use to establish upgrading priorities.

Implicit in this discussion is the recognition that just because crash test procedures and evaluation criteria change does not mean that hardware developed using earlier criteria suddenly becomes unsafe. The process of improving roadside safety hardware is an incremental process where each generation of hardware is thought to be slightly more effective than the previous generation. Prioritizing upgrading policies involves assessing the incremental reduction in the risk of fatal and serious injury expected from upgrading roadside hardware and balancing that risk reduction with the highway agency costs of upgrading the hardware such that funds are expended to maximize overall network safety. Appreciating the underlying risk reductions and costs of upgrading are fundamental to developing effective upgrading policies.

The systematic data-driven process for roadside hardware replacement analysis described in this user guide is not meant to be prescriptive but informative. Engineers are likely to use this process as part of the decision-making process in combination with engineering judgement, agency experience, in-service performance history and other highway agency objectives. The method presented herein is just one of several considerations that should be included in making roadside hardware replacement decisions. A highway agency may also consider ease of maintenance issues, stock-piling materials, project scheduling, contractor familiarity with various designs and other issues. For example, an agency may elect to replace existing hardware that is otherwise in reasonably good repair because it is approaching the end of its service life and another project at the site in the near term is unlikely. Similarly, sometimes numerous spot repairs (e.g., blockout replacements, post replacement, post realignment, replacement of individual guardrail panels) might be needed to return a system to crash-ready condition and the agency may elect to simply replace with new hardware. The method presented herein, therefore is one facet of the decision-making process but could be used in conjunction with other considerations.

2 APPLICABILITY

This Roadside Hardware Replacement Analysis User Guide can be used by highway agency engineers and their consultants when evaluating and planning individual or systemwide projects where existing roadside hardware is in good condition and appropriately located according the AASHTO Roadside Design Guide or highway agency roadside design policy but does not meet the evaluation criteria of MASH 2016 (*8*). A typical example of such projects include pavement restoration projects on roadways with existing guardrails and guardrail terminals where the roadside hardware is incidental to the primary objective of the construction. This method can also be used to develop policies for determining when damaged hardware should be upgraded to MASH 2016 or replaced in-kind.

3 PROCEDURE

The roadside hardware replacement analysis process is comprised of 22 steps organized into four parts:

- Relative risk assessment of existing hardware (Steps 1 through 8),
- Relative risk estimate for replacement hardware (Steps 9 through 11),
- Project details (Steps 12 through 17) and
- Economic analysis (Steps 18 through 22).

A brief description of each step is contained in Table 1 and a more detailed description of each step is contained in the following subsections. In executing this procedure, the analyst should assume the default decision would be to upgrade and replace the hardware. Where assumptions are necessary, the analyst should assume conditions most favorable to replacing the hardware. This ensures that if replacement is not recommended by the procedure, that the decision to leave existing hardware in place is not likely a good use of highway agency funds.

Table 1. Roadside Hardware Replacement Analysis Steps.

Step	Action
	Find the fatal and serious injury crash risk and police-reported crash rate for the existing hardware.
1	Enter the number of years of police-reported crash data obtained (YCD).
2	Enter the number of crashes of all severities involving the hardware under consideration (NC_j) observed in the period reported in Step 1.
3	Enter the number of fatal and serious injury crashes involving the hardware under consideration ($NFSC_j$) observed in the period reported in Step 1.
4	Enter the desired confidence interval (CL) for a two-tailed hypothesis test. The 85th percentile is recommended for design related decisions.
5	Calculate the mean fatal and serious injury crash risk (REH_j) given a crash occurs with the existing hardware under consideration as $[\text{Step3}/\text{Step2}]$. The confidence intervals (CI) shown to the left and right in the worksheet are calculated as: $$\left[\text{CI} = \frac{\text{Step5} \cdot \left[Z_{CL}^2 / 2 \cdot \text{Step2} \right]}{\left[1 + \left(Z_{CL}^2 / \text{Step2} \right) \right]} \pm Z_{CL} \frac{\sqrt{\frac{\text{Step5} \cdot (1 - \text{Step5})}{\text{N}} + \frac{Z_{CL}^2}{4 \cdot \text{Step2}^2}}}{\left[1 + \left(Z_{CL}^2 / Step2 \right) \right]} \right]$$
6	Enter the quantity of existing hardware in the crash reporting area (QEH_j). Choose the appropriate units to the right in the worksheet where units can be in feet (e.g., guardrail, bridge rail, median barrier) or each (e.g., terminal, crash cushion, etc.).
7	Enter the amount of exposure in the crash reporting area over the period of data collection (EEH_j). For continuous hardware (e.g., guardrails) report the exposure in million vehicle miles passing the hardware (MVMP) and for discreet hardware (e.g., terminals and crash cushions) report exposure in million vehicles passing the hardware (MVP).
8	Calculate the total police-reported crash rate for crashes of all severities with the existing hardware ($CREH_j$) as $\left[\text{Step8} = \frac{\text{Step3}}{\text{Step7}} \right]$.
	Estimate the fatal and serious injury crash risk of an impact involving the replaced hardware.
9	Enter an estimate of the risk of a fatal or serious injury given a crash (RRHj) with the replaced hardware being considered occurs.
10	Determine if the difference between the fatal and serious injury crash risk for the existing and replacement hardware is statistically significant by comparing the value in Step8 to the range calculated in Step5. If the value in Step8 is within the range found in Step5, the difference is not statistically significant at the significance level entered in Step4.
11	Calculate the relative risk reduction (RRR_j) of the replacement hardware with respect to the existing hardware as $\left[\frac{\text{Step5} - \text{Step9}}{\text{Step5}} \right]$.
	Determine the costs of upgrading the hardware.
12	Enter the average annual daily traffic (AADT) on the project roadway in vehicles/day in the design year.
13	Enter the amount of replacement hardware in the project (QEHj) in the units selected (i.e., feet or each).
14	Enter the unit installed cost ($UCIH_j$)of the replacement hardware using dollars and the units chosen in Step 6.
15	Enter the unit cost of removing the existing hardware ($UCRH_j$) using dollars and the units chosen in Step 6.
16	Calculate the total installed cost of the replacement hardware (CRH_j) in dollars as $[\text{Step13} \cdot (\text{Step14} + \text{Step15})]$.
17	Estimate the annual number of fatal and serious injury crashes avoided ($FSCA_j$) by installing the replacement hardware as $\left[\frac{365 \cdot \text{Step8} \cdot \text{Step12} \cdot \text{Step13} \cdot \text{Step5} \cdot \text{Step11}}{\text{Units} \cdot 10^6} \right]$ where Units = 5280 for continuous hardware (e.g., guardrails) and 1 for all others.
	Repeat Steps 1 through 15 if there are other hardware items associated with the replacement hardware.

Table 1. Roadside Hardware Replacement Analysis Steps. (continued)

	Use the information collected in the previous steps to perform an economic analysis of the feasibility of replacing the existing roadside hardware.
18	Calculate the total cost of the replacement (TCRH) by summing all the Step16 costs.
19	Enter the value of statistical life (VSL) or use the default value of $12,300,000 based on the FHWA recommended procedure.
20	Calculate the annual societal benefit of crashes avoided (ABCA) by upgrading the hardware as $\left[\text{Step 19} \cdot \sum_{j=1}^{m} \text{Step } 17_j\right]$.
21	Enter the assumed service life of the roadside hardware replacement (YL). Generally, this should be between 20 and 30 years.
22	Calculate the internal rate of return (IRR) for the service life indicated in Step21. The internal rate of return is the interest or discount rate, which makes the net present value of a replacement project zero. In other words, the interest rate makes the investment in the construction year equal to the present value of all future societal benefits of the crash reduction during the service life. The IRR can be found by solving the following equation: $\left[\sum_{i=0}^{\text{Step 21}} \frac{\text{Step 20}}{(1+\text{Step 22})^{i}}\right]$

3.1 Roadside Hardware Replacement Analysis Workbook

The analysis procedure described in the following sections was organized into a convenient Excel macro-enabled workbook, which is shown **Figure 1**. Each step in the workbook is indicated by an integer number at the left and the activity in the step is described (e.g., 1. Enter the number of years of crash data). The 22 steps needed to complete the procedure are listed in Table 1 with a brief explanation for each step. The self-calculating Excel workbook performs all the necessary calculations that are indicated in unshaded boxes. The yellow-shaded cells in the workbook indicate user input is required, the grey-shaded cells indicate a default value which the user can change if desired, and the unshaded cells are self-calculating or descriptive. The worksheet indicated by "Form" can be copied and pasted such that multiple replacement analyses can be stored in a single workbook. The "Example" tab corresponds to the example presented at the end of this user guide.

The workbook includes three primary columns, one for each type of hardware being considered. For example, a typical project might include consideration of replacing guardrails and any associated terminals and transitions. Guardrail data could be placed in one column, terminal data in another, and transition data in the remaining column.

It is useful to assign a specific name to each analysis task in the designated space at the top of the workbook in **Figure 1**. The name may include a route number, mile posts, or a narrative description of the work evaluated. The name is only used to distinguish one project from another and does not affect the results.

Likewise, the yellow-shaded cell at the top of the three main columns should be used to identify the type of hardware that is being considered for replacement. The value entered is not used in the analysis but is helpful for organizing the results.

ROADSIDE HARDWARE REPLACEMENT ASSESSMENT WORKSHEET

Intructions: Enter information on the project or policy being considered in the yellow shaded cells. Values in grey shaded cells are default values but can be changed if desired.

Project Name:

Relative Risk Assessment of Existing Hardware

Using state or district wide police reported crash data determine the number of fatal and serious injury crashes that occurred involving the existing hardware. If an in-service evaluation of the hardware is avaiable use the crash severity performance from that source. Use as many years of crash data as are available and enter the appropriate values in the yellow shaded cells. Three columns are provided to account for associated roadside hardware. For example, replacing a guardrail may also require replacing the associated terminals, anchors and transitions associated with that guardrail. Place information for each type of hardware in one of the three

	Symbol			
1. Enter the number of years of crash data:	YCD			
2. Enter the total number of crashes with the existing hardware:	NC_i			
3. Enter the number of fatal and serious injury crashes with the existing hardware:	$NFSC_i$			
4. Enter the desired cofidence interval (e.g., 85th percentile):	CL	85%	85%	85%
5. Calculate the mean risk of fatal or serious injury with the existing hardware with 85th percentile confidence:	REH_J	< <	< <	< <
6. Enter the quantity of existing hardware in crash reporting area:	QEH_I			
7. Enter the existing hardware exposure during the data collection period (i.e., million vehicle miles passing [MVMP] for guardrails and million vehicles passing for terminals [MVP]).	EEH_J			
8. Calculate the total police reported crash rate.	$CREH_I$			

Relative Risk Estimate for Replacement Hardware

Estimate the smallest likely risk of a fatal or serious injury with the replacement hardware. Generally, crash data or an in-service evaluation will not be available to determine this value so it must be estimated using engineering judgement. It should be less than the observed value for the existing hardware and must be greater than zero. Enter the estimates for each type of replacement hardware below:

9. Estimate of risk of fatal or serious injury given a crash with the replacement hardware:	RRH_J			
10. Are the existing and replacement crash risk outside the 85th confidence interval?				
11. Calculate relative risk reduction of replacement hardware compared to existing hardware:	RRR_J			

Project Details

Enter information about the proposed project. Use the project information along with the values determined in the previous sections to estimate the number of fatal and serious injury crashes avoided by replacing the existing hardware with upgraded hardware.

12. Enter the design year AADT of the project:	AADT		veh/day	-	veh/day	-	veh/day
13. Enter the amount of hardware installed on project:	QEH_J		0		0		0
14. Enter the unit installed cost of the replacement hardware:	$UCIH_J$		$/0		$/0		$/0
15. Enter the unit cost to remove existing hardware:	$UCRH_J$		$/0		$/0		$/0
16. Calculate the total cost of installing the replacement hardware:	CRH_J	-	$	-	$	-	$
17. Estimate the number of annual fatal and serious injury crashes avoided:	$FCSA_J$		crashes/yr		crashes/yr		crashes/yr

Economic Analysis

The expected number of fatal and serious injury crashes avoided calculated in the previous step are summed and assigned an economic value based on the FHWA's value of statistical life (VSL) recommendation. The internal rate of return where the sum of all the benefits in future years equals the construction investment in the design years is calculated. Generally, if the internal rate of return is less than 2% it is not the best use of

18. Calculate the total cost of the hardware replacement:	TCRH	-	$
19. Enter the value of statistical life (VLS) or use the default value of $9,600,000:	VSL	12,300,000	$
20. Calculate the annual societal benefit of the replacement:	ABCA	-	$/yr
21. Enter the assumed service life or retain the assumed 25 year life.	YL	25	yrs
22. Calculate the internal rate of return assuming a 25 year design life.	IIR		%

Type CTRL+SHIFT+R to Clear and Reset Form

Figure 1. Roadside Hardware Replacement Analysis Workbook.

3.2 RISK ASSESSMENTS FOR EXISTING HARDWARE

Knowing how well the existing hardware is performing is a necessary first step in the assessment of the roadside hardware replacement analysis process. Performance of roadside hardware in this analysis procedure is defined as the risk of observing a fatal or serious injury police-reported crash involving the subject roadside hardware given a crash occurs. Minimizing fatal and serious injury crashes is consistent with the design objectives of both the Roadside Design Guide and MASH 2016 (*8, 9*).

3.2.1 Step 1: Number of Years of Available Crash Data

The analyst must first identify and gain access to the highway agency police-reported crash database covering the highway agency's area of responsibility. Many highway agencies routinely have access to five years of police-reported crash data that can be used for safety analysis studies like those discussed in this guide. Ideally, more than one year of data should be used but there is generally no need to use more than 10. Five years of police data is usually sufficient and is recommended. Enter the number of years of available police-reported crash data (YCD) in the yellow-shaded cells for Step 1.

3.2.2 Step 2: Total Number of Crashes with Existing Hardware

The number of crashes with the existing roadside hardware (NC_j) used on the project shall be determined from the highway agency historical police report crash data identified in Step 1. The roadside hardware types listed on a typical police report are often generic. For example, the police report may indicate a guardrail was struck but may not indicate if the guardrail was a cable barrier, w-beam guardrail, or concrete barrier. Some highway agencies have inventory information that can be matched by location to the crash data such that the performance of each specific roadside hardware type can be determined. Other highway agencies may only be able to identify generic types of hardware. Still others may not even have the type of object struck listed with any specificity at all on the police report. As such, there are several methods for estimating the total number of crashes with each type of existing hardware considered.

- Best approach – identify all the crashes in the police-reported data that involve a harmful event involving the roadside hardware of interest (e.g., guardrail, bridge rail, terminal, etc.) during the time period identified in Step 1. If a hardware inventory is available, match highway agency police-reported crashes with generic types of hardware to inventory locations of specific hardware and record the total number crashes for each type of specific roadside hardware. Also record the number of fatal and serious injury crashes for the subject roadside hardware for use in Step 3.
- Acceptable approach – using the generic categories from the police-reported crash data, determine the total number of crashes involving the category of interest during the time period identified in Step 1. Also record the number of fatal and serious injury crashes for the subject roadside hardware for use in Step 2.
- Adequate approach – if local data is not available, the only feasible alternative is to use data from another highway agency with more detailed data for the same types of roadside hardware of interest in the analyzed project. In such a case, use one of the two approaches listed above.

Enter the total number of crashes for each type of roadside hardware in the yellow-shaded cells for Step 2.

3.2.3 Step 3: Number of Fatal and Serious Injury Crashes with Existing Hardware

The number of fatal and serious injury crashes for each type of existing roadside hardware to be considered is a subset of the data collected in the Step 2. Fatal and serious injuries are assessed using the injury scale used on most police reports. The common definition of fatal and serious injury crashes is contained in the Model Minimum Uniform Crash Criteria (MMUCC) where fatal and serious injuries are defined as follows:

Fatal Injury (K): A fatal injury is any injury that results in death within 30 days after the motor vehicle crash in which the injury occurred. If the person did not die at the scene but died within 30 days of the motor vehicle crash in which the injury occurred, the injury classification should be changed from the attribute previously assigned to the attribute "fatal injury."

Suspected Serious Injury (A): A suspected serious injury is any injury other than fatal, which results in one or more of the following:

- Severe laceration resulting in exposure of underlying tissues/muscle/organs or resulting in significant loss of blood
- Broken or distorted extremity (arm or leg)
- Crush injuries
- Suspected skull, chest, or abdominal injury other than bruises or minor lacerations
- Significant burns (second and third degree burns over 10% or more of the body)
- Unconsciousness when taken from the crash scene
- Paralysis." (*10*)

The total number fatal and serious injury crashes involving each the types of roadside hardware ($NFSC_j$) under consideration during the time period found in Step 1 (YDC) is determined using the police-reported crash data for all the roadways maintained and operated by the highway agency. Enter the total number of fatal and serious injury crashes ($NFSC_j$) for each type of roadside hardware in the yellow-shaded cells for Step 3.

3.2.4 Step 4: Confidence Level

The confidence level (CL) is a statistical parameter that describes the likelihood that the measurement observed adequately represents the true population value. For example, the percent of fatal and serious injury crashes involving guardrails will vary from year to year for a particular highway agency. In order to compare the performance of one roadside hardware to another, it is necessary determine if any observed differences are just random variation that occur from year to year or a real difference in performance. As more and more data are collected, the resulting performance measure can be relied on with increasing confidence.

The 85th percentile CL is used in many types of engineering design calculations and is recommended as the default value for these analysis procedures. The 85th percentile represents relatively high confidence while acknowledging the many uncertainties regarding input values. The value chosen should be greater than 80 and less than 100 for conventional analysis. Enter the desired CL or accept the default 85th percentile value in the yellow-shaded cells for Step 4. The value is used to compute a two-tailed CI in Step 5 and a two-tailed hypothesis test in Step 10.

3.2.5 Step 5: Mean Risk and Confidence Interval

The risk of a fatal or serious injury crash involving the subject existing hardware (REH_j) is determined by dividing the number of fatal and serious injury crashes found in Step 3 by the total number of crashes found in Step 2 as follows:

$$\mathrm{REH_j} = \frac{\mathrm{NFSC_j}}{\mathrm{NC_j}} \rightarrow \mathrm{Step5} = \frac{\mathrm{Step3}}{\mathrm{Step2}}$$

REH_j is a direct measure of the performance of the existing hardware since it describes the risk of a fatal or serious injury based on the observed police-reported crash data obtained earlier in Step 1. The risk of a fatal or serious injury crash involving the subject existing hardware (REH_j) is automatically calculated and entered in Step 5.

Table 2 contains some mean risk values for a variety of guardrails, median barrier, bridge rails and guardrail terminals that were collected from the literature. The data were re-analyzed so that the 85th percentile CI could be listed. These data are based on police-reported first and only harmful events with the roadside hardware listed and most only consider passenger vehicles. Values of REH_j measured and calculated for replacement projects are expected to result in similar values and are provided as convenient reference for the user.

Table 2. Typical Mean Risk Values for Select Roadside Hardware.

Roadside Hardware	85th percentile lower bound	Risk of fatal or serious injury	85th percentile lower bound	Source
Guardrails and Median Barriers				
Report 350 Cable	0.0028	0.0050	0.0090	(*11*)
Report 350 W-Beam	0.0068	0.0084	0.0103	(*11*)
Report 350 Concrete	0.0137	0.0159	0.0185	(*11*)
Bridge Railings				
Closed-Face Concrete	0.0137	0.0159	0.0185	(*11*)
Terminals				
Report 350 Tangent Terminals	0.0204	0.0305	0.0455	(*12*)
Report 350 Flared Terminals	0.0218	0.0482	0.1031	(*13*)
Pre-Report 350 Terminals	0.0183	0.0455	0.1084	(*13*)

As discussed in Step 4, differences in the performance measure REH_j for two similar devices (e.g., 27-inch tall w-beam guardrail versus 31-inch tall w-beam guardrail) may be due to random variation that occurs from year to year or may indicate real performance differences. Determining which is most likely requires the calculation of a CI. If the estimate of one REH lies within the CI on another, the difference may be random variation and not a real difference in performance. For example, if REH_A for guardrail A is 0.0094 and REH_B for guardrail B is 0.0120 with an 85th CI of ±0.0050, the difference cannot confidently be attributed to a difference in performance but may just be the result of random variation since the value of REH lies within the confidence range of the other device. On the other hand, if the 85th CI was ±0.0020 for guardrail B, the difference is likely a real difference in performance.

In statistical terms, fatal and serious injury crashes are generally rare events (e.g., less than 0.10). The Wilson score interval is a confidence interval that is used to ensure that the CI does not go below zero. The Wilson score interval is a function of the number of cases (N), the estimate of the percent of total crashes that are fatal and serious injury crashes for the subject hardware (REH_j) and the two-tailed Z score which is based on the CL as shown in Table 3. The Wilson score interval is given by (*14*):

$$CI = \frac{RFEH_j \left[Z_{CL}^2 / 2NC_j \right]}{\left[1 + \left(Z_{CL}^2 / NC_j \right) \right]} \pm Z_{CL} \frac{\sqrt{\frac{REH_j(1 - REH_j)}{N} + \frac{Z_{CL}^2}{4NC_j^2}}}{\left[1 + \left(Z_{CL}^2 / NC_j \right) \right]}$$

$$CI = \frac{Step5 \left[Z_{CL}^2 / 2 \cdot Step2 \right]}{\left[1 + \left(Z_{CL}^2 / Step2 \right) \right]} \pm Z_{CL} \frac{\sqrt{\frac{Step5 \cdot (1 - Step5)}{N} + \frac{Z_{CL}^2}{4 \cdot Step2^2}}}{\left[1 + \left(Z_{CL}^2 / Step2 \right) \right]}$$

The CL (α) is used to calculate the CI for the percent of fatal and serious injury crashes (REH_j) estimated for each hardware type (j). The Z_{CL} score is a value determined from the choice of the CL (α) and is determined from the standard normal distribution assuming a two-tailed test. Values for Z_{CL} for typical confidence levels (α) are shown in Table 3 but are also available in any standard statistical manual or textbook. The CI is automatically calculated by the roadside hardware replacement analysis workbook or it can be manually calculated using the above equation or looked up in Table 2.

Table 3. Common Confidence Levels and Z Scores.

Confidence Level (CL)	**Two-Tailed Z_{CL} Score**
0.99	2.58
0.95	1.96
0.90	1.64
0.85	1.44
0.80	1.28

3.2.6 Step 6: Quantity of Existing Hardware in the Crash Reporting Area

The quantity of existing hardware in the same area used for collecting police-reported crashes (QEH_j) is needed. This value may come from an inventory of roadside hardware maintained by the highway agency or it may be estimated. One way to estimate is to select several typical routes in the data collection area and inventory the hardware on those routes. The total amount of hardware can then be extrapolated based on the total miles of roadway in the area. For guardrails, median barriers, and bridge railings the quantity is entered in ft whereas for terminals, transitions, and other discreet objects they entered in units of "each." Enter the quantity of existing hardware in the same area used to collect police-reported crash data (QEH_j) in the yellow cells for Step 6. Select the appropriate units in the yellow-shaded cell next to the quantity just entered (e.g., ft or ea.).

3.2.7 Step 7: Hardware Traffic Exposure

Most highway agencies collect traffic volume data for a variety of operational and planning purposes. The objective of this step is to calculate the volume of traffic that passed the roadside hardware (EEH_j) during the same period police-reported data was being collected for Steps 1 through 3. Obtain the highway agency traffic data and do one of the following:

- Best Approach – If traffic volume data is available by route and milepost or location and there is an inventory of roadside hardware, the roadside hardware locations can be matched to traffic volume counts. For continuous hardware (e.g., guardrails and median barriers) multiply the length of the hardware in miles by the traffic volume at the site times the number of years of data collection from Step 1. This results in a count of the number vehicles passing during the data collection period in units of million vehicle-miles passing (MVMP). For discreet hardware (e.g., terminals, transitions, etc.) sum the volume at each discreet hardware location and multiply by the number of years of data collection from Step 1. The result is a count of the number of vehicles passing during the data collection period in units of million vehicles passing (MVP).
- Acceptable Approach – Many highway agencies do not have roadside hardware inventory data so another less accurate but acceptable approach is to calculate the AADT in the data collection area and multiply that value by the quantity of existing hardware entered earlier in Step 6 and the number of years of data collected from Step 1. The result is the hardware traffic exposure in MVMP for continuous hardware (e.g., guardrails) and MVP for discreet hardware (e.g., terminals). One way to make the resulting calculation more accurate is to categorize roadways by their functional classification and tabulate the exposure by functional class.
- Adequate Approach – If data was obtained from another jurisdiction to complete Step 2 then the same should be done for estimating the hardware exposure. Use either method in the two paragraphs above depending on the availability of data in the source data collection area.

Enter the resulting existing roadside hardware traffic exposure (EEH_j) in the yellow-shaded cells for Step 7. The units are automatically chosen based on the earlier response to Step 6.

3.2.8 Step 8: Police-Reported Crash Rate

The estimated police-reported crash rate for the existing hardware ($CREH_j$) is automatically calculated in the roadside hardware replacement analysis workbook shown in **Figure 1** as follows:

$$\mathrm{CREH_j} = \frac{\mathrm{NC_j}}{\mathrm{EEH_j}} \rightarrow \mathrm{Step8} = \frac{\mathrm{Step3}}{\mathrm{Step7}}$$

The police-reported crash rate ($CREH_j$) is automatically calculated and entered into the box for Step 8.

3.3 RELATIVE RISK ESTIMATES FOR REPLACEMENT HARDWARE

The most difficult part of the roadside hardware replacement analysis process is estimating the improvement resulting from installing the upgraded replacement hardware.

3.3.1 Step 9: Estimate Fatal and Serious Injury Crash Risk for Replacement Hardware

Estimating the fatal and serious injury crash risk for the replacement hardware (RRHj) is difficult because there will generally be no field performance data available for newly developed devices. Instead, the analyst must make an estimate based on new design features, crash test results and engineering intuition. For example, many highway agencies are transitioning to 31-inch tall w-beam guardrail. The reason 31-inch guardrail was designed and tested was because of poor performance of 27-inch guardrail in Report 350 crash tests with pickup trucks. Since the purpose was to improve the performance with pickup trucks, the analyst could base the risk for the 31-inch guardrail on the anticipated improved performance with pickup trucks. This approach is illustrated at the end of this document in the example problem. Enter the value for the fatal and serious injury crash risk for the replacement hardware (RRHj) in the yellow-shaded cell for Step 9.

3.3.2 Step 10: Statistical Significance

If the estimated fatal and serious injury crash risk for the replacement hardware falls within the CI range for the existing hardware calculated in Step 5 the differences between the risks are not statistically significant. If the replacement hardware risk is outside the range of the existing risk, there is likely a performance differences between the existing and replacement hardware. This information is not used in the analysis but is automatically calculated for the convenience of the analyst.

3.3.3 Step 11: Relative Risk Reduction

The reason for considering replacement of existing roadside hardware with new hardware is to improve roadside safety performance by reducing the risk of observing a fatal or serious injury crash. The risk for the replacement hardware identified in Step 9 should be less than the calculated risk for existing hardware determined in Step 5. The relative risk reduction (RRR_j) measures the reduction in risk as a percentage of the existing risk as follows:

$$RRR_j = \left[\frac{REH_j - RRH_j}{REHS_j}\right] \rightarrow \text{Step11} = \left[\frac{\text{Step5} - \text{Step9}}{\text{Step5}}\right]$$

The relative risk reduction (RRR_j) associated with replacing the existing hardware with upgraded hardware is calculated and automatically entered in the box for Step 11.

3.4 PROJECT DETAILS

The project details are the most easily obtained information since they are generally available on the initial project scoping documents or surveys. Information regarding the project details are entered in Steps 12 through 15.

3.4.1 Step 12: Design Year Traffic Volume

The AADT in the design year for the proposed project may be determined using whatever method is used by the highway agency to make traffic projections for design decisions. The results do not depend on how the AADT is estimated, only the value in the design year is required. One common method for projecting future traffic volume is simple geometric growth as follows:

$$\mathrm{AADT} = \mathrm{AADT}_0 \cdot (1 + \mathrm{G})^{\mathrm{YD}}$$

Enter the design year traffic volume (AADT) in the yellow-shaded boxes for Step 12.

3.4.2 Step 13: Quantity of Replacement Hardware

The quantity of each type of existing roadside hardware (QEH_j) is determined for the proposed project based on the project scope or survey documents. Quantities are entered in ft for continuous roadside hardware like guardrails, median barriers, and bridge railings whereas quantities of "each" are used for discreet roadside hardware like guardrail terminals, transitions, crash cushions, signs, and other appropriate hardware. Recall that this procedure is only used for projects where replacement hardware is only considered where hardware already exists. Enter the quantity of existing hardware (QEH_j) for each type of hardware in the yellow-shaded cells for Step 13.

3.4.3 Step 14: Unit Installed Cost of Replacement Hardware

The unit installed cost of each type of replacement hardware ($UCIH_j$) can usually be determined directly from the highway agency's construction bid data. The cost should include the cost of the materials, labor, equipment charges, and any other expenses associated with installing a complete and final installation of the roadside hardware. For example, if the site of each new MASH terminal requires new grading, this cost should be included in the unit cost of the replacement MASH terminals. Enter the installed unit cost of each type of replacement hardware ($UCIH_j$) in the yellow-shaded cells for Step 14.

3.4.4 Step 15: Unit Cost of Hardware Removal

The unit cost of removing existing hardware ($UCRH_j$) can also usually be determined as a bid item in the highway agencies construction cost data. All labor and equipment costs associated with removing the existing hardware must be included. Usually scrape value is not considered but if highway agency policy is to include the scape value of the removed hardware it should be deducted from the unit cost of hardware removal. Unit costs are in dollars/ft for continuous objects like guardrails and median barrier and dollars/each for discreet hardware like guardrail terminals, crash cushions, transitions, and signs. Enter the unit cost of removing each type of existing hardware ($UCRH_j$) in the yellow-shaded cells for Step 15.

3.4.5 Step 16: Total Cost of Each Type of Replacement Hardware

The total cost of replacing each type of hardware (CRH_j) is the sum of the installation cost and the removal cost multiplied by the quantity of hardware. The total cost of replacing each type of replacement roadside hardware is calculated as:

$$\mathrm{CRH_j} = \mathrm{QEH_j} \cdot \left(\mathrm{UCIH_j} + \mathrm{UCRH_j}\right) \rightarrow \mathrm{Step16} = \mathrm{Step13} \cdot (\mathrm{Step14} + \mathrm{Step15})$$

The total cost of replacement hardware (CRH_j) is automatically calculated and shown in the box for Step 16.

3.5 ECONOMIC ANALYSIS

The last portion of the analysis is an economic analysis where the expected annual number of the fatal and serious crashes avoided on the project are transformed into a dollar value and compared to the total cost of replacing the existing hardware with new upgraded hardware.

3.5.1 Step 17: Annual Number of Fatal and Serious Injury Crashes Avoided

The reduction of risk resulting from installing the new replacement hardware is expected to result in fewer fatal and serious injury crashes. This reduction in the fatal and serious injury crash risk is the benefit that will be accrued to society in the future if the hardware is replaced. The number of fatal and serious injury crash avoided ($FSCA_j$) is estimated as follows:

$$FSCA_j = \frac{365 \cdot CREH_j \cdot AADT \cdot QEH_j \cdot REH_j \cdot RRR_j}{Units \cdot 10^6}$$
$$Step17 = \frac{365 \cdot Step8 \cdot Step12 \cdot Step13 \cdot Step5 \cdot Step11}{Units \cdot 10^6}$$

The value of "units" in the above equation are 5280 for continuous hardware measured in ft and 1 for discreet hardware. The calculated annual number of fatal and serious injury crashes avoided ($FSCA_j$) is automatically calculated and shown in the box for Step 16.

3.5.2 Step 18: Total Cost of Replacement Hardware

The total cost of replacement hardware (TCRH) is simply the sum of all the hardware replacement costs (CRH_j) listed earlier in Step 16 for each type of hardware. Most projects involve several types of hardware. For example, if guardrails are replaced, the associated terminals and transitions attached to the guardrails would likely also be replaced in the same project (i.e., m = 3). The costs of all hardware replaced on the project are summed to find the total project replacement cost (THRC) as follows.

$$TCRH = \sum_{i=1}^{m} CRH_j \rightarrow Step\ 19 = \sum_{i=1}^{m} Step\ 16_i$$

The TCRH is automatically calculated and shown in the box for Step 18.

3.5.3 Step 19: Value of Statistical Life

According to Kniesner, "the VSL is the local tradeoff rate between fatality risk and money. When the tradeoff values are derived from choices in market contexts the VSL serves as both a measure of the population's willingness to pay for risk reduction and the marginal cost of enhancing safety. Given its fundamental economic role, policy analysts have adopted the VSL as the economically correct measure of the benefit individuals receive from enhancements to their health and safety" (*15*). The U.S. DOT, including the FHWA, has used the VSL as a measure of crash cost since 2008 (*16*). The VSL can roughly be considered the cost of a fatal crash. A U.S. DOT memorandum on the use of the VSL states that "the relative values of injuries of varying severity were set as a percentage of the economic value of a life" (*15*). In 2008, the FHWA recommended using a VSL value of $5.8 million. The VSL has been periodically revised in subsequent years and in

2016 the recommend value was $9.6 million (*17*). The VSL increases from year to year and the FHWA provides a method for estimating a new VSL (*17*). Using the FHWA method for extrapolating the VSL to the year 2020 results in a VSL of $12.3 million, which is used in this procedure as the default value.

The VSL is a method used to transform the number of crashes avoided into dollars so that an economic analysis can be performed. The methodology was specifically developed to assess the economic impacts of safety design decisions, so it is appropriate for use in roadside hardware replacement analysis. In these guidelines, the VSL is used to represent the benefit in dollars for both fatal and serious injury crashes. This is a conservative approach since it will tend to overestimate the benefit of replacing roadside hardware.

If the highway agency uses its own locally derived crash cost values, the crash cost for a fatal crash can be substituted for the VSL. The analyst may retain the default VSL of $12.3 million shown in the grey-shaded box for Step 19 or enter another value if a different VSL is desired.

3.5.4 Step 20: Annual Societal Benefit of Crashes Avoided

The ABCA by replacing existing roadside hardware with upgraded replacement hardware is calculated by summing the estimated number of annual fatal and serious injury crashes avoided ($FSCA_j$) from Step 17 and multiplying by the VSL in Step 19 as follows:

$$\text{ABCA} = \left[\sum_{j=1}^{m} \text{FSCA}_j\right] \cdot \text{VSL} \rightarrow \text{Step 20} = \text{Step 19} \cdot \sum_{j=1}^{m} \text{Step 17}_j$$

The ABCA is assumed to be a constant value that is realized each year throughout the project life. The annual societal benefits of crash avoided by (ABCA) by replacing the hardware are calculated and displayed in the box for Step 20.

3.5.5 Step 21: Design Life

Roadside hardware can remain crash-ready and functional in the field for a very long time. A design life of 25 or 30 years is not unreasonable if the hardware is properly maintained and repaired after a crash. A design life (YL) of 25 years is assumed in the procedure (Table 1), but the analyst could choose any other reasonable value based on local highway agency policy. The analyst may retain the default 25-year design life shown in the grey-shaded box for Step 21 or enter another value if a different design life is desired.

3.5.6 Step 22: Internal Rate of Return

The IRR is the discount or interest rate that makes all net present worth values of the alternative zero. The IRR is the interest rate where the annual benefit of avoiding fatal and serious injury crashes by replacing hardware is exactly equal to the cost of implementing the replacement hardware alternative. In other words, the present worth of the annual benefit of fatal and serious injury crashes avoided (ABCA) over the life of the project exactly equals the total hardware replacement costs (THRC). The final step of the economic analysis is to calculate the IRR for the expected service life as follows: (*18*)

$$\text{THRC} = \sum_{i=0}^{YL} \frac{\text{ABCA}}{(1+\text{IRR})^{\text{i}}} \rightarrow \text{Step 22} = \sum_{i=0}^{\text{Step 21}} \frac{\text{Step 20}}{(1+\text{Step 22})^{\text{i}}}$$

The IRR is automatically calculated and shown in the box for Step 22.

3.6 Interpreting Results

The IRR calculated in Step 22 is the rate of return where the societal benefits accrued over the life of the replacement hardware exactly equals the cost of removing the existing hardware and installing the upgraded hardware. Larger IRR values indicate a higher rate of return and are, therefore, a better use of scare highway agency funds than projects with lower values of IRR.

Recently, the United States gross domestic product (GDP) growth has been about two percent annually. The most optimistic estimates of GDP growth for the next several years are just under four percent annually. A highway improvement project should have an IRR greater than the actual GDP growth and probably should be above the optimistic GDP growth values. If the IRR is less than about four percent, the replacement project is probably not a good way to spend scare highway agency resources. The IRR can also be viewed as a measure of priority, projects with the highest IRR should have the highest priority since they generate the largest societal benefit for the funds expended. A replacement project with an IRR = 8 would be a much better use of highway agency funds than another project with an IRR = 6 for example. Project with negative IRR values would be a poor use of funds under any economic conditions.

4 EXAMPLE

4.1 Replacing Strong-Post W-Beam Guardrail

The following example both illustrates the roadside hardware replacement analysis approach to analyzing the need for roadside hardware replacement while also addressing one of the most important particular cases: evaluating the need to replace 27-inch tall w-beam guardrail and its associated terminals with 31-inch tall w-beam guardrail.

Assume a highway agency is planning a 6.2-mile-long mill and resurface project on a two-lane rural highway with an AADT of 1,450 vehicles/day. The project is what has often been described as a 3R project and involves no new construction or reconstruction. The roadway alignment will not be changed, the basic nature of the roadway will not change, and only roadside hardware that is already in place will be considered for replacement. The total cost of the project is estimated as $920,186 not including any hardware replacement.

Aside from signs, the roadside hardware on the anticipated 6.2-mile long project consists of 1,775 ft of 27-inch tall w-beam guardrail with 18 Report 350 guardrail terminals. The guardrails and terminals are in generally good condition and an inspection of the highway segment indicates the guardrails and terminals are crash-ready and located properly according to local highway agency policies. In this situation, should the 27-inch w-beam guardrails and Report 350 terminals be replaced by 31-inch tall w-beam guardrails and MASH terminals? The following sections will examine this question for this particular roadway. The filled in workbook book for this example is shown in Figure 2.

4.1.1 Steps 1-8: Risk Assessment of Existing Guardrails

First, the performance of the existing 27-inch w-beam guardrails must be established by examining crash records or an in-service evaluation. Based on 2010 through 2015 Pennsylvania Department of Transportation (PennDOT) police-reported crash data there were 1,711 passenger car crashes with guardrail face Type D installations (i.e., 27-inch tall strong-post w-beam with blockouts) and 689 pickup truck and sport utility vehicles (SUV) crashes with Type D guardrail face installations. The total number of passenger vehicle Type D guardrail face crashes, therefore, was 2,400 (i.e., 1,711+689=2,400). Of the 2,400 total Type D guardrail face crashes, 17 were fatal or serious crashes so the proportion of fatal and serious injury crashes for all types of passenger vehicles was 0.0071 [0.0050, 0.0100] (note: the values in brackets in this section are the bounds of the 85th percentile CI). For passenger cars, the proportion of fatal and serious Type D guardrail face crashes was 0.0053 [0.0033, 0.0085] and for pickup trucks and SUV the proportion was 0.0116 [0.0071, 0.0192]. The proportion of fatal and serious crashes was higher (almost twice) for pickup trucks and SUVs although the result was not statistically significant at the 85 percent CL (i.e., the confidence intervals overlap).

According to the PennDOT roadway inventory, there were 6,683 miles (35,286,240 ft) of Type D guardrail in the state in 2016. According to the FHWA highway statistics for Pennsylvania, the average AADT on a PennDOT maintained roadway was 2,260 vehicles/day so there were 6,683·365·6·2,260/106=33,077 MVMP guardrails during the same data collection period as the six years of crash data. The crash rate for Type D guardrails was therefore the 2400 Type D guardrail face crashes divided by the traffic volume passing guardrails or 2400/33,077=0.0726 Type D guardrail face crashes/MVMP.

4.1.2 Steps 9-11: Relative Risk Estimates for Replacement Guardrail

Next, the relative risk of the proposed replacement 31-inch tall w-beam guardrails must be estimated. Since 31-inch guardrails are relatively new, there is little if any field data available to use in assessing the field performance. Since the field performance is not known, the engineer must use judgement and develop an estimate based on the best available information.

In this case, the motivation for developing and deploying 31-inch tall w-beam guardrail is to attempt to reduce the number of penetration and rollover crashes associated with pickup trucks and SUVs. This seems reasonable based on the PennDOT data since pickup trucks and SUV have a fatal and serious injury crash proportion that is more than double that of passenger cars though it is still very small and it is not definitively known if the difference is due to rollovers and penetration. The assumption in upgrading from 27- to 31-inch tall guardrails is that the 31-inch tall guardrails will reduce the percent of fatal and serious injury pickup truck and SUV crashes to the same level as passenger cars (i.e., 0.0053).

As shown in the last section, the fatal and serious injury proportion of Type D guardrail face crashes was 0.0053 [0.0033, 0.0085] for passenger cars, 0.0116 [0.0071, 0.0192] for pickup trucks and SUVs and 0.0071 [0.0050, 0.0100] for all passenger vehicle types. If 31-inch guardrail was successful in reducing the KA ROR crash rate with type D guardrail faces such that the performance of pickup trucks and SUVs was the same as passenger cars, the risk reduction would be (0.0071-0.0053)/0.0071 = 0.2518 or a 25 percent relative risk reduction. It is important to recognize that this is an estimate of the expected performance based on the design objective of the crash tests and engineering judgement but only a review of crash records in the future can positively confirm that the relative risk reduction was real.

4.1.3 Steps 12-17: Project Details for Guardrails

Now that the relative risks of the existing and potential replacement guardrails are known or estimated, the specific details of a project can be examined. As discussed earlier there are 1,775 ft of w-beam guardrail in the 6.2-mile long project. Recent bid prices indicate Type D guardrail costs between 15 and 20 $/ft so 17 $/ft for materials and installation was assumed. Similarly, removing the existing guardrail costs about 2 $/ft based on recent bid prices. The cost of removing the existing 1,775-ft of w-beam guardrail and replacing it with 31-inch guardrail is, therefore, $33,725.

In the last section, the police-reported Type D guardrail crash rate was found to be 0.0726 crashes/MVMP and replacing Type D guardrail with 31-inch guardrail would result in a 25.18 percent relative risk reduction. If it is assumed that the frequency of crashes remains the same (i.e., no major changes in traffic mix or volume or roadway alignment) it is reasonable to expect $0.0726 \cdot 0.0071 \cdot 0.2518 \cdot (1{,}450 \cdot 365 \cdot 1{,}775/5{,}280 \cdot 10^6) = 0.0000323$ fewer fatal and serious injury w-beam guardrail crashes/yr on the project segment after 31-inch guardrails replace the existing 27-inch tall guardrails.

4.2 Replacing Report 350 Terminals with MASH 2016 Terminals

Guardrails like the Type D guardrails in Pennsylvania discussed in the previous sections, are not replaced in isolation. Every guardrail has at least one terminal and an anchor so if the guardrail height is raised the terminals, anchors and transitions will also need to be modified. This section examines the risks and costs associated with replacing the associated terminals on the 6.2-mile long example project.

4.2.1 Steps 1–8: Risk Assessment of Existing Terminals

As for the guardrail, the first task in examining the effectiveness of replacing the guardrail terminals is assessing the existing guardrail terminal performance. Unfortunately, the inventory of terminals in Pennsylvania is not as extensive as the guardrail inventory so it could not be used to match police reports to terminal installations. Instead, terminal crash rate was estimated based on data from another state, Ohio.

The Ohio DOT 2009-2011 guardrail and guardrail terminal inventory indicates that there were 19,724 Type E guardrail terminals on state-maintained roadways (*19*). Type E guardrail terminals at the time were all tangent Report 350 terminals. Ray reported that in 2002 through 2012 there were 286 Type E terminal crashes, eight of which were fatal or serious injury crashes so the proportion of Type E terminal crashes that were fatal or serious was 0.0280 [0.0158, 0.0490].

The crash rate for terminals also needs to be estimated. Ideally, the number of vehicles passing terminals should be known for the same data collection period and area as the crash data. The best way to calculate this would be based on an inventory linked to traffic data as described earlier for Step 8. Unfortunately, such a linkage is not available for the Ohio data so it must be estimated instead. In 2009 there were 113,673 MVMT on 122,926 miles of state-maintained roads so the average AADT of a roadway in Ohio was 2,533 vehicles/day (*20*). The estimated exposure for terminals would be approximately the average AADT multiplied by 365 days/year multiplied by the 19,724 terminals on public roads times the 11-year data collection period or $365 \cdot 2{,}533 \cdot 19{,}724 \cdot 11/10^6 = 200{,}592$ MVP Type E terminals. The crash rate was, therefore, approximately 286/200,592 = 0.0014Type E terminal crashes/MVP.

4.2.2 Steps 9–11: Relative Risk Assessment of Replacement Terminals

Quantifying the improved performance in the field of MASH 2016 guardrail terminals is challenging. The changes to the test matrix of MASH from those in Report 350 with respect to terminals were relatively minor. In addition to both the small and large passenger vehicle increasing slightly in weight, the gating tests were changed from 15 degrees to a range of 5 to 15 degrees. Testers are instructed to choose the most critical impact angle. Many of the MASH terminals are slight reworkings of the prior Report 350 terminals. More to the point, while the FHWA and AASHTO found that all Report 350 energy absorbing terminals had three performance limitations (i.e., side impact, shallow-angle corner impact, and high-energy impact crashes), MASH does not address any of these in its test recommendations or evaluation criteria so MASH terminals may have similar performance limitations to the Report 350 terminals (*21*).

For the sake of this example, assume that the MASH terminals result in a 50 percent reduction in the fatal and serious injury crash risk. Clearly, this is simply a guess that assumes MASH terminals are much more effective than Report 350 terminals. This is also an example of making an assumption that favors the replacement option. If the procedure results in a recommendation to not replace the hardware, not doing so is likely the correct use of funds since the replacement option was favored but still failed. If MASH terminals do in fact perform at this level, replacement hardware risk would be 0.0140.

4.2.3 Steps 12–17: Project Details for Terminals

As discussed earlier, there are 18 guardrail terminals on the 6.2-mile long project. The cost of removing each existing guardrail terminal is estimated to be about $600 and the cost of installing a new MASH 2016 terminal is estimated as $2,000 so the replacement cost is 2,600 $/terminal. The total cost of replacing the 18 terminals would be $46,800.

Assuming the replacement terminals result in a 50 percent risk reduction ratio and the terminal crash rate is 0.0140 terminal crashes/MVP as calculated in the last section, the replacement of the terminals should result in $0.0280 \cdot 0.50 \cdot 0.0014 \cdot 18 \cdot 1{,}450 \cdot 365/10^6 = 0.000190$ fewer fatal and serious injury terminal crashes annually.

4.3 ECONOMIC ANALYSIS

For this example, project, replacing 1,775-ft of 27-inch guardrail with 31-inch tall guardrail would cost $33,725 and replacing the 18 Report 350 terminals with MASH terminals would cost $46,800. The total cost of the replacement hardware would, therefore, be $80,525.

According to the FHWA guidance on economic analysis, the 2020 VSL is $12.3 million (*22*). The annual benefit of replacing 27-inch guardrail with 31-inch guardrail and replacing Report 350 terminals with MASH terminals is the VSL multiplied by the number of fatal and serious crashes avoided. The previous sections estimated that 0.000023 fatal and serious guardrail crashes would be avoided annually, and 0.000190 fatal and serious terminal crashes would be avoided annual for a total of 0.000213 fatal and serious injury crashes are expected to be avoided annually by replacing the current hardware with MASH hardware. The annual benefit of the replacement project is, therefore, expected to be $0.000214 \cdot 12{,}300{,}00 = \$2{,}626$.

In this example, the IRR is –1.51 percent over the 25-year design life. In other words, for the economic and site conditions of this example, replacing the existing hardware with MASH tested hardware is not a good investment of highway agency resources. In fact, the investment required to replace the existing hardware with MASH hardware would take more than 30 years to achieve an IRR of zero.

4.4 DISCUSSION

The results of the analysis of the example problem discussed in the previous sections is sensitive to the assumptions that form the basis of estimating the replacement hardware performance. By definition, the new hardware likely has no field observed performance so estimating the performance will often be based on a combination of engineering judgement and intuition based on crash test results. The advantage to this method, however, is that it is possible to examine these assumptions by performing “what-if” analyses.

For example, in the previous example the effectiveness of both 31-inch tall w-beam guardrail and MASH guardrail terminals had to be estimated. For the conditions used in the example, the IRR was negative indicating the benefit would never equal the cost of construction during the design life. In the workbook, the estimated hardware effectiveness is easily changed. For example, the MASH terminals would have to perform such that the proportion fatal and serious injury crashes was less than 0.0100 for the IRR to just equal zero. This would represent a more than 64 percent risk reduction ratio from Report 350 terminals to MASH terminals. Given the relatively modest changes in MASH compared to Report 350 for guardrail terminal crash tests and the similarities between Report 350 and MASH terminal technologies, a 64 percent risk ratio reduction seems unlikely. Similarly, 27-inch w-beam guardrail already performs at a very low risk (i.e., 0.0071) so reducing it significantly seems unlikely. Increasing the risk reduction ratio to over 90 percent still results an IRR of near zero. Little improvement can be expected in replacing still functional guardrail for this modest AADT two-lane rural roadway.

On the other hand, using the original risk estimates presented in the example (i.e., terminals with a proportion of fatal and serious injuries of 0.0140 and guardrails with 0.0053), changing the traffic conditions can make replacement more attractive. For example, if the AADT is changed from 1,450 vehicles/day to 3,000 vehicles/day the IRR is 4.5 percent, which is essentially at the breakpoint of deciding to recommend the project. A highway agency could use an analysis like this, for example, to develop a policy to only replace existing functional crash-ready roadside hardware with replacement MASH hardware on rural two-lane roads with AADTs over 3,000 vehicles/day. The IRR increases to over 10 for AADT greater than 5,000 vehicles/day.

Even though the analysis results in this example indicate replacing the existing hardware with MASH hardware is not a good use of funds for that particular roadway, a highway agency also has other considerations to balance. The particular roadway may have a crash history that is not well represented by the results or there may be public pressure to replace certain roadside hardware. Similarly, engineering judgement has an important role to play and an agencies experience with particular local design issues may overrule a purely economic decision. The roadside hardware replacement analysis presented here should not be considered the sole basis for a definitive decision but one consideration among many for determining when and where roadside hardware is best replaced and where it is best left in place.

ROADSIDE HARDWARE REPLACEMENT ASSESSMENT WORKSHEET

Intructions: Enter information on the project or policy being considered in the yellow shaded cells. Values in grey shaded cells are default values but can be changed if desired.

Project Name: Replace 27-inch PennDOT Type D guardrail and R350 Type E terminals with 31-inch MGS guardrail and MASH 2016 terminals

Risk Assessment of Existing Hardware

Using state or district wide police reported crash data determine the number of fatal and serious injury crashes that occurred involving the existing hardware. If an in-service evaluation of the hardware is avaiable use the crash severity performance from that source. Use as many years of crash data as are available and enter the appropriate values in the yellow shaded cells. Three columns are provided to account for associated roadside hardware. For example, replacing a guardrail may also require replacing the associated terminals, anchors and transitions associated with that guardrail. Place information for each type of hardware in one of the three columns.

	Symbol		27" Type D GR			R350 Type E				
1. Enter the number of years of crash data:	YCD		6			11				
2. Enter the total number of crashes with the existing hardware:	NC_i		2400			286				
3. Enter the number of fatal and serious injury crashes with the existing hardware:	$NFSC_i$		17			8				
4. Enter the desired cofidence interval (e.g., 85th percentile):	CL		85%			85%			85%	
5. Calculate the mean risk of fatal or serious injury with the existing hardware with 85th percentile confidence:	REH_J	0.0050 <	0.0071	< 0.0100	0.0171 <	0.0280	< 0.0460	<		<
6. Enter the quantity of existing hardware in crash reporting area:	QEH_I		35,286,240	ft		19,724	ea			
7. Enter the existing hardware exposure during the data collection period (i.e., million vehicle miles passing [MVMP] for guardrails and million vehicles passing for terminals [MVP]).	EEH_J		33,077	MVMP		200,592	MVP			
8. Calculate the total police reported crash rate.	$CREH_I$		0.0726	crashes/MVMP		0.0014	crashes/MVP			

Relative Risk Estimate for Replacement Hardware

Estimate the smallest likely risk of a fatal or serious injury with the replacement hardware. Generally, crash data or an in-service evaluation will not be available to determine this value so it must be estimated using engineering judgement. It should be less than the observed value for the existing hardware and must be greater than zero. Enter the estimates for each type of replacement hardware below:

		31" MGS GR	MASH	
9. Estimate of risk of fatal or serious injury given a crash with the replacement hardware:	RRH_J	0.0053	0.0140	
10. Are the existing and replacement crash risk outside the 85th confidence interval?		No	Yes	
11. Calculate relative risk reduction of replacement hardware compared to existing hardware:	RRR_J	0.2518	0.5013	

Project Details

Enter information about the proposed project. Use the project information along with the values determined in the previous sections to estimate the number of fatal and serious injury crashes avoided by replacing the existing hardware with upgraded hardware.

12. Enter the design year AADT of the project:	AADT	1,450	veh/day	1,450	veh/day	1,450	veh/day
13. Enter the amount of hardware installed on project:	QEH_J	1,775	ft	18	ea		
14. Enter the unit installed cost of the replacement hardware:	$UCIH_J$	17.00	$/ft	2000.00	$/ea		$/ea
15. Enter the unit cost to remove existing hardware:	$UCRH_J$	2.00	$/ft	600.00	$/ea		$/ea
16. Calculate the total cost of installing the replacement hardware:	CRH_J	33,725	$	46,800	$	-	$
17. Estimate the number of annual fatal and serious injury crashes avoided:	$FCSA_J$	0.000023	crashes/yr	0.000190	crashes/yr		crashes/yr

Economic Analysis

The expected number of fatal and serious injury crashes avoided calculated in the previous step are summed and assigned an economic value based on the FHWA's value of statistical life (VSL) recommendation. The internal rate of return where the sum of all the benefits in future years equals the construction investment in the design years is calculated. Generally, if the internal rate of return is less than 2% it is not the best use of funds.

18. Calculate the total cost of the hardware replacement:	TCRH	80,525	$
19. Enter the value of statistical life (VLS) or use the default value of $12.3 million:	VSL	12,300,000	$
20. Calculate the annual societal benefit of the replacement:	ABCA	2,626	$/yr
21. Enter the assumed service life or retain the assumed 25 year life.	YL	25	yrs
22. Calculate the internal rate of return assuming a 25 year design life.	IIR	-1.51	%

Type CTRL+SHIFT+R to Clear and Reset Form

Figure 2. Worksheet for Considering the Replacement of 27-inch W-Beam Guardrail with 31-inch W-Beam Guardrail and Associated Terminals.

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