Pilot In-Service Performance Evaluation of Impact Attenuators in Washington State

WA-RD 915.1

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by

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16. ABSTRACT:

A pilot routine in-service performance evaluation (ISPE) was undertaken for impact attenuators following the process outlined in NCHP 22-33. Controlled stop, 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 differences between the performance of the major types of impact attenuators in use on state highways within WSDOT jurisdiction.

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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 impact attenuators maintained by the Washington State Department of Transportation (WSDOT) utilizing the crash database for 2016 through 2020 in conjunction with the WSDOT collected impact attenuator 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 impact attenuator systems maintained by WSDOT under real-world field conditions. The ISPE used the following evaluation measures from NCHRP 22-33:

- Controlled penetration, redirection, or stop (Evaluation Measure C)
- 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 an impact attenuator crash test. For example, Controlled Penetration, Redirection, or Stop (Evaluation Measure C) evaluates if the impact attenuator is meeting the objective of bringing the vehicle to a controlled stop. Furthermore, defining these Evaluation Measures provide interoperability with data and results from other states. Other evaluation measures applicable to impact attenuators 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 controlled penetration, redirection, or stop (Evaluation Measure C) would be the rate of occurrence of the impact attenuator stopping the vehicle and preventing no further post-impact harmful events. 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 impact attenuators used by WSDOT. 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 impact attenuators evaluated individually along with inventory counts. The analysis itself only reports data for the system that was in place when the crash occurred.

Table 1 - Evaluated Impact Attenuator Types

Photograph	**Description**
	CAT 350 51 units or 6% of inventory A total of 14 crashes with this type occurred in 2016-2020, with no fatal and suspected serious injury crashes.
	Guardrail Energy Absorbing Terminal (GREAT) 151 units or 18% of inventory A total of 45 crashes with this type occurred in 2016-2020, with 3 fatal and suspected serious injury crashes (6.6%)
	Hex Foam Sandwich 35 units or 4% of inventory A total of 23 crashes with this type occurred in 2016-2020, with 1 fatal and suspected serious injury crashes (4.3%)

Photograph	Description
	Inertial Barrels 24 units or 3% of inventory A total of 14 crashes with this type occurred in 2016-2020, with no fatal and suspected serious injury crashes.
	QuadGuard (multiple variants) 243 units or 30% of inventory A total of 152 crashes with this type occurred in 2016-2020, with 2 fatal and suspected serious injury crashes (1.3%)
	REACT 350 136 units or 16% of inventory A total of 119 crashes with this type occurred in 2016-2020, with 4 fatal and suspected serious injury crashes (3.4%)
	SCI 100GM/70GM 29 units or 5% of inventory A total of 45 crashes with this type occurred in 2016-2020, with 1 fatal and suspected serious injury crashes (2.2%)

Photograph	Description
	Universal Tau-II 153 units or 18% of inventory A total of 114 crashes with this type occurred in 2016-2020, with 2 fatal and suspected serious injury crashes (1.75%)

Table 2 shows photographs of the different impact attenuators in use by WSDOT but not included in this ISPE due to their very small percentage of the total inventory. There is not enough crash data involving these devices to draw any meaningful conclusions about their performance.

Table 2 Excluded Impact Attenuator Types

Photograph	Description
	AIDEM 2 units or 0.2% of inventory No crashes with this type occurred in 2016-2020.
	BrakeMaster 350 3 units or 0.4% of inventory A total of 1 crash with this type occurred in 2016-2020, with no fatal and suspected serious injury crashes.

Photograph	
	NEAT 1 unit or 0.1% of inventory No crashes with this type occurred in 2016-2020.
	TRACC 2 units or 0.2% of inventory No crashes with this type occurred in 2016-2020.

Limitations

The main limitations of the study are related to the data and methodology as discussed in the following paragraph.

The WSDOT Crash Location & Analysis System (CLAS) contains the detailed type of first 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 object struck type was used to filter the dataset to only include crashes where impact attenuators were struck, and the sequence of events 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. 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 impact attenuator was struck first as only crashes where impact attenuators was the first 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 impact attenuator. 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 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 impact attenuator). This makes determination of Controlled Penetration, Redirection, or Stop (Evaluation Measure C) difficult as it is not known if the vehicle struck the impact attenuator head on, granting it the opportunity to stop the vehicle in a controlled manner as designed, or merely grazed it. Additionally, they 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 device 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 impact attenuator.

This in-service performance evaluation is the third of its kind in WA state and is 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 impact attenuator as the first object struck within the study timeframe. The crashes were then matched to impact attenuators that were within 250 feet of the crash location with a matching route number and direction of travel. Impact attenuator types and locations were determined using the impact attenuator inventory. If multiple impact attenuators were identified, the crash reports and impact attenuator inventory were manually reviewed to determine the correct device 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 the impact attenuator. In these cases, the crash report was reviewed and the harmful event data for that crash was determined manually.

The Driver Action fields were also used to determine if the impact attenuator brought the vehicle to a controlled stop (Evaluation Measure C). If there were no harmful driver actions after the crash with the impact attenuator, it was assumed that the device brought the vehicle to a stop as designed. However, it cannot be determined from the available data if the vehicle struck the impact attenuator head on, grazed it, or struck it at an angle it was not designed for. The results for Evaluation Measure C must be viewed with this fact in mind.

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 “2” for impact attenuators
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
SPEED_LIMIT	Speed limit	CLAS Database Posted Speed

Field Name	Definitions	Source
		If no value was found, the crash location was matched to speed limit GIS layer spatially. The speed limit for ramps (which are not defined) was set to 50mph so devices at these locations would not be disproportionally excluded from the PAL_3 and PAL_4 results.
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 crashes with impact attenuators.
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	Not applicable for impact attenuators.
BREAK	Predictable breakaway	Not applicable for impact attenuators.
PRC	Controlled penetration, redirection, or stop	If there is no post-harmful event, it was assumed that the impact attenuator brought the vehicle to a controlled stop.
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 Impact Attenuator Type Determined by the 250-foot spatial join between the crashes and impact attenuator inventory. 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 impact attenuators are inspected on installation.
MAINT	Maintenance Inspection	Always false; the maintenance records for impact attenuators were not extracted.

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	WSDOT Engineering 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

Vehicle Type	WSDOT Engineering Crash Data Mart Values
	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 impact attenuator. 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 impact attenuator. 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.
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 impact attenuator is the most harmful event (MHE); impact attenuator 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 impact attenuator type to the single-character NAME codes used in the NCHRP 22-33 spreadsheet.

Table 8 NAME Equivalence

NAME	Impact Attenuator Type
A	ABSORB 350 TL-2, TL-3
B	ADIEM
D	BrakeMaster 350
E	CAT 350
F	Guard Rail Energy Absorption Terminal
G	Hex Foam Sandwich
H	Inertial Barriers
I	N-E-A-T
J	QuadGuard
K	REACT 350
L	SCI 100GM, 70GM
M	TRACC
N	Universal Tau-II
O	Wide REACT 350

ANALYSIS AND FINDINGS

Introduction

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

- Controlled penetration, redirection, or stop (Evaluation Measure C)
- 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 impact attenuators corresponding to the NCHRP 350 Test Level 3 crash test impact conditions for which the impact attenuator 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 impact attenuators are listed in Table 9.

Table 9 - Unexpected Events for Evaluation Measures

Evaluation Measure	Unexpected Event	Data Source
C – Controlled Penetration, Redirection, or Stop	The vehicle did not come to a controlled stop after impact with the impact attenuator.	The PRC (penetration, redirection, or stop) field where the value is NONE. See Table 3.
F – Rollover	The vehicle rolled over after impact with the impact attenuator.	The PostHE (post-harmful event) field where the value is RFS (rollover field side), RSS (rollover same side), or ROLL (rollover). See Table 3and Table 7.
H – Vehicle Mix	A fatal or serious injury occurred after impact with the impact attenuator.	The MAX_SEV (maximum crash severity) field where the value is K (fatal) or A (serious). See Table 3and 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 impact attenuator.	The PostHE (post-harmful event) field where the value is FO (fixed object) or BA (breakaway object). See Table 3and Table 7.
K – Secondary Impact on Road	The vehicle struck another barrier, vehicle, or pedestrian after impact with the impact attenuator.	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 C as an example, if there are 100 crashes where the vehicle came to a controlled stop (PRC value is CNTL) and 20 crashes where the vehicle did not (PRC value is NONE). 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

The results indicate that the vehicle did not come to a controlled stop 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 is more likely when the unexpected event occurs than when the event is expected. Continuing the previous example for Evaluation Measure C, 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

From equation 2, a fatal or serious injury is crash 2.5 times more likely to result if an unexpected outcome occurs. Or a fatal or serious injury crash is 2.5 times less likely if the impact attenuator performs as expected. An ES of one indicates that there is no difference in the severity outcomes whether the terminal perform as expected or when there is unexpected vehicle behavior during or after the impact with the terminal.

R2 is a measure of how frequently the impact attenuator 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 terminal.

Effect Size is not presented per device type as it is for R2 in this report. The team assessed the effect size for each device 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 impact attenuator type. The chart graphically presents the PAL 4 values for each impact attenuator type from the second table with bars for the confidence interval. According to the NCHRP 22-33 methodology, the performance of two different impact attenuator 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 terminal type in the five-year study period. Zero R2 values will also result in identical confidence intervals for the same terminal types across multiple evaluation measures because the calculation is based solely on the total number of crashes for that guardrail end type.

Controlled Penetration, Redirection, or Stop (Evaluation Measure C)

Controlled Penetration, Redirection, or Stop assesses the probability that the impact attenuator will bring a vehicle to a controlled stop. 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 Controlled Penetration, Redirection, or Stop (Evaluation Measure C). 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 C (Controlled Penetration, Redirection, or Stop) for all Performance Assessment Levels (PALs) and all impact attenuator types. It also shows the effect size (ES).

Table 10 Performance Assessment for Controlled Penetration, Redirection, or Stop by Level Across All Impact Attenuator Types: Mean values and 95th percentile confidence interval

Evaluation Criteria		**PAL1**	**PAL2** Evaluates the performance of the IA limited by the vehicle types it was design and evaluated for in the crash tests	**PAL3** Evaluates the performance of the IA limited to conditions where posted speed limit ≤ 65	**PAL4** Evaluates the performance of the IA limited to vehicle type and speed designed and tested for
Evaluation C (Controlled Penetration, Redirection, or Stop)	$R2_C$	27.41% 23.52% - 31.68%	27.92% 23.92% - 32.3%	27.78% 23.84% - 32.09%	28.24% 24.2% - 32.66%
	ES_C	3.97 0.67 – 23.49			

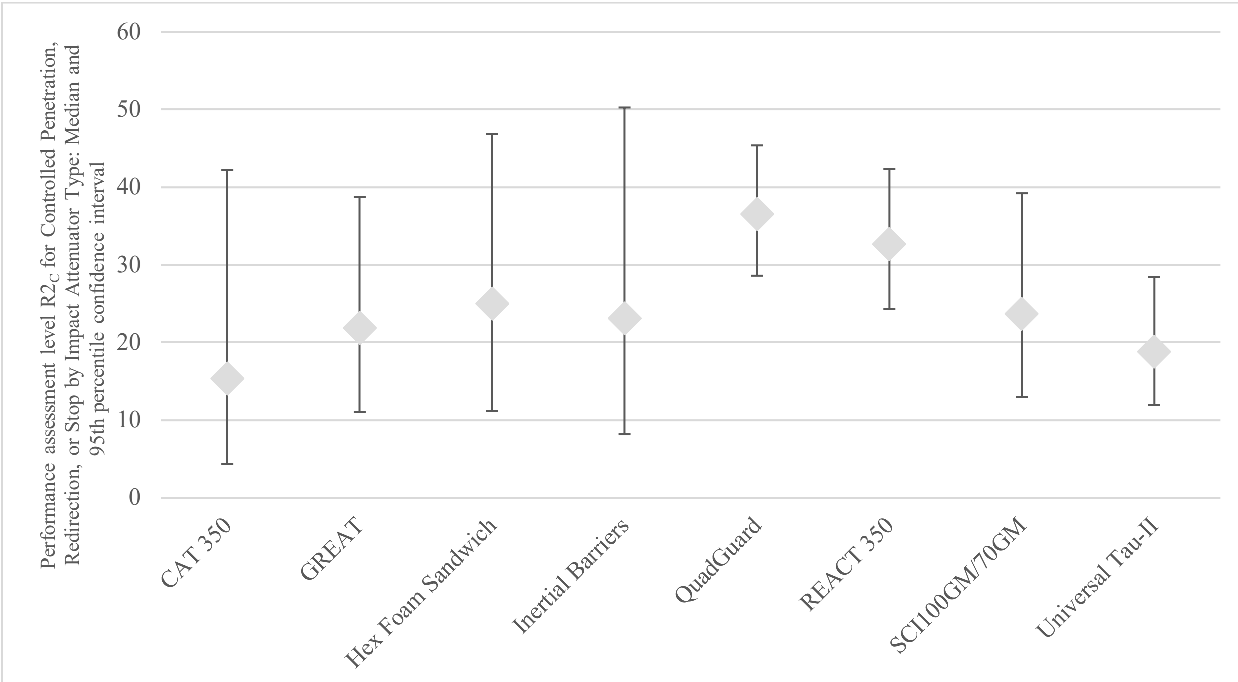
Table 11 shows the R2 values with confidence intervals at the 95-percentile confidence for Evaluation Measure C (Controlled Penetration, Redirection, or Stop) for all Performance Assessment Levels (PALs) broken down by impact attenuator type.

Table 11 Performance Assessment for Controlled Penetration, Redirection, or Stop by Impact Attenuator Type: Mean values and 95th percentile confidence interval

Evaluation Criteria	**IA Type**	**PAL1, $R2_C$**	**PAL2, $R2_C$**	**PAL3, $R2_C$**	**PAL4, $R2_C$**
Evaluation C (Controlled Penetration, Redirection, or Stop)	CAT 350	15.38% 4.33% - 42.24%	15.38% 4.33% - 42.24%	15.38% 4.33% - 42.24%	15.38% 4.33% - 42.24%
	GREAT	20.59% 10.35% – 36.8%	21.21% 10.68% – 37.75%	21.21% 10.68% – 37.75%	21.88% 11.02% – 38.76%
	Hex Foam Sandwich	23.81% 10.63% – 45.09%	25.0% 11.19% – 46.87%	23.81% 10.63% – 45.09%	25.0% 11.19% – 46.87%
	Inertial Barriers	21.43% 7.57% – 47.59%	23.08% 8.18% – 50.26%	21.43% 7.57% – 47.59%	23.08% 8.18% – 50.26%
	QuadGuard	35.11% 27.47% – 43.61%	36.59% 28.6% – 45.38%	35.11% 27.47% – 43.61%	36.59% 28.6% – 45.38%
	REACT 350	32.69% 24.43% – 42.18%	32.67% 24.31% – 42.31%	32.69% 24.43% – 42.18%	32.67% 24.31% – 42.31%
	SCI 100GM / 70GM	25.64% 14.57% – 41.08%	23.68% 12.99% – 39.21%	25.64% 14.57% – 41.08%	23.68% 12.99% – 39.21%
	Universal Tau-II	17.2% 10.88% – 26.13%	17.98% 11.38% – 27.23%	18.18% 11.51% – 27.51%	18.82% 11.93% – 28.41%

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 Controlled Penetration, Redirection, or Stop by Impact Attenuator Type: Mean values and 95th percentile confidence interval



Discussion

- There is no measurable difference in Controlled Penetration, Redirection, or Stop between the impact attenuators currently maintained by WSDOT according to the NCHRP 22-33 methodology as all confidence intervals overlap. The one exception is Universal Tau-II is outperforming the QuadGuard family of impact attenuators.
- When a vehicle fails to come to a controlled stop the likelihood for fatal and serious injury crashes are four times (ES_C) higher than when a controlled stop occurred (see Table 10).
- Controlled stop failure occurred in 38% of the reported crashes. However, it is not possible to determine how forcefully a vehicle struck an impact attenuator from the available data. In many of these cases, the vehicle may have grazed the impact attenuator or otherwise not made full contact, bypassing the opportunity for a controlled stop as designed.

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 impact attenuator types. It also shows the effect size (ES).

Table 12 Performance Assessment for Rollover by Level Across All Impact Attenuator Types: Mean values and 95th percentile confidence interval

Evaluation Criteria		PAL1	PAL2	PAL3	PAL4
Evaluation F (Rollover)	$R2_F$	6.78% 4.56% – 9.97%	7.1% 4.78% – 10.43%	6.91% 4.65% – 10.15%	7.21% 4.85% – 10.59%
	ES_F	13.73 2.03 – 93.13			

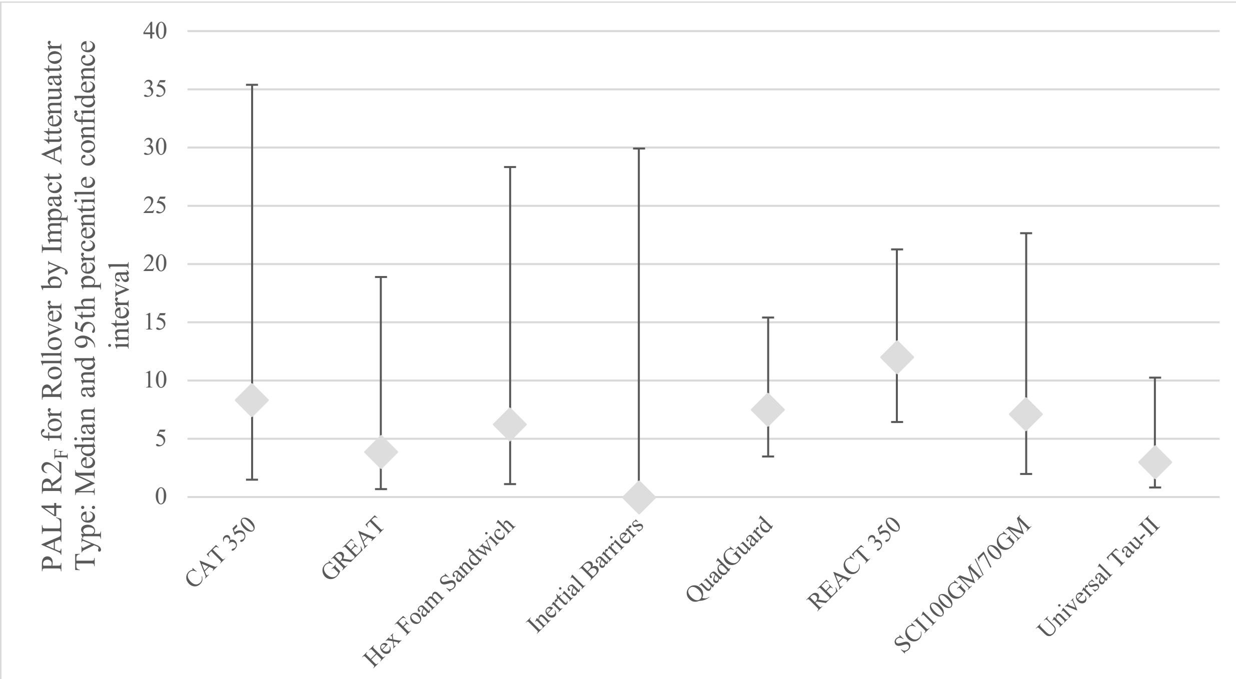
Table 13 shows the R2 values with confidence intervals for Evaluation Measure F (Rollover) for all Performance Assessment Levels (PALs) broken down by impact attenuator type.

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

Evaluation Criteria	IA Type	PAL1, $R2_F$	PAL2, $R2_F$	PAL3, $R2_F$	PAL4, $R2_F$
Evaluation F (Rollover)	CAT 350	8.33% 1.49% – 35.39%	8.33% 1.49% – 35.39%	8.33% 1.49% – 35.39%	8.33% 1.49% – 35.39%
	GREAT	3.57% 0.63% – 17.71%	3.7% 0.66% – 18.28%	3.7% 0.66% – 18.28%	3.85% 0.68% – 18.89%
	Hex Foam Sandwich	5.88% 1.05% – 26.98%	6.25% 1.11% – 28.33%	5.88% 1.05% – 26.98%	6.25% 1.11% – 28.33%
	Inertial Barriers	0% 0% – 27.75%	0% 0% – 29.92%	0% 0% – 27.75%	0% 0% – 29.92%
	QuadGuard	6.9% 3.2% – 14.24%	7.5% 3.48% – 15.41%	6.9% 3.2% – 14.24%	7.5% 3.48% – 15.41%
	REACT 350	11.84% 6.36% – 21.0%	12.0% 6.44% – 21.26%	11.84% 6.36% – 21.0%	12.0% 6.44% – 21.26%
	SCI 100GM/70GM	7.14% 1.98% – 22.65%	7.14% 1.98% – 22.65%	7.14% 1.98% – 22.65%	7.14% 1.98% – 22.65%
	Universal Tau-II	2.67% 0.73% – 9.21%	2.82% 0.78% – 9.7%	2.86% 0.79% – 9.83%	2.99% 0.82% – 10.25%

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 Impact Attenuator 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 impact attenuators currently maintained by WSDOT according to the NCHRP 22-33 methodology as all confidence intervals overlap.
- When a vehicle rolls over after engaging the impact attenuator the likelihood for a fatal and serious injury crash is 14 times (ES_F) higher than when no rollover occurred (see Table 12).
- Rollover occurred in 7% of the 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.

Because the R2 value for Vehicle Mix is based on fatal or serious injury crashes as the unexpected event, ES is not calculated. Referring to Equation 2, the number of fatal or serious injury crashes for the expected event would always be zero, which would result in division by zero.

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	1.2% 0.53% – 2.86%	1.03% 0.4% – 2.61%	1.26% 0.54% – 2.91%	1.01% 0.39% – 2.57%
	First Harmful Event	1.23% 0.52% – 2.84%	1.03% 0.4% – 2.61%	1.24% 0.53% – 2.88%	1.04% 0.4% – 2.64%
	Most Harmful Event	0.53% 0.14% – 2.5%	0.28% 0.05% – 1.55%	0.53% 0.15% – 1.93%	0.28% 0.05% – 1.57%
	First and Only Harmful Event	0.63% 0.17% – 2.28%	0.33% 0.06% – 1.86%	0.65% 0.18% – 2.32%	0.34% 0.06% – 1.89%

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 impact attenuator type.

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

Evaluation Criteria	IA Type	PAL1, $R2_H$	PAL2, $R2_H$	PAL3, $R2_H$	PAL4, $R2_H$
Evaluation H (Vehicle Mix) Any Harmful Event	CAT 350	0% 0% – 24.25%	0% 0% – 24.25%	0% 0% – 24.25%	0% 0% – 24.25%
	GREAT	3.13% 0.55% – 15.74%	0% 0% – 11.03%	3.23% 0.57% – 16.19%	0% 0% – 11.35%
	Hex Foam Sandwich	0% 0% – 16.11%	0% 0% – 16.82%	0% 0% – 16.11%	0% 0% – 16.82%
	Inertial Barriers	0% 0% – 22.81%	0% 0% – 24.25%	0% 0% – 22.81%	0% 0% – 24.25%
	QuadGuard	0.85% 0.15% – 4.64%	0.91% 0.16% – 4.97%	0.85% 0.15% – 4.64%	0.91% 0.16% – 4.97%
	REACT 350	2.22% 0.61% – 7.74%	2.27% 0.63% – 7.91%	2.22% 0.61% – 7.74%	2.27% 0.63% – 7.91%
	SCI 100GM/70GM	3.13% 0.55% – 15.74%	3.23% 0.57% – 16.19%	3.13% 0.55% – 15.74%	3.23% 0.57% – 16.19%
	Universal Tau-II	0% 0% – 4.37%	0% 0% – 4.58%	0% 0% – 4.64%	0% 0% – 4.81%

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 Impact Attenuator Type: Mean values and 95th percentile confidence interval

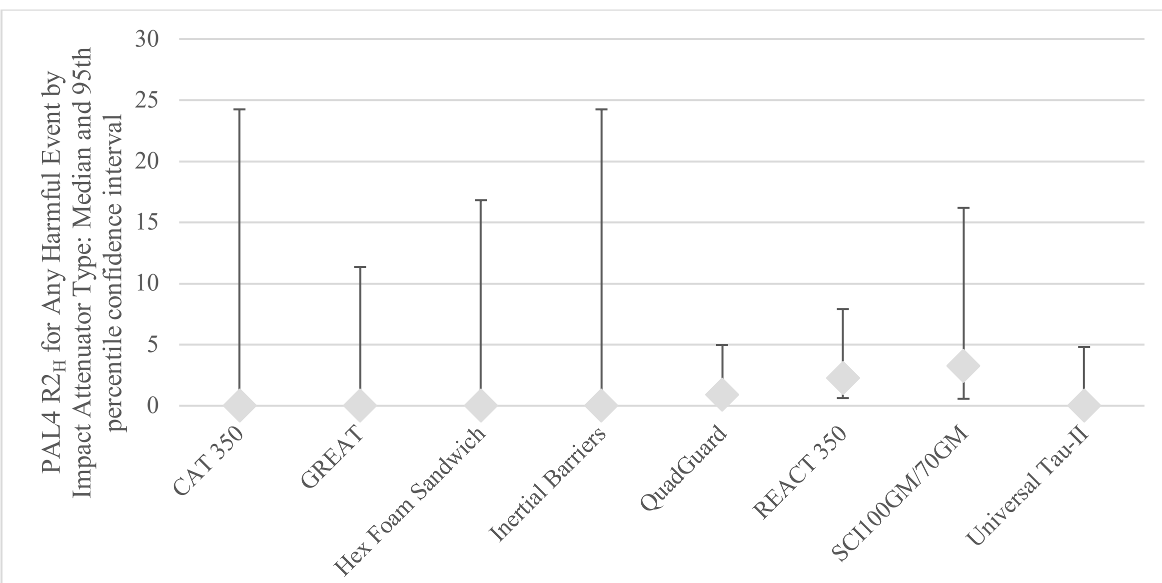


Table 16 shows the R2 values with confidence intervals for Evaluation Measure H (Vehicle Mix) for First Harmful Event and all Performance Assessment Levels (PALs), broken down by impact attenuator type.

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

Evaluation Criteria	IA Type	PAL1, $R2_H$	PAL2, $R2_H$	PAL3, $R2_H$	PAL4, $R2_H$
Evaluation H (Vehicle Mix) First Harmful Event	CAT 350	0% 0% – 24.25%	0% 0% – 24.25%	0% 0% – 24.25%	0% 0% – 24.25%
	GREAT	3.13% 0.55% – 15.74%	0% 0% – 11.03%	3.23% 0.57% – 16.19%	0% 0% – 11.35%
	Hex Foam Sandwich	0% 0% – 16.11%	0% 0% – 16.82%	0% 0% – 16.11%	0% 0% – 16.82%
	Inertial Barriers	0% 0% – 22.81%	0% 0% – 24.25%	0% 0% – 22.81%	0% 0% – 24.25%
	QuadGuard	0.85% 0.15% – 4.64%	0.91% 0.16% – 4.97%	0.85% 0.15% – 4.64%	0.91% 0.16% – 4.97%
	REACT 350	2.22% 0.61% – 7.74%	2.27% 0.63% – 7.91%	2.22% 0.61% – 7.74%	2.27% 0.63% – 7.91%
	SCI 100GM/70GM	3.13% 0.55% – 15.74%	3.23% 0.57% – 16.19%	3.13% 0.55% – 15.74%	3.23% 0.57% – 16.19%
	Universal Tau-II	0% 0% – 4.37%	0% 0% – 4.58%	0% 0% – 4.64%	0% 0% – 4.81%

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 Impact Attenuator Type: Mean values and 95th percentile confidence interval

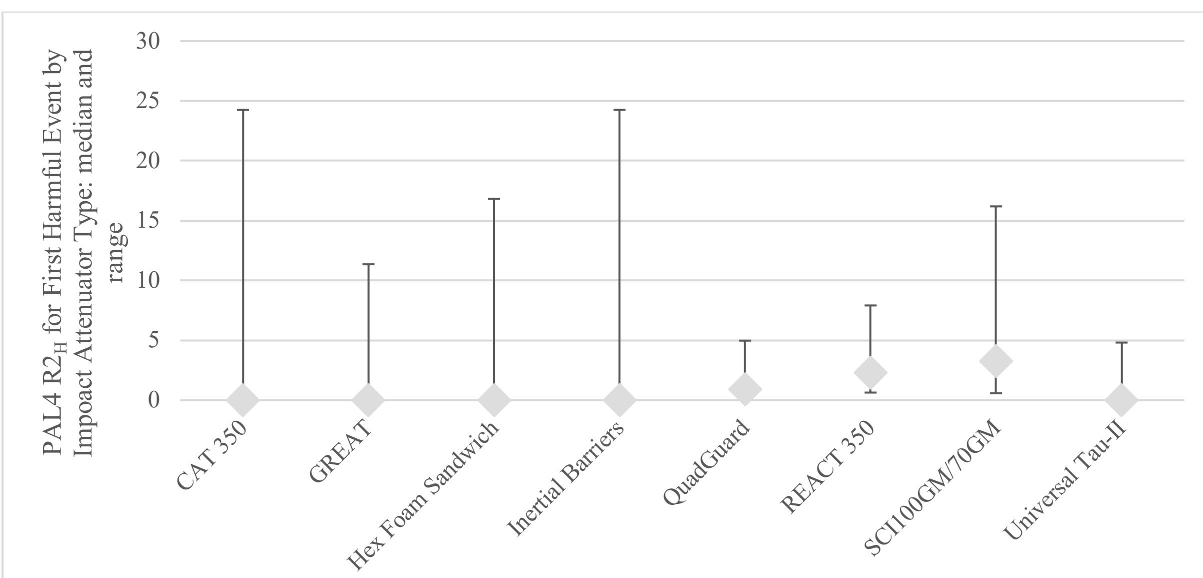


Table 17 shows the R2 values with confidence intervals for Evaluation Measure H (Vehicle Mix) for Most Harmful Event and all Performance Assessment Levels (PALs), broken down by impact attenuator type.

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

Evaluation Criteria	IA Type	PAL1, R2H	PAL2, R2H	PAL3, R2H	PAL4, R2H
Evaluation H (Vehicle Mix) Most Harmful Event	CAT 350	0% 0% – 25.88%	0% 0% – 25.88%	0% 0% – 25.88%	0% 0% – 25.88%
	GREAT	3.23% 0.57% – 16.19%	0% 0% – 11.35%	3.33% 0.59% – 16.82%	0% 0% – 11.7%
	Hex Foam Sandwich	0% 0% – 16.82%	0% 0% – 17.59%	0% 0% – 16.82%	0% 0% – 17.59%
	Inertial Barriers	0% 0% – 24.25%	0% 0% – 25.88%	0% 0% – 24.25%	0% 0% – 25.88%
	QuadGuard	0% 0% – 3.37%	0% 0% – 3.63%	0% 0% – 3.37%	0% 0% – 3.63%
	REACT 350	0% 0% – 4.64%	0% 0% – 4.75%	0% 0% – 4.64%	0% 0% – 4.75%
	SCI 100GM/70GM	3.33% 0.59% – 16.67%	3.45% 0.61% – 17.18%	3.33% 0.59% – 16.67%	3.45% 0.61% – 17.18%
	Universal Tau-II	0% 0% – 4.48%	0% 0% – 4.69%	0% 0% – 4.75%	0% 0% – 4.94%

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 Impact Attenuator Type: Mean values and 95th percentile confidence interval

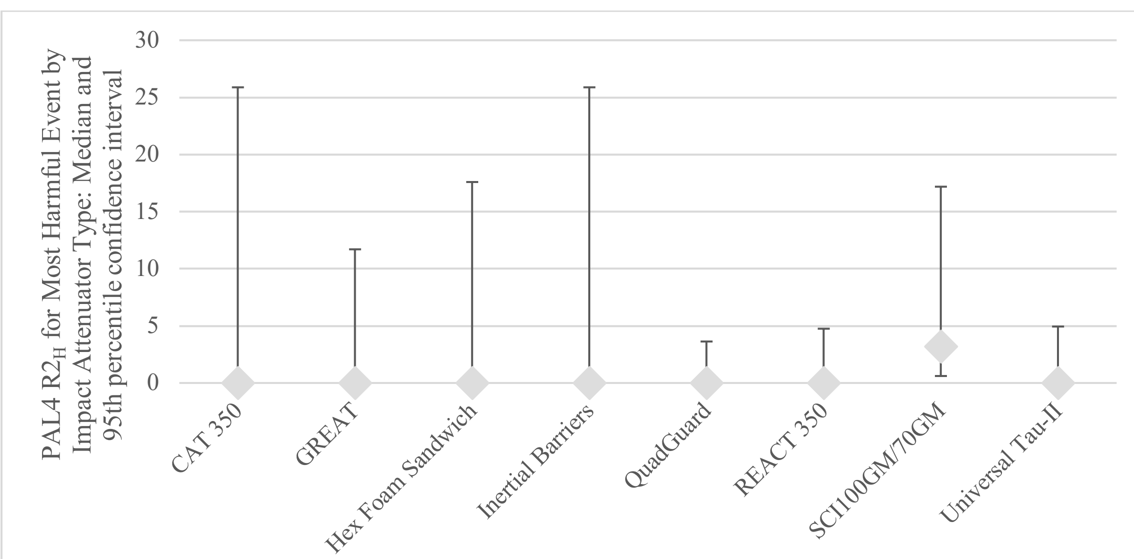


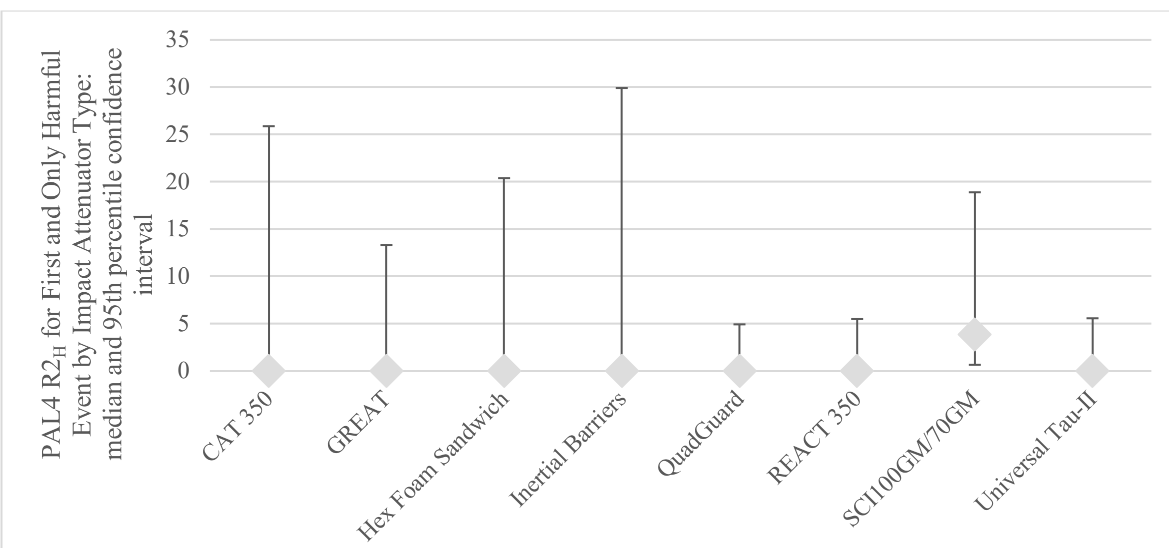
Table 18 shows the R2 values with confidence intervals for Evaluation Measure H (Vehicle Mix) for First and Only Harmful Event and all Performance Assessment Levels (PALs), broken down by impact attenuator type.

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

Evaluation Criteria	IA Type	PAL1, $R2_H$	PAL2, $R2_H$	PAL3, $R2_H$	PAL4, $R2_H$
Evaluation H (Vehicle Mix) First and Only Harmful Event	CAT 350	0% 0% – 25.88%	0% 0% – 25.88%	0% 0% – 25.88%	0% 0% – 25.88%
	GREAT	3.7% 0.66% – 18.28%	0% 0% – 12.87%	3.85% 0.68% – 18.89%	0% 0% – 13.32%
	Hex Foam Sandwich	0% 0% – 19.36%	0% 0% – 20.39%	0% 0% – 19.36%	0% 0% – 20.39%
	Inertial Barriers	0% 0% – 27.75%	0% 0% – 29.92%	0% 0% – 27.75%	0% 0% – 29.92%
	QuadGuard	0% 0% – 4.53%	0% 0% – 4.94%	0% 0% – 4.53%	0% 0% – 4.94%
	REACT 350	0% 0% – 5.42%	0% 0% – 5.5%	0% 0% – 5.42%	0% 0% – 5.5%
	SCI 100GM/70GM	3.85% 0.68% – 18.89%	3.85% 0.68% – 18.89%	3.85% 0.68% – 18.89%	3.85% 0.68% – 18.89%
	Universal Tau-II	0% 0% – 5.0%	0% 0% – 5.27%	0% 0% – 5.35%	0% 0% – 5.58%

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 Impact Attenuator 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 impact attenuators currently maintained by WSDOT according to the NCHRP 22-33 methodology as all confidence intervals overlap.
- Fatal and serious injury outcomes occurred in one percent of reported crashes.

Secondary Impact on Roadside (Evaluation Measure J)

Secondary Impact on Roadside is intended to evaluate secondary (post-impact attenuator) impacts with fixed objects versus no secondary impact. For this evaluation only single unit crashes where striking the impact attenuator is the first harmful event are used. Impacts with 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 impact attenuator types. It also shows the Effect Size (ES).

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

Evaluation Criteria		PAL1	PAL2	PAL3	PAL4
Evaluation J (Secondary Impact on Roadside)	$R2_J$	4.24% 2.54% – 6.99%	4.14% 2.44% – 6.95%	4.32% 2.59% – 7.12%	4.21% 2.47% – 7.06%
	ES_J	0			

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 impact attenuator type.

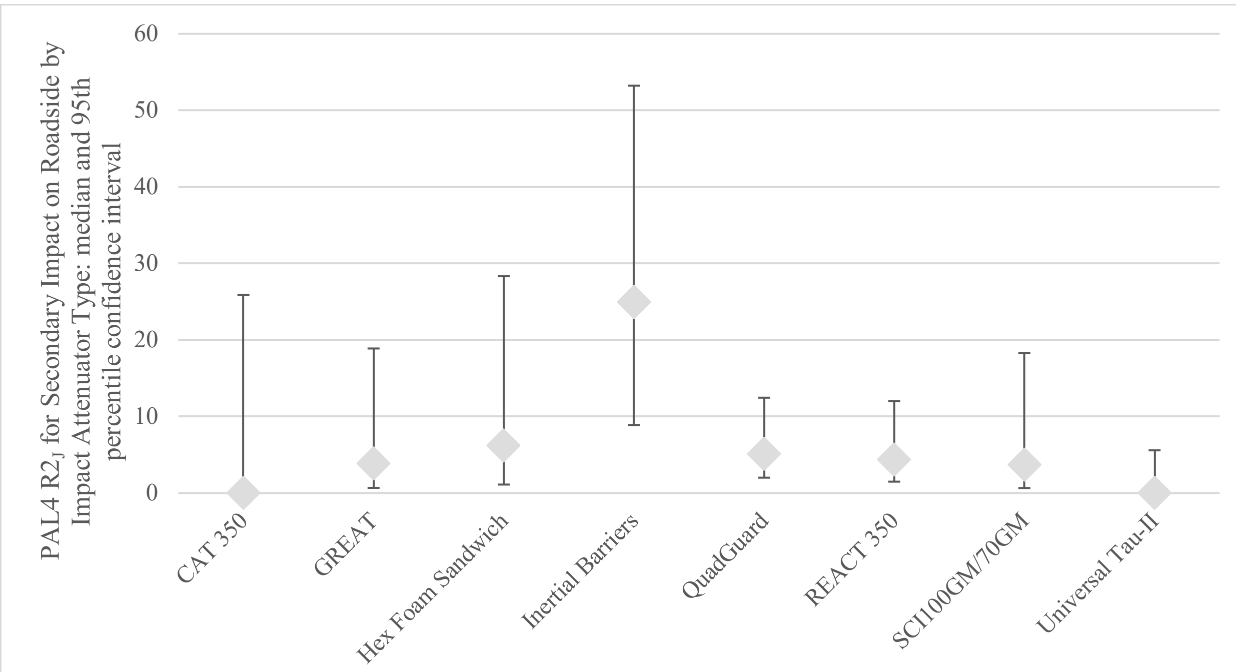
Table 20 Performance Assessment for Secondary Impact on Roadside by Impact Attenuator Type: Mean values and 95th percentile confidence interval

Evaluation Criteria	IA Type	PAL1, $R2_J$	PAL2, $R2_J$	PAL3, $R2_J$	PAL4, $R2_J$
Evaluation J (Secondary Impact on Roadside)	CAT 350	0% 0% – 25.88%	0% 0% – 25.88%	0% 0% – 25.88%	0% 0% – 25.88%
	GREAT	3.57% 0.63% – 17.71%	3.7% 0.66% – 18.28%	3.7% 0.66% – 18.28%	3.85% 0.68% – 18.89%
	Hex Foam Sandwich	5.88% 1.05% – 26.98%	6.25% 1.11% – 28.33%	5.88% 1.05% – 26.98%	6.25% 1.11% – 28.33%
	Inertial Barriers	23.08% 8.18% – 50.26%	25.0% 8.89% – 53.23%	23.08% 8.18% – 50.26%	25.0% 8.89% – 53.23%
	QuadGuard	4.71% 1.84% – 11.48%	5.13% 2.01% – 12.46%	4.71% 1.84% – 11.48%	5.13% 2.01% – 12.46%

Evaluation Criteria	IA Type	PAL1, $R2_J$	PAL2, $R2_J$	PAL3, $R2_J$	PAL4, $R2_J$
	REACT 350	4.29% 1.47% – 11.86%	4.35% 1.49% – 12.02%	4.29% 1.47% – 11.86%	4.35% 1.49% – 12.02%
	SCI 100GM/70GM	7.14% 1.98% – 22.65%	3.7% 0.66% – 18.28%	7.14% 1.98% – 22.65%	3.7% 0.66% – 18.28%
	Universal Tau-II	0% 0% – 5.0%	0% 0% – 5.27%	0% 0% – 5.35%	0% 0% – 5.58%

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 Impact Attenuator 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 impact attenuators currently maintained by WSDOT according to the NCHRP 22-33 methodology as all confidence intervals overlap.
- When a secondary impact on roadside occurs the likelihood for fatal and serious injury crashes are no higher (ES_J) higher than when no secondary impact occurred as the effect size is zero (see Table 19).
- Secondary impact on roadside occurred in 4% of the reported crashes.

Secondary Impact on Road (Evaluation Measure K)

Secondary Impact on Road is intended to evaluate secondary (post-impact attenuator) 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 impact attenuator types. It also shows the effect size (ES).

Table 21 Performance Assessment for Secondary Impact on Road by Level Across All Impact Attenuator Types

Evaluation Criteria		PAL1	PAL2	PAL3	PAL4
Evaluation K (Secondary Impact on Road)	$R2_K$	20.67% 17.06% – 24.82%	21.11% 17.38% – 25.38%	20.98% 17.31% – 25.18%	21.37% 17.61% – 25.69%
	ES_K	1.92 0.17 – 20.91			

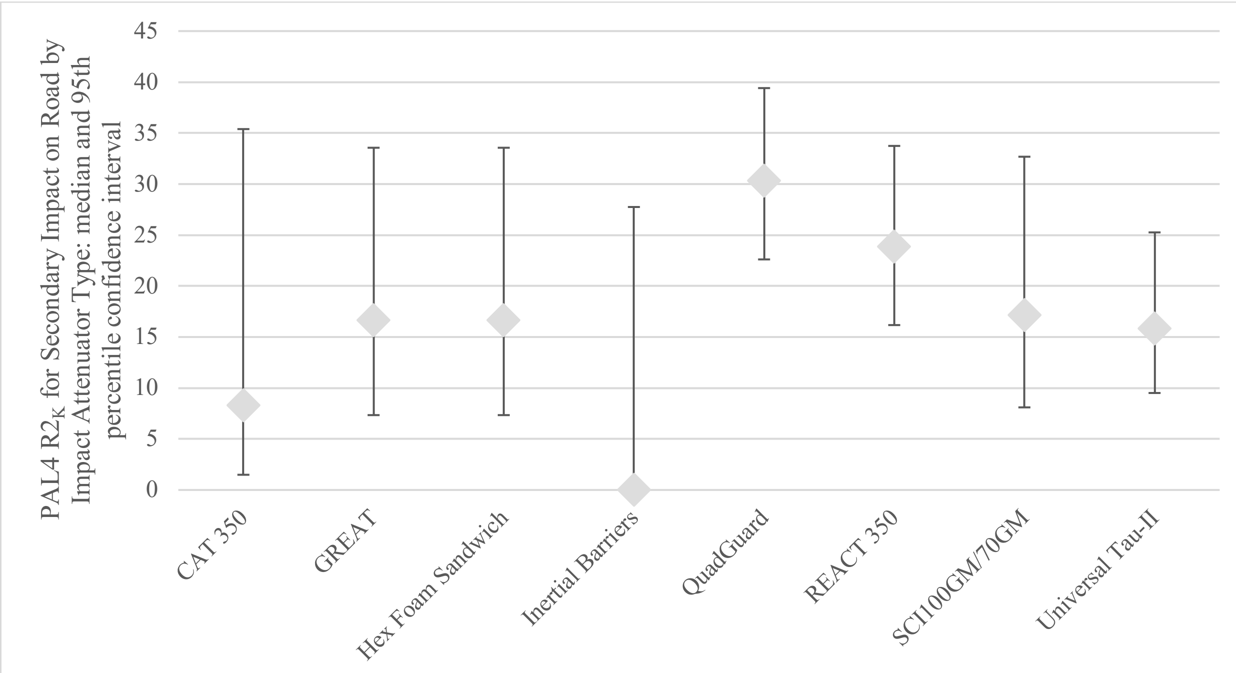
Table 22 shows the R2 values with confidence intervals for Evaluation Measure K (secondary impact on road) for all performance assessment levels (PALs) broken down by impact attenuator type.

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

Evaluation Criteria	IA Type	PAL1, $R2_K$	PAL2, $R2_K$	PAL3, $R2_K$	PAL4, $R2_K$
Evaluation K (Secondary Impact on Road)	CAT 350	8.33% 1.49% – 35.39%	8.33% 1.49% – 35.39%	8.33% 1.49% – 35.39%	8.33% 1.49% – 35.39%
	GREAT	15.63% 6.86% – 31.75%	16.13% 7.09% – 32.63%	16.13% 7.09% – 32.63%	16.67% 7.34% – 33.56%
	Hex Foam Sandwich	15.79% 5.52% – 37.57%	16.67% 5.84% – 29.22%	15.79% 5.52% – 37.57%	16.67% 5.84% – 39.22%
	Inertial Barriers	0% 0% – 25.88%	0% 0% – 27.75%	0% 0% – 25.88%	0% 0% – 27.75%
	QuadGuard	29.17% 21.78% – 37.84%	30.36% 22.61% – 39.41%	29.17% 21.78% – 37.84%	30.36% 22.61% – 39.41%
	REACT 350	24.18% 16.54% – 33.9%	23.86% 16.17% – 33.74%	24.18% 16.54% – 33.9%	23.86% 16.17% – 33.74%
	SCI 100GM/70GM	17.14% 8.1% – 32.68%	17.14% 8.1% – 32.68%	17.14% 8.1% – 32.68%	17.14% 8.1% – 32.68%
	Universal Tau-II	14.44% 8.64% – 23.16%	15.12% 9.05% – 24.16%	15.29% 9.16% – 24.43%	15.85% 9.51% – 25.56%

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 Impact Attenuator Type: Mean values and 95^th^ 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 impact attenuators currently maintained by WSDOT according to the NCHRP 22-33 methodology as all confidence intervals overlap.
- When a secondary impact on roadside occurs the likelihood for fatal and serious injury crashes are two times (ES_K) higher than when no secondary impact occurred (see Table 21).
- Secondary impact on road occurred in 21% of the reported crashes.

CONCLUSIONS AND RECOMMENDATIONS

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 the differences in performance between the different types of impact attenuators maintained by WSDOT are not measurably different in the areas of:

- Controlled Penetration, Redirection, or Stop (Evaluation Measure C),
- Rollover (Evaluation Measure F),
- Vehicle Mix (Evaluation Measure H), and
- Secondary Impacts (Evaluation Measures J and K).

Controlled Penetration, Redirection, or Stop (Evaluation Measure C) has the maximum Performance Assessment Level (PAL) among all Evaluation Criteria followed by Secondary Impact on Roadside (Evaluation Measure J) as shown in Table 23.

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

Evaluation Criteria	PAL_{max}	Definition
Evaluation C (Controlled Penetration, Redirection, or Stop)	28.24%	The percentage of all events where there was a harmful event after the impact attenuator was struck.
Evaluation F (Rollover)	7.21%	The percentage of all events where rollover occurred post-impact with the impact attenuator.
Evaluation H (Vehicle Mix)	1.24%	The percentage of all events where a fatal or serious injury occurred.
Evaluation J (Secondary Impact on Roadside)	4.32%	The percentage of all events where a secondary impact on the roadside (fixed object) occurred.
Evaluation K (Secondary Impact on Road)	21.37%	The percentage of cases where a secondary impact on the road (other vehicle, other barrier, or pedestrian) occurred.

The available data do not contain information about the impact orientation (the acute angle between the vehicle trajectory on impact and the impact attenuator). This makes determination of Controlled Penetration, Redirection, or Stop difficult as it is not known if the vehicle struck the impact attenuator head on, granting it the opportunity to stop the vehicle in a controlled manner as designed, or merely grazed it. The methodology assumes that the impact attenuator is engaged with the barrier during all crashes with the barrier: this can overinflate the results for Evaluation Measure C.

Additionally, the available data do not contain information about the type of object struck on the roadside. If a vehicle struck an impact attenuator and then a relatively harmless object such as a fence, the crash was coded as FO (Fixed Object). It is the opinion of the study team that this assumption can also artificially inflate values for Evaluation Measure J.

Because there are no measurable differences in the performance between the different types of impact attenuators maintained by WSDOT, no specific recommendations are offered.

REFERENCES

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