Pilot In-Service Performance Evaluation of Cable Barrier in Washington State

WA-RD 913.1

Paul Abbott
Brad Manchas
Ida van Schalkwyk
John Donahue
Jim Mahugh

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PILOT IN-SERVICE PERFORMANCE EVALUATION OF CABLE BARRIER IN WASHINGTON STATE

by

Paul Abbott
Brad Manchas
Ida van Schalkwyk
John Donahue
Jim Mahugh

Washington State Department of Transportation
Development Division

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16. ABSTRACT:

A pilot routine in-service performance evaluation (ISPE) was undertaken for cable barrier following the process outlined in NCHRP 22-33. Barrier breach, rollover, vehicle mix, and secondary impacts on the roadside and roadway were evaluated as performance measures using data sourced from the Crash Location & Analysis System (CLAS) database and the WSDOT Engineering Crash Data Mart for years 2016 through 2020. Four Performance Assessment Levels, ranging from no exclusions of crash data to exclusions of crash data limited to vehicle type and speed limit were assessed. For all five performance measures, the study found no measurable difference between the performance of the four major types of cable barrier in use on state highways within WSDOT jurisdiction, including three-strand versus four-strand.

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- The WSDOT Crash Data and Reporting Branch for coding the seven sequences of events for all vehicle units involved in state route lane departure crashes for use in our in-service performance work and for making these data part of standard crash coding at WSDOT.
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INTRODUCTION

A routine In-Service Performance Evaluation (ISPE) was undertaken using the uniform criteria presented in the ISPE Guidance Document, developed under NCHRP 22-33, "Multi-State In-Service Performance Evaluations of Roadside Safety Hardware" (Carrigan, 2021). This report documents a routine, statewide ISPE of cable barriers maintained by the Washington State Department of Transportation (WSDOT) utilizing the crash database for 2016 through 2020 in conjunction with the WSDOT collected longitudinal barrier inventory.

The primary objectives of this ISPE were to evaluate fatal and serious injury outcomes (not considering contributing factors), structural adequacy, and post impact vehicle trajectory among the various cable barrier systems maintained by WSDOT under real-world field conditions. The ISPE used the following evaluation measures from NCHRP 22-33:

- Safety feature breach (Evaluation Measure A)
- Rollover (Evaluation Measure F)
- Vehicle mix (Evaluation Measure H)
- Secondary impact on the roadside (Evaluation Measure J)
- Secondary impact on the road (Evaluation Measure K)

These evaluation measures were chosen to match the design objectives of a cable barrier crash test. For example, Safety Feature Breach (Evaluation Measure A) evaluates if the cable barrier is meeting the objective of containing and redirecting a vehicle. Furthermore, defining these Evaluation Measures provide interoperability with data and results from other states. Other evaluation measures applicable to longitudinal barriers developed under NCHRP 22-33 were not evaluated because the required data are not available in the WSDOT Engineering Crash Data Mart.

- Occupant Compartment Penetration (Evaluation Measure D)
- Impact Orientation (Evaluation Measures L and M)

The data for each evaluation measure is grouped into performance assessment levels that use either the entire dataset or subset of the dataset depending on the design vehicle and design speed of the crash test criteria being used. The performance metric for the assessment levels is R2 which is the rate of occurrence of the unexpected event associated with the evaluation measure. For example, R2 for Safety Feature Breach (Evaluation Measure A) would be the rate of occurrence of the barrier being penetrated.

Additionally, each evaluation measure has an Effect Size, or ES, the observed occurrence of a fatal and suspected serious injury. If the Effect Size is greater than one, the unexpected outcome (a fatal and serious injury crash) has a higher potential than the expected outcome (a crash that is not a fatal or serious injury crash) when the unexpected event associated with the evaluation measure is encountered. Refer to the section on Data and Methodology for further detail.

This report presents the collection, assembly, and analysis of in-service performance data for this ISPE. Conclusions are provided at the end of this report which provide further discussion and conclusions based on the analysis. Suggested application of the results and limitations of the results are also discussed as part of the conclusions and recommendations.

SCOPE AND LIMITATIONS OF THE STUDY

This section presents the scope and limitations of the study. As a pilot in-service performance project, this report is the first of its kind for WSDOT and sets the stage for future evaluations and baseline for performance of these systems.

Scope of the Study

This report examines the in-service performance of the cable barrier systems used by WSDOT. Since 2016 WSDOT funded several three to four strand cable barrier system conversions. The table below lists pre and post conversion inventory percentages. The study used crash data from January 1st, 2016 and ended on December 31, 2020, encompassing five years. Table 1 shows photographs of the different cable barrier types evaluated individually along with length of the system pre and post three-to-four strand conversion. Table 2 shows the other cable barrier types that were not individually evaluated but were included in the overall cable barrier assessment. The analysis itself only reports data for the system that was in place when the crash occurred.

Table 1 - Evaluated Cable Barrier Types

Photograph	Description
	Trinity CASS S3 M10 (Four Strand) Pre-conversion: 61 miles or 28% of inventory by length Post-conversion: 70 miles or 31% of inventory by length A total of 932 crashes with this barrier type occurred in 2016-2020, with 20 fatal and suspected serious injury crashes (2.1%).
	Gibraltar (Four Strand) Pre-conversion: 20 miles or 9% of inventory by length Post-conversion: 94 miles or 41% of inventory by length A total of 812 crashes with this barrier type occurred in 2016-2020, with 18 fatal and suspected serious injury crashes (2.2%).

Photograph	Description
	Trinity CASS C-Shaped Post (Three Strand) Pre-conversion: 133 miles or 59% of inventory by length Post-conversion: 41 miles or 18% of inventory by length A total of 703 crashes with this barrier type occurred in 2016-2020, with 12 fatal and suspected serious injury crashes (1.7%).
	Brifen (Four Strand) Pre-conversion: 1 mile or 0.5% of inventory by length Post-conversion: 17 miles or 7.5% of inventory by length A total of 128 crashes with this barrier type occurred in 2016-2020, with 7 fatal and suspected serious injury crashes (5.5%).

Table 2 - Cable barriers not included in the analysis of individual systems

Photograph	Description
	US High Tension (Three Strand) Pre-conversion: 7 miles or 3% of inventory by length Post-conversion: 0.6 miles or 0.2% of inventory by length A total of 12 crashes with this barrier type occurred in 2016-2020, with 1 fatal and suspected serious injury crashes (8.3%). Not included because of limited length.
N/A	Unknown (Four Strand) Pre-conversion: 1.5% of inventory by length Post-conversion: 6 miles or 2.5% of inventory by length A total of 10 crashes with this barrier type occurred in 2016-2020, with 2 fatal and suspected serious injury crashes (20%). The specific type of cable barrier is unknown because there is no imagery available in SRView or Google Street View to determine the specific brand, usually due to installation in late 2020 and beyond.

Limitations

The main limitations of the study are related to the data and methodology.

The WSDOT Crash Location & Analysis System (CLAS) contains the detailed type of first and second object struck and up to seven sequence of events for each crash based on the information provided in the Police Traffic Collision Reports (PCTRs). For example, a vehicle may depart the roadway to the right, strike a fixed object, be redirected back into the roadway, and then collide with a second vehicle. The first and second object struck type was used to filter the dataset to only include crashes where cable barrier was struck, and the sequence of event data were used to generate a significant portion of the harmful event dataset for this ISPE. However, the sequence of events data only documents striking a fixed object and does not go into further detail such as barrier type. If the sequence of events documents an impact with a fixed object and then an impact with another vehicle, then it is obvious that the cable barrier was struck first as only crashes where cable barrier was the first or second object struck were extracted for analysis. But if the sequence of events documents two or more impacts with fixed objects, it is not known which impact involves the cable barrier. In these cases, manual review was required by reviewing the PCTRs. Additionally, the sequence of events was not available for most of 2019, requiring manual review for that year.

One of the key pieces of information derived from the sequence of events is the determination of Most Harmful Event. Table 7 ranks the "harmful" events, for example a rollover is considered more severe than a crash with another vehicle. This ranking is often reasonable but is nonetheless an assumption; there are scenarios where a rollover could be the *least* severe harmful event in a crash. This is a limitation of the input data and the ISPE process since the determination of Most Harmful Event will always have a degree of subjectivity.

The CLAS database and PCTRs do not contain information about the impact orientation (the acute angle between the vehicle trajectory on impact and the barrier), nor do they contain information about occupant compartment penetration, so Evaluation Measure L, M, and D were not performed.

A further limitation was that the methodology itself does not assess whether the crash conditions exceeded the design conditions for the barrier and uses posted speed as a proxy for impact speed. Posted speed do not represent mean operating speeds and is unlikely to reflect the speed during impact with the traffic barrier.

This in-service performance evaluation is the first of its kind in WA state and was considered a pilot project using the proposed methodology from NCHRP 22-33 as specified by the contractor.

DATA AND METHODOLOGY

Data were drawn by selecting crashes that indicated cable barrier as the first or second object struck within the study timeframe. The crashes were then matched cable barriers that were within 250 feet of the crash location with a matching route number and direction of travel. Cable barrier types and locations were determined using the cable barrier inventory. If multiple cable barriers were identified, the crash reports and cable barrier inventory were manually reviewed to determine the correct barrier involved in the crash. The remaining required data were sourced from the WSDOT Engineering Crash Data Mart and from the detailed sequence of events from the Crash Location & Analysis System (CLAS) database as outlined in Table 3 through Table 6.

For the CLAS database, the seven Driver Action fields were used to determine the sequence of events of the crash. All possible Driver Action values were reviewed, and the "harmful" Driver Action values were identified and ranked as shown in Table 7. If there were multiple "Collision Involving Fixed Object" events, the sequence of events could not be determined in an automated fashion because it is not known which "Collision Involving Fixed Object" event involved cable barrier. In these cases, the crash report was reviewed and the harmful event data for that crash was determined manually.

Because cable barriers are currently undergoing a three to four strand conversion, the previous barrier type, current barrier type, and conversion date was needed so older crashes were correctly matched to older hardware. The Construction Data Mart was used to retrieve construction contracts involved in three to four strand conversion and identify the individual cable barriers in inventory that were converted. If a crash occurred after the Operationally Complete Date, the crash was matched to the new (four strand) hardware. If the crash occurred up to three months prior to the Operationally Complete Date, it was excluded from the dataset because the type of barrier struck could not be determined. If the crash occurred more than three months prior to the Operationally Complete Date, it was assumed the old (three strand) hardware was struck.

Table 3 lists the data fields that are used by the proposed NCHRP 22-33 ISPE process, and the source(s) used to populate the data from available WSDOT sources.

Table 3 - Compiled ISPE Dataset and Source Material

Field Name	Definitions	Source
SFUE	Safety Feature Under Evaluation	Always "1" for cable barrier.
CRN	Crash number	WSDOT Engineering Crash Data Mart Police Traffic Collision Report Number
CRASH_DATE	Date of crash	WSDOT Engineering Crash Data Mart Full Date
TOTAL_UNITS	Number of units involve in the crash	WSDOT Engineering Crash Data Mart Vehicle Count
MAX_SEV	Maximum severity of the crash	WSDOT Engineering Crash Data Mart Crash Indicator fields See Table 4
VEH_TYPE	Body type of vehicle	WSDOT Engineering Crash Data Mart Vehicle Type See Table 5

Field Name	Definitions	Source
SPEED_LIMIT	Speed limit	CLAS Database Posted Speed
PostHE	Post harmful event after safety feature interaction	CLAS Database Driver Action fields The first "harmful" Driver Action (if any) that occurred after the "Collision Involving Fixed Object" Driver Action. See Table 7.
MHE	Safety feature was most harmful event	CLAS Database Driver Action fields The Rank from Table 7 was used to determine if any Driver Actions more severe than "Collision Involving Fixed Object" occurred in the sequence of events.
FHE	Safety feature was first harmful event	CLAS Database Driver Action fields Determined by checking if "Collision Involving Fixed Object" was the first harmful Driver Action.
AHE	Safety feature was any harmful event	Always true because the crashes were pre-filtered to only include collisions with cable barrier.
FOHE	Safety feature was first and only harmful event	CLAS Database Driver Action fields Determined by checking if "Collision Involving Fixed Object" was the only harmful Driver Action.
BREACH	Vehicle breached safety feature	CLAS Database Driver Action fields If a Driver Action of "Crossed the Center Median (CCM)" was present, then it was assumed the barrier was breached.
BREAK	Predictable breakaway	Not applicable for cable barrier.
PRC	Controlled penetration, redirection, or stop	Not applicable for cable barrier.
PEN	Safety Feature Intrusion	This information does not exist in our data, so the value was set to unknown unless the crash report was manually reviewed.
ICP	Initial contact point	This information does not exist in our data, so the value was set to unknown.

Field Name	Definitions	Source
NAME	The type (brand) of safety feature	Barrier Inventory Barrier Type Determined by the 250-foot spatial join between the crashes and cable barrier inventory. Three to four strand conversions were accounted for. See Table 1
AADT	Average Annual Daily Traffic in vehicles per day	Frozen WSDOT Engineering Crash Data Mart Collision Estimated AADT Note: AADT is not actually used in the ISPE calculations and may be removed in a future version.
INSTALL	Construction inspection	Always true because all cable barrier is inspected on installation.
MAINT	Maintenance Inspection	Always true because all cable barrier is inspected yearly.

Table 4 lists the translation from the crash severity data in the WSDOT Engineering Crash Data Mart to the KABCO Injury Classification Scale.

Table 4 - ISPE Dataset MAX_SEV Equivalence Table

Crash Severity	Crash Data Mart Values
K	Fatal Crash Indicator = 1
A	Serious Injury Crash Indicator = 1
B	Evident Injury Crash Indicator =1
C	Possible Injury Crash Indicator = 1
O	Property Damage Only Crash Indicator = 1
U	Unknown

Table 5 lists the translation from the vehicle type data in the WSDOT Engineering Crash Data Mart to the Vehicle Types used in NCHRP 22-33.

Table 5 - Equivalency of the State Motor Vehicle Body Type to Dataset Variables

Vehicle Type	WSDOT Engineering Crash Data Mart Values
MC	12. Motorcycle 13. Scooter Bike 15. Moped
PC	1. Passenger Car 9. Taxi
PU	2. Pickup, Panel Truck or Vanette under 10,000 lb.
SUT	3. Truck (Flatbed, Van, etc.)
BUS	10. Bus or Motor Stage 11. School Bus
TT	4. Truck & Trailer 5. Truck Tractor 6. Truck Tractor & Semi-Trailer 7. Truck - Double Trailer Combinations 8. Farm Tractor and/or Farm equipment
Other	16. Railway Vehicle 17. Neighborhood Electronic Vehicle 18. Golf Cart 14. Other

Table 6 documents how the post harmful event (PostHE) values were determined from the detailed sequence of events, also known as driver actions, available in the CLAS (Crash Location & Analysis System) database for each crash.

Table 6 - ISPE Dataset PostHE Equivalence Table

Post Harmful Event (PostHE)	Driver Actions
00	No harmful Driver Action (see Table 7) occurred after the “Collision Involving Fixed Object” Driver Action.
RFS	There is no information in our data whether the rollover occurred on the field side or the same side as the barrier. The generic ROLL value was used unless the crash report was manually reviewed.
RSS	There is no information in our data whether the rollover occurred on the field side or the same side as the barrier. The generic ROLL value was used unless the crash report was manually reviewed.
ROLL	An “Overturn (Rollover)” Driver Action occurred after the “Collision Involving Fixed Object” Driver Action.
VEH	A “Collision Involving Motor Vehicle in Transport” Driver Action occurred after the “Collision Involving Fixed Object” Driver Action.
PED	A “Collision Involving Pedestrian” Driver Action occurred after the “Collision Involving Fixed Object” Driver Action.

Post Harmful Event (PostHE)	Driver Actions
FO	Determined by manual review of the crash report; there would be more than one "Collision Involving Fixed Object" Driver Action.
BA	Determined by manual review of the crash report; there would be more than one "Collision Involving Fixed Object" Driver Action.
BAR	Determined by manual review of the crash report; there would be more than one "Collision Involving Fixed Object" Driver Action.
OTR	Other Driver Actions from Table 7 or determined by manual review of the crash report.

Table 7 lists the translation from the driver actions in the detailed sequence of events to the post harmful event. The ranking is used to determine if the crash with the cable barrier is the most harmful event (MHE); barrier crashes are coded as "Collision Involving Fixed Object" so if there are any driver actions with a rank greater than four, most harmful event was set to false.

Table 7 - Translation of Sequence of Events to Post Harmful Events (PostHE)

Driver Action	Rank	Equivalent ISPE Event
Overturn (Rollover)	1	ROLL
Collision Involving Motor Vehicle in Transport	2	VEH
Collision Involving Parked Vehicle	3	OTR
Collision Involving Fixed Object	4	FO
Collision Involving Pedestrian	5	PED

Table 8 lists the translation from the cable barrier type to the single-character NAME codes used in the NCHRP 22-33 spreadsheet.

Table 8 - NAME Equivalence

NAME	Cable Barrier Type
A	Brifen
B	Gibraltar
C	Trinity C-Shaped
D	Trinity CASS M10

ANALYSIS AND FINDINGS

Introduction

This section presents the results of the in-service performance evaluation of cable barriers. Based on NCHRP 22-33, "Multi-State In-Service Performance Evaluations of Roadside Safety Hardware", the cable barriers are assessed on the following evaluation measures:

- Safety feature breach (Evaluation Measure A)
- Rollover (Evaluation Measure F)
- Vehicle mix (Evaluation Measure H)
- Secondary impact on the roadside (Evaluation Measure J)
- Secondary impact on the road (Evaluation Measure K)

These performance metrics are identified as necessary and possible, given the available WSDOT data, by the NCHRP Project 22-33. The performance metrics will vary between system types and this is roughly based on expected performance during crash testing.

Four Performance Assessment Levels (PALs) were calculated to a 95% confidence interval to evaluate the performance for crashes with cable barriers corresponding to the NCHRP 350 Test Level 3 crash test impact conditions for which the cable barrier systems were designed.

- Performance Assessment Level 1 (PAL1) evaluates all crashes in the dataset.
- Performance Assessment Level 2 (PAL2) limits the dataset by design vehicle type (passenger cars, trucks, and single unit trucks). In other words, crashes involving other vehicles are excluded.
- Performance Assessment Level 3 (PAL3) limits the dataset by to those with a posted speed limit of 65mph or less, using posted speed limit as a proxy for design speed (62.4 mph).
- Performance Assessment Level 4 (PAL4) limits the dataset by posted speed limit and vehicle type, a combination of PAL2 and PAL3.

For each of the performance assessment levels, R2 and ES are calculated. R2 is the rate of occurrence of the unexpected event associated with the evaluation measure in percentage. The unexpected events for the evaluation measures relevant to cable barrier are listed in Table 9.

Table 9 - Unexpected Events for Evaluation Measures

Evaluation Measure	Unexpected Event	Data Source
A – Safety Feature Breach	The vehicle penetrated the cable barrier.	The BREACH (vehicle breached safety feature) field where the value is UNEX. See Table 3.
F – Rollover	The vehicle rolled over after impact with the cable barrier.	The PostHE (post-harmful event) field where the value is RFS (rollover field side), RSS (rollover same side), or ROLL (rollover). See Table 3 and Table 6.
H – Vehicle Mix	A fatal or serious injury occurred after impact with the cable barrier.	The MAX_SEV (maximum crash severity) field where the value is K (fatal) or A (serious). See Table 3 and Table 5.

Evaluation Measure	Unexpected Event	Data Source
J – Secondary Impact on Roadside	The vehicle struck a fixed roadside object (excluding other barriers) after impact with the cable barrier.	The PostHE (post-harmful event) field where the value is FO (fixed object) or BA (breakaway object). See Table 3 and Table 7.
K – Secondary Impact on Road	The vehicle struck another barrier, vehicle, or pedestrian after impact with the cable barrier.	The PostHE (post-harmful event) field where the value is VEH (other vehicle), BAR (barrier), or PED (pedestrian). See Table 3 and Table 7.

Using Evaluation Measure F as an example, if there are 100 crashes where the vehicle did not roll over (PostHE value is not ROLL, RFS, or RSS) and 20 crashes where the vehicle did (PostHE value is ROLL, RFS, or RSS). The R2 value would be the number of crashes with an unexpected outcome divided by the total number of crashes, or

$$\frac{n_{unexpected}}{n_{unexpcected} + n_{expected}} = \frac{20}{20 + 100} = 16.67\%$$

Equation 1 - Calculation for R2

In other words, the vehicle rolled over 16.67% of the time.

ES is the Effect Size or likelihood of a fatal and suspected serious injury crash for an unexpected event. If the Effect Size is greater than one, a fatal or serious injury crash is more likely when the unexpected event occurs than when the event is expected. Continuing the previous example for Evaluation Measure F, if there are five fatal or serious injury crashes for the 20 crashes where the unexpected event occurred, and there are ten fatal or serious injury crashes for the 100 crashes where the expected event occurred, the ES would be

$$\frac{n_{unexpected\ KA} \,/\, n_{unexpected}}{n_{expected\ KA} \,/\, n_{expected}} = \frac{5/20}{10/100} = 2.5$$

Equation 2 - Calculation for ES

In other words, a fatal or serious injury crash is 2.5 times more likely to result if an unexpected outcome occurs. An ES of one indicates that there is no difference in the severity outcomes whether the cable barrier perform as expected or when there is unexpected vehicle behavior during or after the impact with the cable barrier.

R2 is a measure of how frequently the cable barrier is performing as expected and ES is a measure of how likely a fatal or serious injury crash is when there is unexpected vehicle behavior after the impact with the barrier.

Effect Size is not presented per cable barrier type as it is for R2 in this report. The team assessed the effect size for each barrier and only one value could be calculated because the number of fatal or serious injury crashes when the expected event occurred ($n_{expected\ KA}$) is zero in many cases, rendering ES as undefined.

For each evaluation measure, the results are presented in two tables and one chart. The first table summarizes the R2 values (with 95th percentile confidence interval) for Performance Assessment Levels (PAL) 1 through 4 with the overall Effect Size (ES), a ratio. The second table summarizes the Performance Assessment Levels broken down by individual barrier type. The chart graphically presents the PAL 4 values for each barrier type from the second table with bars for the confidence interval. According to the NCHRP 22-33 methodology, the performance of two different barrier types is equivalent if the confidence intervals overlap.

Confidence intervals are calculated using a Wilson Score Interval, which is asymmetric (in other words, point values are not necessarily in the middle of the interval). The Wilson Score Interval is also effective for small samples and skewed observations and is designed to correct for zero values. A zero R2 value indicates that no unexpected events occurred for the specified evaluation measure and cable barrier type in the five-year study period. Zero R2 values will also result in identical confidence intervals for the same cable barrier types across multiple evaluation measures because the calculation is based solely on the total number of crashes for the cable barrier type.

Note: US High Tension cable barrier was excluded from most of the analysis because it is a small percentage of the barrier inventory and does not have enough related crash data to derive any meaningful conclusions.

Safety Feature Breach (Evaluation Measure A)

Safety Feature Breach assesses the probability that a vehicle will penetrate the cable barrier by going over, under, or through. Both single and multi-vehicle crashes are included in this measure to include the full range of impact conditions the safety feature is exposed to while in-service.

Analysis

Computations were conducted to find the values of R2 and the associated 95th percentile confidence interval for Safety Feature Breach (Evaluation Measure A). These computations are summarized by the Performance Outcome in Table 10 through Table 11 and charted in Figure 1.

Table 10 shows R2 values with confidence intervals for Evaluation Measure A (Breach) for all Performance Assessment Levels (PALs) and all barrier types. It also shows the effect size (ES).

Table 10 - Performance Assessment for Safety Feature Breach by Level Across All Cable Barriers: Mean values and 95^th percentile confidence interval

Evaluation Criteria		**PAL1**	**PAL2** Evaluates the performance of the cable barrier limited by the vehicle types it was design and evaluated for in the crash tests	**PAL3** Evaluates the performance of the cable barrier limited to conditions where posted speed limit ≤ 65	**PAL4** Evaluates the performance limited to vehicle type and design speed
Evaluation A (Breach)	$R2_A$	2.27% 1.71% – 3.01%	2.25% 1.68% – 3.01%	2.07% 1.43% – 3.0%	2.0% 1.36% – 2.94%
	ES_A	9.79 3.88 – 24.7			

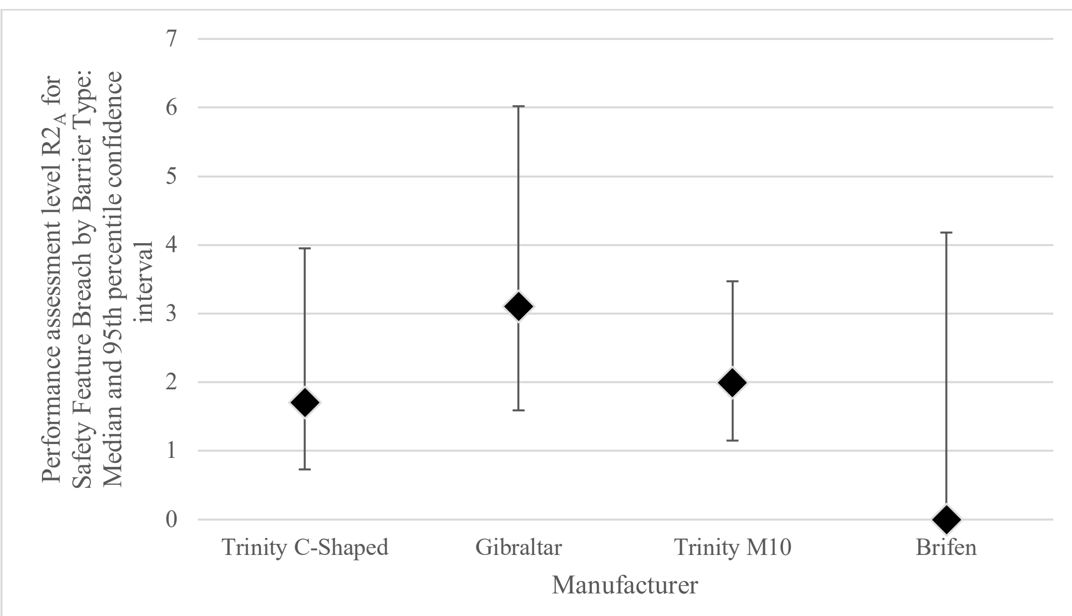
Table 11 shows the R2 values with confidence intervals at the 95-percentile confidence for Evaluation Measure A (Breach) for all Performance Assessment Levels (PALs) broken down by barrier type. The PAL values for Brifen are zero because Brifen represents only 7.5% of the inventory and barrier penetration was sufficiently rare which drove the mean value to effectively zero within the confidence interval.

Table 11 - Performance Assessment for Safety Feature Breach by Barrier Type: Mean values and 95th percentile confidence interval

Evaluation Criteria	Barrier Type	PAL1, $R2_A$	PAL2, $R2_A$	PAL3, $R2_A$	PAL4, $R2_A$
Evaluation A (Breach)	Trinity C-Shaped (3 Strand)	2.29% 1.37% - 3.8%	2.02% 1.16% - 3.49%	2.28% 1.11% - 4.63%	1.71% 0.73% - 3.95%
	Gibraltar (4 Strand)	3.18% 2.02% – 4.97%	3.38% 2.15% – 5.27%	2.89% 1.47% – 5.59%	3.11% 1.59% – 6.02%
	Trinity M10 (4 Strand)	1.91% 1.14% – 3.18%	1.96% 1.17% – 3.26%	1.94% 1.12% – 3.37%	2.00% 1.15% – 3.47%
	Brifen (4 Strand)	0% 0% – 3.66%	0% 0% – 3.74%	0% 0% – 4.14%	0% 0% – 4.18%

Figure 1 shows the R2 values for Performance Assessment Level 4 (PAL4) from Table 11 plotted with confidence intervals.

Figure 1 - PAL4 $R2_A$ for Safety Feature Breach by Barrier Type: Mean values and 95th percentile confidence interval



Discussion

- There is no measurable difference in barrier penetration between the types of cable barriers currently maintained by WSDOT according to the NCHRP 22-33 methodology as all confidence intervals overlap.
- There is no measurable difference in barrier penetration between three strand (Trinity C-Shaped) and four strand (Gibraltar, Trinity M10) cable barriers.
- When a vehicle breaches the barrier the likelihood for fatal and serious injury crashes are 9.8 times (ES_A) higher than when no penetration occurred (see Table 10).
- Breach occurred in 2.3% of the reported crashes.

Rollover (Evaluation Measure F)

The Rollover assessment is intended to evaluate influence of and propensity for rollover that results from interaction with the safety feature under evaluation. For this evaluation measure, only single vehicle crashes are used.

Analysis

Computations were conducted to find the values of R2 and the associated 95th percentile confidence interval for Rollover (Evaluation Measure F). These computations are summarized by the Performance Outcome in Table 12 through Table 13 and charted in Figure 2.

Table 12 shows R2 values with confidence intervals for Evaluation Measure F (Rollover) for all Performance Assessment Levels (PALs) and all barrier types. It also shows the effect size (ES).

Table 12 - Performance Assessment for Rollover by Level Across All Cable Barriers: Mean values and 95th percentile confidence interval

Evaluation Criteria		PAL1	PAL2	PAL3	PAL4
Evaluation F (Rollover)	$R2_F$	4.46% 3.59% – 5.52%	4.33% 3.46% – 5.40%	4.21% 3.19% – 5.53%	4.12% 3.09% – 5.47%
	ES_F	8.75 6.97 – 50.41			

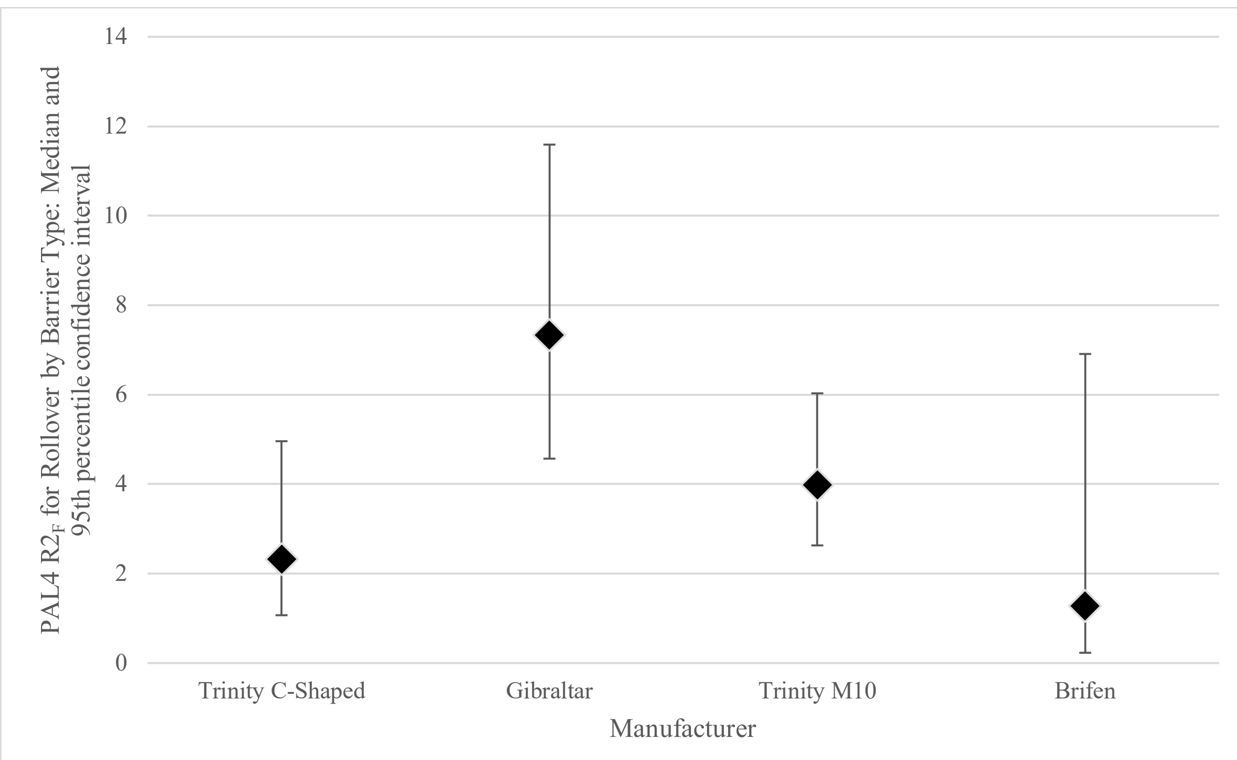
Table 13 shows the R2 values with confidence intervals for Evaluation Measure F (Rollover) for all Performance Assessment Levels (PALs) broken down by barrier type.

Table 13 - Performance Assessment for Rollover by Barrier Type: Mean values and 95th percentile confidence interval

Evaluation Criteria	Barrier Type	PAL1, $R2_F$	PAL2, $R2_F$	PAL3, $R2_F$	PAL4, $R2_F$
Evaluation F (Rollover)	Trinity C-Shaped (3 Strand)	3.54% 2.28% - 5.46%	3.45% 2.19% - 5.38%	2.57% 1.25% - 5.22%	2.32% 1.07% - 4.96%
	Gibraltar (4 Strand)	6.92% 5.0% – 9.52%	6.49% 4.59% – 9.12%	7.59% 4.86% – 11.68%	7.34% 4.57% – 11.59%
	Trinity M10 (4 Strand)	3.74% 2.53% – 5.51%	3.85% 2.6% – 5.66%	3.87% 2.55% – 5.85%	3.99% 2.63% – 6.03%
	Brifen (4 Strand)	1.1% 0.19% – 5.97%	1.12% 0.2% – 6.09%	1.27% 0.22% – 6.83%	1.28% 0.23% – 6.91%

Figure 2 shows the R2 values for Performance Assessment Level 4 (PAL4) from Table 13 plotted with confidence intervals.

Figure 2 - PAL4 $R2_F$ for Rollover by Barrier Type: Mean values and 95th percentile confidence interval



Discussion

Based on the analysis, the following are noted:

- There is no measurable difference in rollover between the types of cable barriers currently maintained by WSDOT according to the NCHRP 22-33 methodology as all confidence intervals overlap.
- There is no measurable difference in rollover between three strand (Trinity C-Shaped) and four strand (Gibraltar, Trinity M10, and Brifen) cable barriers. US High Tension was not evaluated because it represents only 0.2% of total installations by length.
- When a vehicle rolls over after impacting the cable barrier, the likelihood for fatal and suspected serious injury crashes was 8.8 times (ES_F) higher than when no rollover occurred (see Table 12).
- Rollover occurred in 4.5 percent of reported crashes.

Vehicle Mix (Evaluation Measure H)

The Vehicle Mix assessment is intended to evaluate the occurrence of fatal and serious injury across and within the vehicle and speed mix the safety feature is exposed to while in-service. This assesses the crash severity in terms of the maximum injury experienced by the impacting vehicle's occupants. This evaluation measure is limited to single vehicle crashes.

Analysis

Computations were conducted to find the values of R2 and the associated 95th percentile confidence interval for Vehicle Mix (Evaluation Measure H). These computations are summarized by the Performance Outcome in Table 14 through Table 18 and charted in Figure 3 through Figure 6.

Table 14 shows the R2 values with confidence intervals for Evaluation Measure H (Vehicle Mix) for all Performance Assessment Levels (PALs) broken down by Any Harmful Event, First Harmful Event, Most Harmful Event, and First and Only Harmful Event.

Table 14 - Performance Assessment for Vehicle Mix by Level: Mean values and 95th percentile confidence interval

Evaluation Criteria		PAL1, $R2_H$	PAL2, $R2_H$	PAL3, $R2_H$	PAL4, $R2_H$
Evaluation H (Vehicle Mix)	Any Harmful Event	0.87% 0.54% – 1.42%	0.56% 0.30% – 1.03%	1.11% 0.65% – 1.88%	0.60% 0.29% – 1.24%
	First Harmful Event	0.86% 0.53% – 1.40%	0.00% 0.30% – 1.03%	1.09% 0.64% – 1.86%	0.61% 0.30% – 1.26%
	Most Harmful Event	0.45% 0.23% – 0.89%	0.18% 0.06% – 0.54%	0.61% 0.30% – 1.26%	0.18% 0.05% – 0.67%
	First and Only Harmful Event	0.47% 0.24% – 0.93%	0.18% 0.06% – 0.54%	0.64% 0.31% – 1.31%	0.19% 0.05% – 0.69%

Table 15 shows the R2 values with confidence intervals for Evaluation Measure H (Vehicle Mix) for Any Harmful Event and all Performance Assessment Levels (PALs), broken down by barrier type.

Table 15 - Performance Assessment for Any Harmful Event by Barrier Type: Mean values and 95th percentile confidence interval

Evaluation Criteria	Barrier Type	PAL1, $R2_H$	PAL2, $R2_H$	PAL3, $R2_H$	PAL4, $R2_H$
Evaluation H (Vehicle Mix) Any Harmful Event	Trinity C-Shaped (3 Strand)	1.03% 0.47% - 2.23%	0.53% 0.18% - 1.55%	1.35% 0.52% - 3.41%	0.35% 0.06% - 1.98%
	Gibraltar (4 Strand)	0.93% 0.40% - 2.17%	0.6% 0.02% - 1.74%	1.16% 0.4% - 3.36%	0.42% 0.07% - 2.34%
	Trinity M10 (4 Strand)	0.71% 0.31% - 1.66%	0.59% 0.23% - 1.5%	0.84% 0.36% - 1.96%	0.7% 0.27% - 1.77%
	Brifen (4 Strand)	2.06% 0.57% - 7.21%	2.11% 0.58% - 7.35%	2.35% 0.65% - 8.18%	2.38% 0.66% - 8.27%

Figure 3 shows the R2 values for Performance Assessment Level 4 (PAL4) from Table 15 plotted with confidence intervals.

Figure 3 - PAL4 $R2_H$ for Any Harmful Event by Barrier Type: Mean values and 95th percentile confidence interval

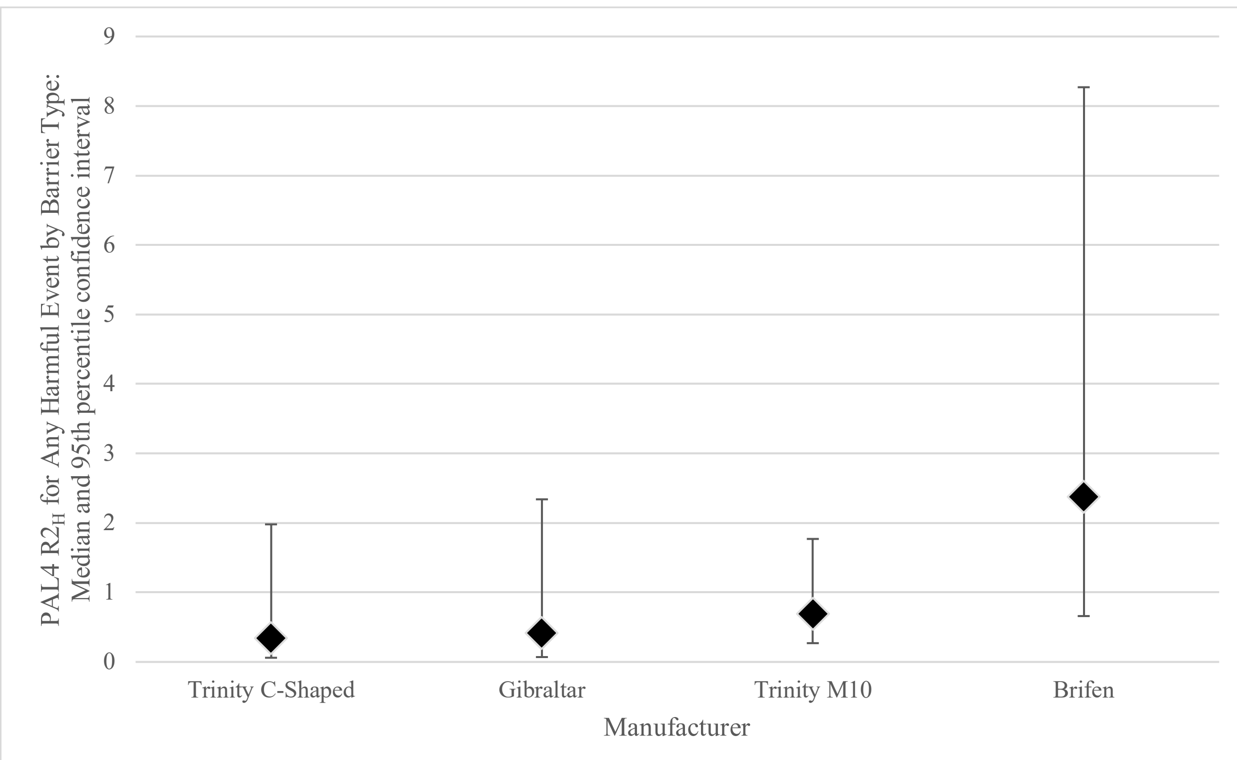


Table 16 shows the R2 values with confidence intervals for Evaluation Measure H (Vehicle Mix) for First Harmful Event and all Performance Assessment Levels (PALs), broken down by barrier type.

Table 16 - Performance Assessment for First Harmful Event by Barrier Type: Mean values and 95th percentile confidence interval

Evaluation Criteria	Barrier Type	PAL1, $R2_H$	PAL2, $R2_H$	PAL3, $R2_H$	PAL4, $R2_H$
Evaluation H (Vehicle Mix) First Harmful Event	Trinity C-Shaped (3 Strand)	0.72% 0.28% - 1.83%	0.18% 0.03% - 1.04%	1.06% 0.36% - 3.08%	0% 0% - 1.41%
	Gibraltar (4 Strand)	0.97% 0.41% - 2.24%	0.61% 0.21% - 1.79%	1.2% 0.41% - 3.48%	0.43% 0.08% - 2.42%
	Trinity M10 (4 Strand)	0.6% 0.23% - 1.53%	0.46% 0.16% - 1.35%	0.71% 0.28% - 1.81%	0.55% 0.19% - 1.59%
	Brifen (4 Strand)	2.11% 0.58% - 7.35%	2.15% 0.59% - 7.51%	2.41% 0.66% - 8.37%	2.44% 0.67% - 8.46%

Figure 4 shows the R2 values for Performance Assessment Level 4 (PAL4) from Table 16 plotted with confidence intervals.

Figure 4 - PAL4 $R2_H$ for First Harmful Event by Barrier Type: Mean values and 95th percentile confidence interval

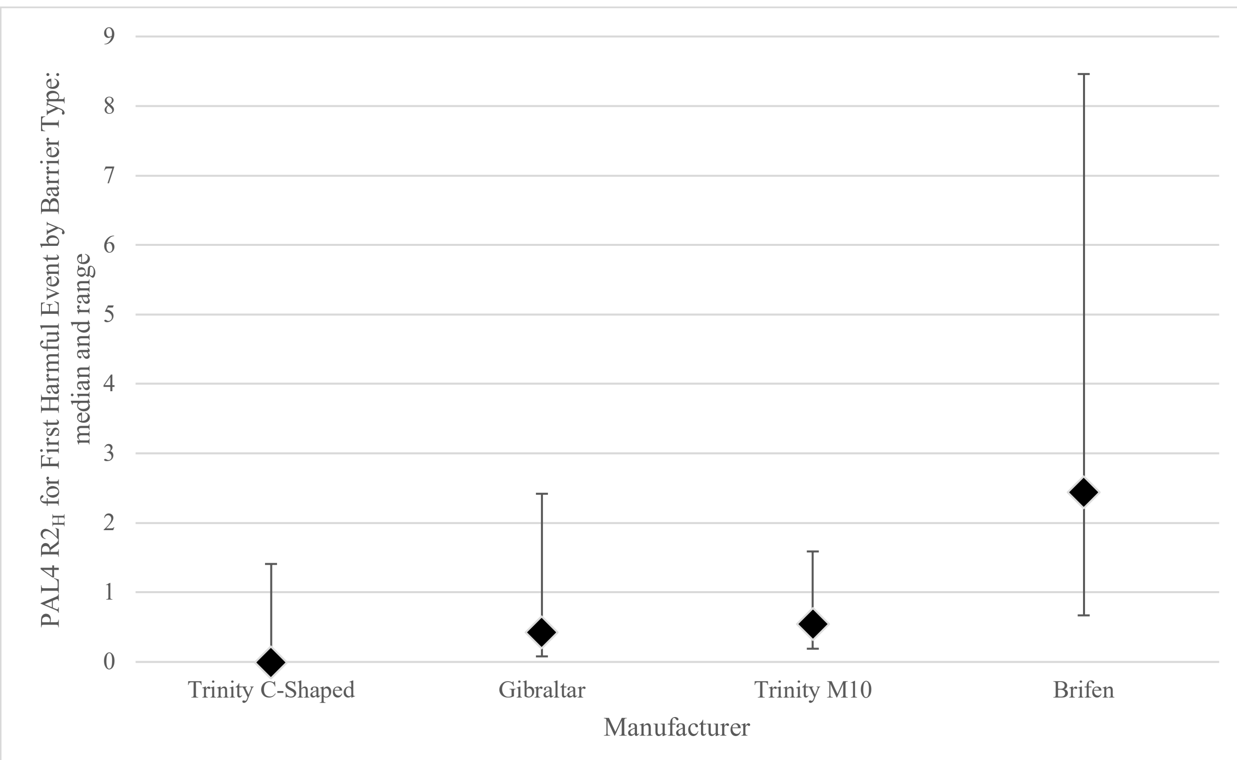


Table 17 shows the R2 values with confidence intervals for Evaluation Measure H (Vehicle Mix) for Most Harmful Event and all Performance Assessment Levels (PALs), broken down by barrier type.

Table 17 - Performance Assessment for Most Harmful Event by Barrier Type: Mean values and 95th percentile confidence interval

Evaluation Criteria	Barrier Type	PAL1, R2H	PAL2, R2H	PAL3, R2H	PAL4, R2H
Evaluation H (Vehicle Mix) Most Harmful Event	Trinity C-Shaped (3 Strand)	0.37% 0.1% - 1.34%	0% 0% - 0.73%	0.72% 0.2% - 2.59%	0% 0% - 1.43%
	Gibraltar (4 Strand)	0.63% 0.21% - 1.83%	0.22% 0.04% - 1.24%	0.88% 0.24% - 3.14%	0% 0% - 1.79%
	Trinity M10 (4 Strand)	0.31% 0.09% - 1.13%	0.16% 0.03% - 0.9%	0.37% 0.1% - 1.33%	0.19% 0.03% - 1.07%
	Brifen (4 Strand)	1.08% 0.19% - 5.84%	1.1% 0.19% - 5.97%	1.23% 0.22% - 6.67%	1.25% 0.22% - 5.75%

Figure 5 shows the R2 values for Performance Assessment Level 4 (PAL4) from Table 17 plotted with confidence intervals.

Figure 5 - PAL4 R2$_H$ for Most Harmful Event by Barrier Type: Mean values and 95th percentile confidence interval

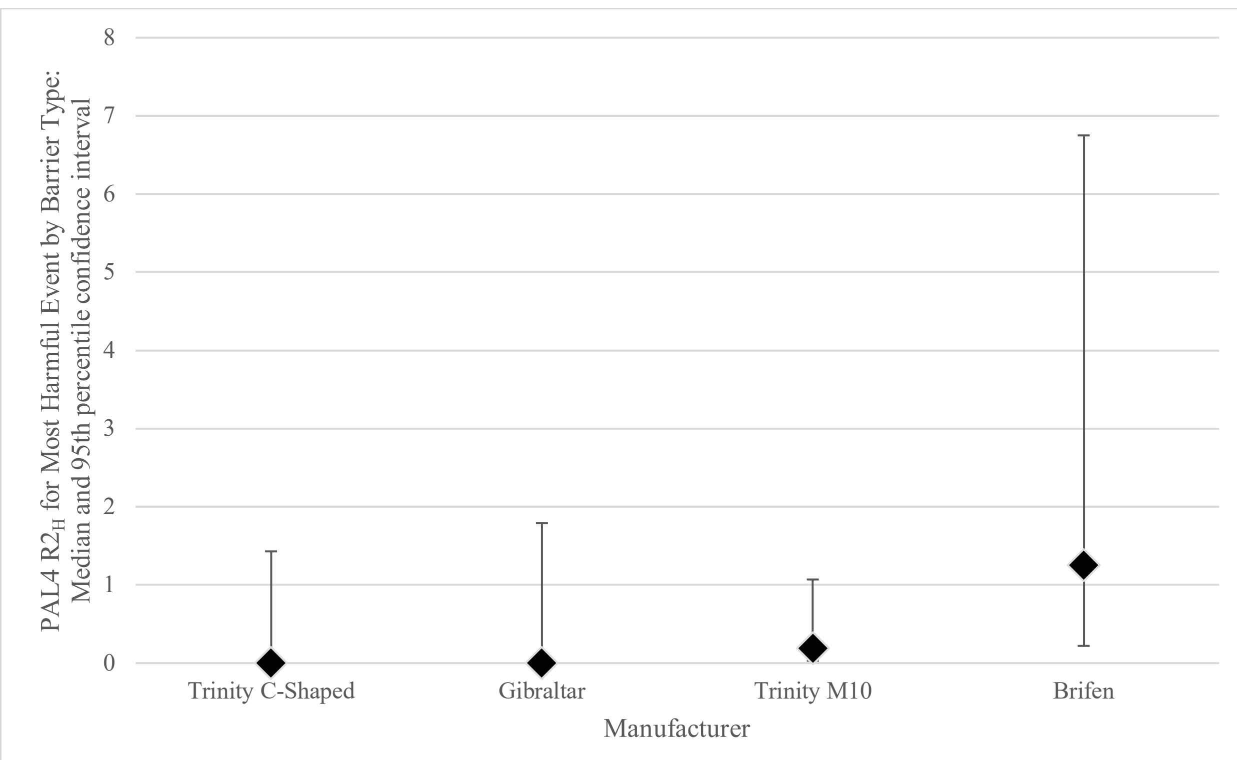


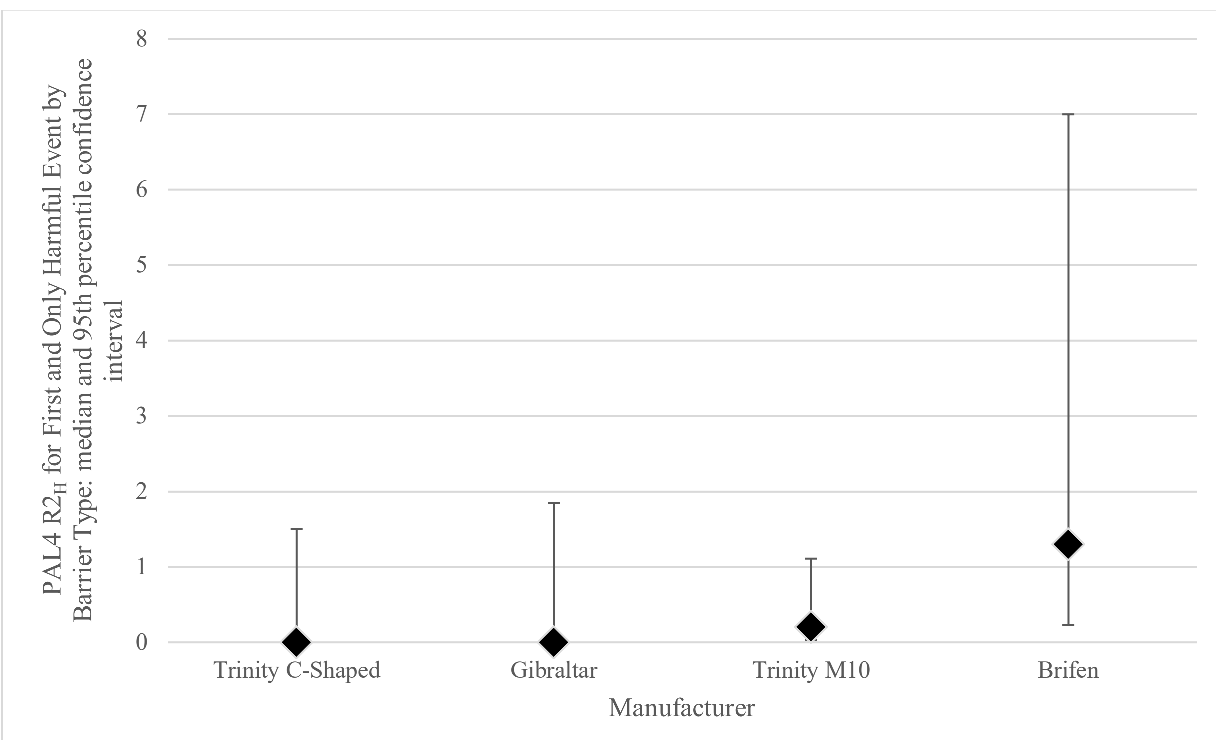
Table 18 shows the R2 values with confidence intervals for Evaluation Measure H (Vehicle Mix) for First and Only Harmful Event and all Performance Assessment Levels (PALs), broken down by barrier type.

Table 18 - Performance Assessment for First and Only Harmful Event by Barrier Type: Mean values and 95th percentile confidence interval

Evaluation Criteria	Barrier Type	PAL1, $R2_H$	PAL2, $R2_H$	PAL3, $R2_H$	PAL4, $R2_H$
Evaluation H (Vehicle Mix) First and Only Harmful Event	Trinity C-Shaped (3 Strand)	0.39% 0.11% - 1.39%	0% 0% - 0.75%	0.75% 0.21% - 2.71%	0% 0% - 1.5%
	Gibraltar (4 Strand)	0.65% 0.22% - 1.9%	0.23% 0.04% - 1.29%	0.9% 0.25% - 3.24%	0% 0% - 1.85%
	Trinity M10 (4 Strand)	0.32% 0.09% - 1.17%	0.17% 0.03% - 0.94%	0.38% 0.11% - 1.39%	0.2% 0.03% - 1.11%
	Brifen (4 Strand)	1.11% 0.2% - 6.03%	1.14% 0.2% - 6.16%	1.28% 0.23% - 6.91%	1.3% 0.23% - 7.0%

Figure 6 shows the R2 values for Performance Assessment Level 4 (PAL4) from Table 18 plotted with confidence intervals.

Figure 6 - PAL4 $R2_H$ for First and Only Harmful Event by Barrier Type: Mean values and 95th percentile confidence interval



Discussion

Based on the analysis, the following are noted:

- There is no measurable difference in the likelihood for fatal and serious injury outcomes between the types of cable barriers currently maintained by WSDOT according to the NCHRP 22-33 methodology as all confidence intervals overlap.
- There is no measurable difference in the likelihood for fatal and serious injury outcomes between three strand (Trinity C-Shaped) and four strand (Gibraltar, Trinity M10, and Brifen) cable barriers. US High Tension was not evaluated because it represents only 0.2% of total installations by length.
- Fatal and serious injury outcomes occurred in 0.87 percent of reported crashes.

Secondary Impact on Roadside (Evaluation Measure J)

Secondary Impact on Roadside is intended to evaluate secondary (post-cable barrier) impacts with fixed objects versus no secondary impact. For this evaluation only single unit crashes where striking the cable barrier is the first harmful event are used. Impacts with other longitudinal barriers are excluded.

Analysis

Computations were conducted to find the values of R2 and the associated 95th percentile confidence interval for Secondary Impact on Roadside (Evaluation Measure J). These computations are summarized by the Performance Outcome in Table 19 through Table 20 and charted in Figure 7.

Table 19 shows R2 values with confidence intervals for Evaluation Measure J (secondary impact on roadside) for all Performance Assessment Levels (PALs) and all barrier types. It also shows the Effect Size (ES). Secondary impact on roadside after impacting a cable barrier is rare (a total of six crashes out of over 2,000) with only one serious injury crash where the vehicle crashed into a tree on the other side of the road after the barrier was struck. The low secondary impact on roadside count combined with the single fatal and serious injury crash results in an artificially high effect size.

Table 19 - Performance Assessment for Secondary Impact on Roadside by Level Across All Cable Barriers: Mean values and 95th percentile confidence interval

Evaluation Criteria		PAL1	PAL2	PAL3	PAL4
Evaluation J (Secondary Impact on Roadside)	$R2_J$	0.35% 0.16% – 0.77%	0.37% 0.17% – 0.80%	0.36% 0.14% – 0.93%	0.38% 0.15% – 0.97%
	ES_J	35.27 5.18 – 240.13			

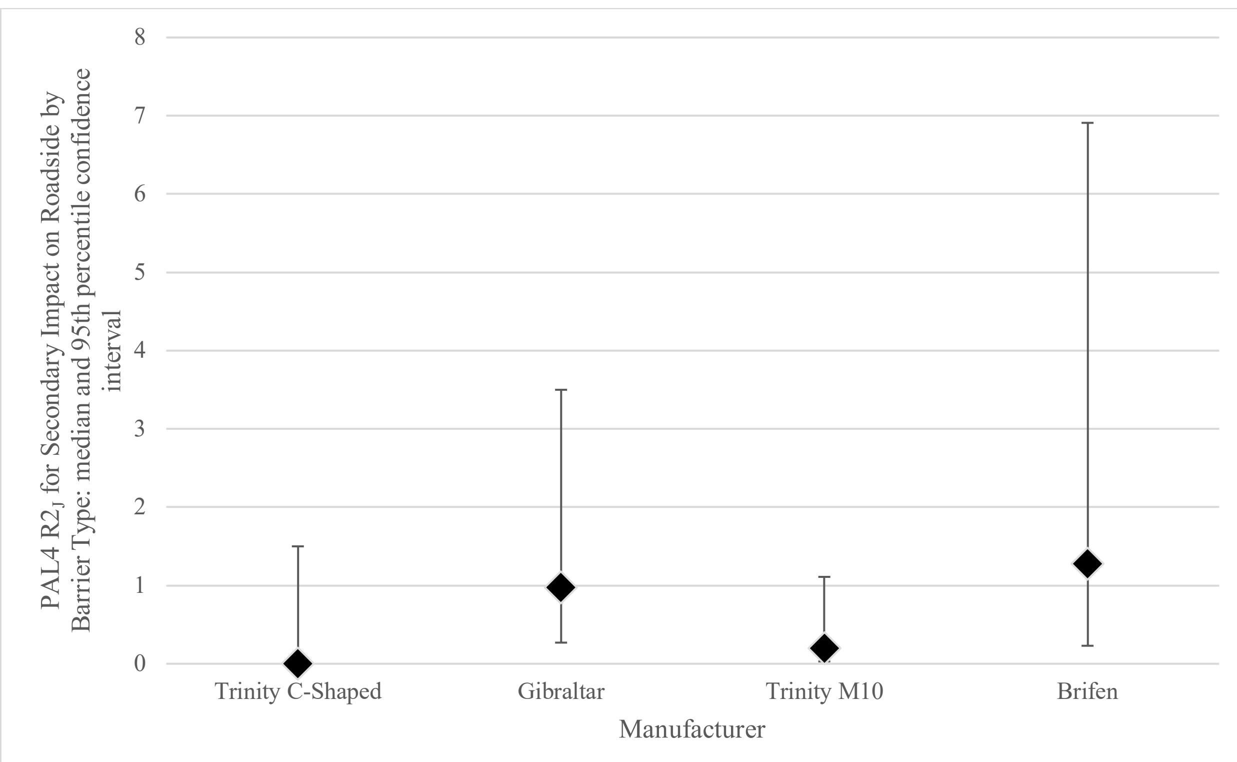
Table 20 shows the R2 values with confidence intervals for Evaluation Measure J (Secondary Impact on Roadside) for all Performance Assessment Levels (PALs) broken down by barrier type.

Table 20 - Performance Assessment for Secondary Impact on Roadside by Barrier Type: Mean values and 95th percentile confidence interval

Evaluation Criteria	Barrier Type	PAL1, $R2_J$	PAL2, $R2_J$	PAL3, $R2_J$	PAL4, $R2_J$
Evaluation J (Secondary Impact on Roadside)	Trinity C-Shaped (3 Strand)	0.19% 0.03% – 1.08%	0.2% 0.03% – 1.11%	0% 0% – 1.43%	0% 0% – 1.5%
	Gibraltar (4 Strand)	0.65% 0.22% – 1.9%	0.69% 0.23% – 2.01%	0.9% 0.25% – 3.24%	0.98% 0.27% – 3.5%
	Trinity M10 (4 Strand)	0.16% 0.03% – 0.91%	0.17% 0.03% – 0.94%	0.19% 0.03% – 1.08%	0.2% 0.03% – 1.11%
	Brifen (4 Strand)	1.1% 0.19% – 5.97%	1.12% 0.2% – 6.09%	1.27% 0.22% – 6.83%	1.28% 0.23% – 6.91%

Figure 7 shows the R2 values for Performance Assessment Level 4 (PAL4) from Table 20 plotted with confidence intervals.

Figure 7 - PAL4 $R2_J$ for Secondary Impact on Roadside by Barrier Type: Mean values and 95th percentile confidence interval



Discussion

Based on the analysis, the following are noted:

- There is no measurable difference in secondary impact on roadside between the types of cable barriers currently maintained by WSDOT according to the NCHRP 22-33 methodology as all confidence intervals overlap.
- There is no measurable difference in secondary impact on roadside between three strand (Trinity C-Shaped) and four strand (Gibraltar, Trinity M10, and Brifen) cable barriers. US High Tension was not evaluated because it represents only 0.2% of total installations by length.
- When a vehicle has a secondary impact on the roadside the likelihood for fatal and serious injury crashes are 35 times (ES_J) higher than when no secondary impact on roadside occurred (see Table 19). While this value is high, the percentage of reported crashes in this category is very low (less than 0.35%).
- In 0.35% of reported crashes a secondary impact occurred on the roadside after the vehicle impacted the cable barrier.

Secondary Impact on Road (Evaluation Measure K)

Secondary Impact on Road is intended to evaluate secondary (post-cable barrier) impacts with vehicles, pedestrians, and longitudinal barriers versus no secondary impact. Each of these crash types indicate the vehicle was redirected back onto the roadway. For this evaluation measure, multiple unit and single unit crashes are used.

Analysis

Computations were conducted to find the values of R2 and the associated 95th percentile confidence interval for Secondary Impact on Road (Evaluation Measure K). These computations are summarized by the Performance Outcome in Table 21 through Table 22 and charted in Figure 8.

Table 21 shows R2 values with confidence intervals for Evaluation Measure K (Secondary Impact on Road) for all performance assessment levels (PALs) and all barrier types. It also shows the effect size (ES).

Table 21 - Performance Assessment for Secondary Impact on Road by Level Across All Cable Barriers

Evaluation Criteria		**PAL1**	**PAL2**	**PAL3**	**PAL4**
Evaluation K (Secondary Impact on Road)	$R2_K$	6.24% 5.22% – 7.44%	6.34% 5.3% – 7.57%	5.66% 4.48% – 7.12%	5.81% 4.59% – 7.32%
	ES_K	6.01 1.91 – 18.87			

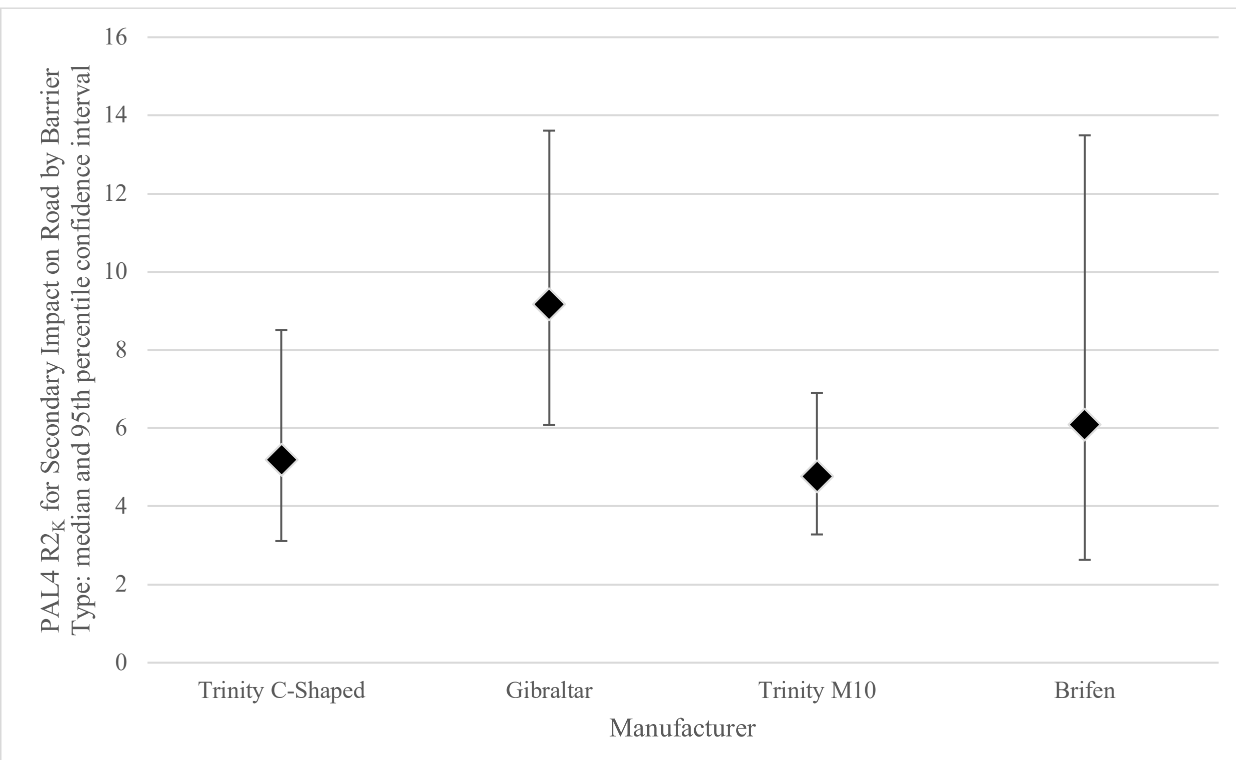
Table 22 shows the R2 values with confidence intervals for Evaluation Measure K (secondary impact on road) for all performance assessment levels (PALs) broken down by barrier type.

Table 22 - Performance Assessment for Secondary Impact on Road by Barrier Type: Mean values and 95th percentile confidence interval

Evaluation Criteria	Barrier Type	PAL1, $R2_K$	PAL2, $R2_K$	PAL3, $R2_K$	PAL4, $R2_K$
Evaluation K (Secondary Impact on Road)	Trinity C-Shaped (3 Strand)	6.94% 5.12% – 9.35%	6.95% 5.1% – 9.39%	5.3% 3.24% – 8.56%	5.19% 3.11% – 8.51%
	Gibraltar (4 Strand)	7.51% 5.52% – 10.14%	7.72% 5.66% – 10.47%	8.54% 5.65% – 12.7%	9.17% 6.08% – 13.61%
	Trinity M10 (4 Strand)	4.93% 3.53% – 6.85%	5.07% 3.63% – 7.03%	4.63% 3.18% – 6.69%	4.77% 3.28% – 6.9%
	Brifen (4 Strand)	5.26% 2.27% – 11.74%	5.38% 2.32% – 11.97%	6.02% 2.6% – 13.34%	6.1% 2.63% – 13.49%

Figure 8 shows the R2 values for Performance Assessment Level 4 (PAL4) from Table 22 plotted with confidence intervals.

Figure 8 - PAL4 $R2_K$ for Secondary Impact on Road by Barrier Type: Mean values and 95th percentile confidence interval



Discussion

Based on the analysis, the following are noted:

- There is no measurable difference in secondary impact on road between the types of cable barriers currently maintained by WSDOT according to the NCHRP 22-33 methodology as all confidence intervals overlap.
- There is no measurable difference in the individual performance of the three strand (Trinity C-Shaped) and four strand (Gibraltar, Trinity M10, and Brifen) cable barriers. US High Tension was not evaluated because it only represents 0.2% of total installations by length.
- When a vehicle has a secondary impact on the road the likelihood for fatal and serious injury crashes are six times (ES_K) higher than when no secondary impact on road occurred after impact with the cable barrier (see Table 21).
- In 6.2 percent of reported crashes secondary impacts took place with objects or other vehicles on the roadway after vehicles impacted cable barrier systems.

CONCLUSIONS

One of the key pieces of information used in this in-service performance evaluation, most harmful event, is derived from the sequence of events. During this derivation process assumptions are made about which event is most severe when there is more than one harmful event (see Table 7) and this directly influence analysis results. For the purposes of this ISPE, a rollover is assumed most severe; however, scenarios are possible where a crash with another vehicle is more severe than a rollover in the sequence of events. The only way to truly determine the most harmful event in complex (multi-harmful event) crashes would be a full crash reconstruction by highly trained personnel using detailed measurements of the scene and vehicle damage. This is not feasible for a statewide, multi-year ISPE. This is not only a limitation of the study data but also of the ISPE process in general since the determination of most harmful event relies on a degree of subjectivity.

Based on the analysis, the study team determined that:

- There is no measurable difference in performance between the different types of cable barrier maintained by WSDOT in the areas of:
    - Breach (Evaluation Measure A),
    - Rollover (Evaluation Measure F),
    - Vehicle Mix (Evaluation Measure H), and
    - Secondary Impacts (Evaluation Measures J and K).
- There is no measurable difference in performance between three and four cable barrier systems for these evaluation measures.
- The existing crash coding by the WSDOT Crash Data and Reporting Branch tracks the penetration of guardrail and concrete barriers but not for cable barriers. This greatly increased the manual effort related to the ISPE pilot.

Secondary Impact on Road (Evaluation Measure K) has the maximum Performance Assessment Level (PAL) among all Evaluation Criteria followed by Rollover (Evaluation Measure F) as shown in Table 23.

Table 23 - Maximum Performance Assessment Level (PAL) for Evaluation Criteria

Evaluation Criteria	PAL_{max}	Definition
Evaluation A (Breach)	2.27%	The percentage of all events where the cable barrier was breached.
Evaluation F (Rollover)	4.46%	The percentage of all events where rollover occurred post-impact with the cable barrier.
Evaluation H (Vehicle Mix)	0.87%	The percentage of all events where a fatal or serious injury occurred.
Evaluation J (Secondary Impact on Roadside)	0.38%	The percentage of all events where a secondary impact on the roadside (fixed object) occurred.
Evaluation K (Secondary Impact on Road)	6.34%	The percentage of cases where a secondary impact on the road (another vehicle, other barrier, or pedestrian) occurred.

While the effect size (ES_J value), or potential for fatal and suspected serious injury crashes involving a secondary impact on roadside after interacting with a safety feature was 35 times higher than when no secondary impact on roadside occurred, the occurrence of these events are rare, with PAL 4 R_2 value of 0.38%.

RECOMMENDATIONS

Based on the pilot ISPE for cable barriers on state highways under WSDOT jurisdiction, and findings presented in the previous chapters, the following recommendations are made for WSDOT to consider:

- WSDOT suspend conversion of three strand cable barrier to four strand cable barrier because there is no measurable difference between their performance based on the metrics used in this study.
- WSDOT continue to use the guidance and metrics defined by the NCHRP Project 22-33 project team and the available crash data for other in-service performance evaluation projects in the future, with the understanding that various opportunities for customization of the process by WSDOT exist.
- The Crash Data and Reporting Branch at WSDOT adds code to report on cable barrier penetration (over, under, or through) to the day-to-day crash coding.

REFERENCES

Carrigan, C. (2021). *Multi-State In-Service Performance Evaluations of Roadsafe Safety Hardware.* National Cooperative Highway Research Program No. 22-33.