PROPOSAL

Developing a New Barrier Condition Index (BCI) to Optimize Barrier Improvements in Wyoming

by

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1. INTRODUCTION

Roadside safety has always beenknown as an important component of highway systems. Based on the statistics, only 16% of crashes in the US occurs on the roadside; however, these crashes mostly conclude in fatalities or high-severity injuries (NHTSA 2009). For instance, run-off-the-road (ROTR) crashes included 23% of the fatal crashes in 2008 (AASHTO 2011). This rate has been increasing significantly. According to Jalayer and Zhou (2016), 62% of the fatal crashes were ROTR in the US in 2013.Using road barriers is known as one of the popular and traditional strategies in roadside designs. An appropriate road barrier system reduces the severity of crashes as well as providing a second chance for the ROTR drivers to get the control of their vehicles back (in low-speed run-offs). On the other hand, a poor performance would cause a serious safety problem by switching its role to a dangerous fixed-object. In fact, barriers were the third most common objects (after trees and the utility poles) among all the fixed-object fatalities by object struck in 2008 (AASHTO 2011). Figure 1 shows an overview of the fixed-object fatalities statistics.

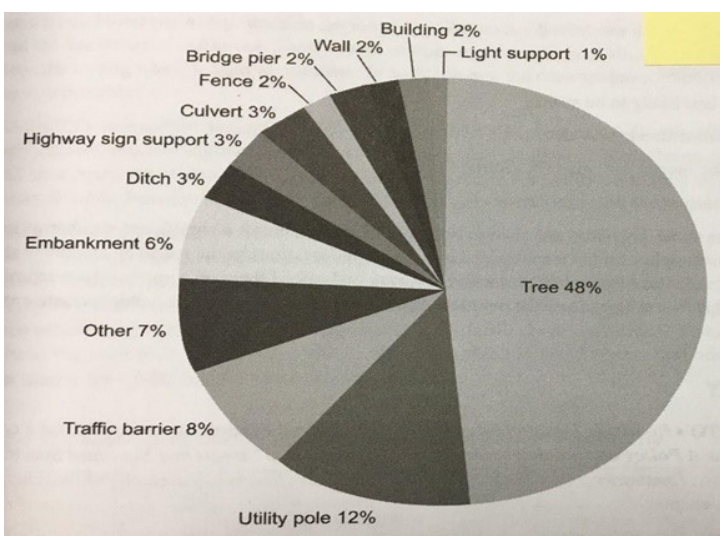

Figure 1. Percent distribution of fixed-object fatalities by object struck (AASHTO 2011).

According to another available statistic, barriers had a direct influence in about 1,000 fatalities and 28,000 injuries in the US in 2010 (NHTA 2012).

The initial goal of using guardrails was keeping vehicles from running off of the road (or into roadside sharp slopes or the fixed-objects such as culverts), and no consideration was taken into account about the severity of crashes when the vehicles hit the barrier (Wiebelhaus et al. 2013). For this reason, inappropriate configurations such as blunt-end (spoon) terminals, turned-down (sloped-end) terminals, and concrete posts became widespread in the early 1960s. Despite the report of Federal Highway Administration (FHWA) in 1994 for not allowing the useof blunt-end and turned-down terminals, there are still many of them due to the limited budget to replace them (Wiebelhaus et al. 2013). Figure 2 shows the typical turned-down and blunt-end terminals.

Figure 2. Typical turned-down (left side) and blunt-end (right side) terminals which became popular in the early 1960s.

From another point of view, design and construction is a majority part of the current barrier system in the US andgoes back to more than 30 years ago when the traffic volumes, speed limits, types of vehicles, and the regulations were different from today.Vehicles are heavier than before and pickup trucks are more widespread, while most of the existing barrier systems are not designed based on the impact of large vehicles.Figure 3shows the number of vehicles in a 50-

year span between 1960 and 2010 in the US. According to Figure 3, an average increase of 3.7 million vehicles per year has been shown in the US.

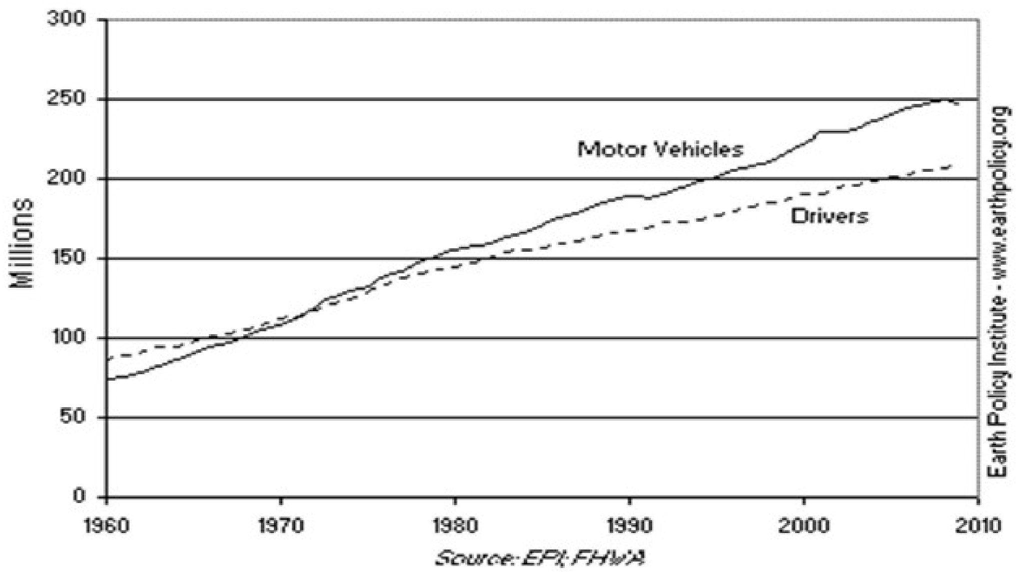

Figure 3. Number of drivers and vehicles in the United States (FHWA 2010).

Speed limits in the US have seen significant changes since 1974 when the first national speed limit was set up in the US. Until 1995, the maximum speed limit in the US was 65 mph, while it has been increasedup to 85 mph in recent years. Higher posted speed limits will lead to highseverity impacts with the barriers systems, especially in states like Wyoming with a maximum speed limit of 80 mph. Also, due to the specific topography in Wyoming (especially, in mountainous areas), many of the flare barrier systems were located on steep sideslopes which might not be practical in redirecting the vehicles in collisions. These facts build a seriousconflictin terms of the consistency of the barrier systems with current traffic features (volume, speed, etc.).The old barriers also pose a great risk to the vehicles due to their non-crashworthy status at the moment.From another pointof view, some barriers heightsare probably inappropriate for the following two reasons:

(1) Recent studies recommend new values for the height. For instance, a 27-inch height (from the ground to the top level of the barrier) used to be recommended for the typical W-Beam guardrails; however, the value is upgraded to 31 inches based on the 2011 edition of roadside guide design (RDG) (AASHTO 2011). Note that the old standard 27-in height for W-Beam guardrails was failed by the tests done in NCHRP report No. 350 (NCHRP 1993); however, the 27-inch height is still acceptable for Box beam guardrails.

(2) The height (from the ground to the top level of barriers) has been decreasing gradually due to pavement strategies such as adding new pavement layers. Overlays increase the elevation of the pavement while barriersarestuckat the same elevations.

The low-height barriers raise the propensity of vehicle rollover and override, while very tall-barriers are also promoting the vehicle underride (Julin et al. 2017). According to Wiebelhaus et al. (2013), the low-height of 24, and 26 inches will increase the potential of vehicle override in W-Beam guardrails. However, the 27 (the old recommendation of RDG in AASHTO 1989), 29, and 30 inches height will lead a redirection of the vehicle. This override can be even more dangerous for the vehicles with high center of gravity (CG) in low-height barriers. Based on FHWA's W-Beam Guardrail repair (FHWA 2008), the guardrails with a lower height of 24 inches were categorized as "no longer reasonably functional." On the other hand, a height more than 36 inches will increase the potential of an underride crashes in guardrails (Julin et al 2017). Figure 4 shows a summary of the discussion regarding the effect of height on safety.

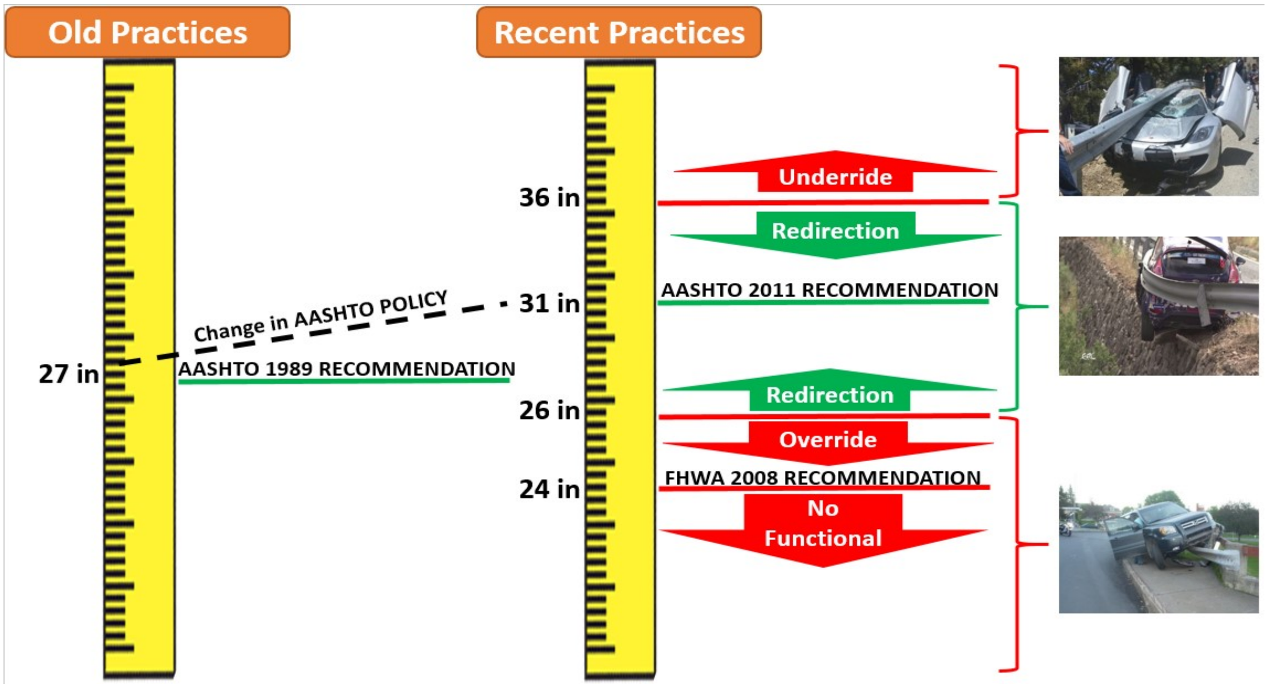

Figure 4. A summary of the effect of guardrail height on crashes.

Therefore, it is always an essential task for highway agencies to have a considerable attention to the short-term and long-term improvement activities for keeping the performance of barriers at an acceptable level. According to Cafiso et al. (2014), a crash modification factor (CMF) about 0.78 (22% reduction in crashes) was examined for improving the old guardrails with barriers meeting the new standards while the influence was observed even more significant in the ROTR crashes by a CMF of 0.67.

2. OBJECTIVES

The primary objective of this study is to evaluate the condition of barrier systems in Wyoming. Afterward, improvement recommendations will be provided and optimized for each barrier system (segment) to upgrade the performance of the barriers in a cost-effective way. The main part of the condition analysis will be performed based on the available datafrom 4,170 miles of roadway collected in theWyoming Department of Transportation (WYDOT) statewide guardrail inventory project no. HPR1217. The existing data provides the required information in terms of the type of barriers, and the geometry (height, offsets, slope, etc.). This data will be used to compare the condition of barriers with the recent design alignments published by "Roadside Design Guide (RDG)" (AAHSTO 2011), NCHRP report 656 (NCHRP 2010) and other valid references.

A secondary goal of this study is to develop CMFs forbarriersin Wyoming.Also, the relationship between safety performance (severity of crashes) andthe barrier condition(geometric features and the type) can be predicted using regression modeling to estimate the benefits of improvement. This analysis will be helpful to establish a life cycle analysis (LCA) for the barriers.

3. METHODOLOGY

The methodology includes two main phases: developing a rating systemfor barriersand proposing the optimized improvements.

In the firstphase, simulation modeling and crash analysis are required to build the main structure of the rating system. The performance (reaction) of barriers in collisions will be analyzedconsidering simulation modeling to investigate the risk of various barriers and end-treatments. Also, the crash analysis will reveal the effect of different geometric variables of barriers (height, offset, length, etc.) on safety to examine the impact of inadequate dimensions on crashes. For this purpose, a two-way analysis of variances (ANOVA) is considered to estimate the significance level of each variable. ANOVA is a statistical technique utilized to test differences between two or more means. Afterward, barrier segmentswill be rated on a scale from 1 to 4to investigate the sections with the most severecondition. The study team named the rating system as “Barrier Condition Index (BCI).”The score 4 means an ideal condition with no errorin terms of design, dimensions, and the type of barrier and end-treatments used, while a 1-rated site shows a high-severity condition that the barrier is obsoleteand is no longer able to provide a safe service. The rates 2, and 3 also belong to the medium, and low severity conditions, respectively. An example of the rating scale in BCI is presented in Figure 5.The low-height, the short-offset (from the roadway), and having no end-treatments were the critical problems that causea low BCI in the photo provided in the left side of Figure 5; however, the picture on the right side shows a barrier with perfect condition. Note that the criteria used for investigating the severities were inspired based on the tests done in NCHRP report 656 (2010) and provided detail of various types of barriers in the RDG (AASHTO 2011). The implemented BCI would be one of the primary contributions of the project. The reason for developing the new BCI is to uniform the barrier condition assessments for all the barrier segments statewide.

Figure5. An example of the proposed BCI rating system.

Finally, appropriate improvements and upgrades will berecommended for each barrier system evaluated in the study. This phase requires a series of analyses toidentify the hazardous sites and estimate CMF. CMF is considered as a representative of benefits of improvements due to reducing severity of crashes by increasing the barrier height. Investigation of hazardous sites is also essential for prioritizing the barrier segments located at a higher risk of crashes. The combination of these results and the BCI will result in a comprehensive ranking for the improvement phase. Using only the BCI ranking could be misleading in some cases. As an example, a location with a poor BCI but with low risk of collisions due to low traffic volume or low-speed limit should have a low overall ranking in the optimization.The optimization will also bebased on avarious range of budget to facilitate the decision-making of the improvement phase. For this purpose, the study will use the "Dynamic Programming Technique (DPT)" for the optimization part. The DPT simplify a multistage decision problem into a series of simpler (one-stage) decision problems. Therefore, the best improvement strategies will be presentedfordifferent level of budget. Conducting a cost estimation based on the most recent updates from manufacturers is also anothertask in this part of the study.

The methodology will be first developed on the data that is currently available and then it will also be upgraded once the data has been collected for the rest of the state (from WYDOT project no. HPR1217). More information regarding data collection will be provided in section 5.2.

4. BACKGROUND

Despite of the widespread use of road barriers and their effect on highway safety, there are not enough studies regarding barrier assessment and improvement.One of the main focuses of the previous studies was on upgrading the dimension of barriers by conducting field tests or simulation runs. Julin et al. (2017) conducted crash testing and computer simulation to investigate the maximum guardrail height for the Midwest guardrail systems (MGS). The objective for finding the maximum height was to keep an acceptable heightfor barriers (with no need to replacement)even after future roadway overlay improvements. According to their results, a 36-inch height was found (5 inches higher than the recommended height for MGS) safe with no threat of underride for vehicles in collisions.However, it should be mentioned that the recommended maximum of 36-inch height should not be used in all conditions due to the limitations in the methodology. As other studies regarding the dimension of barriers, Schmidt et al. (2015), and Albuquerque et al. (2015) evaluated the length-of-need of barriers. Albuquerque et al. (2015) suggested that shorter length can be considered for barriers when the sideslops are flat. This fact is excluded in the existing method presented by RDG (AASHTO 2011) since the effect of the sideslops is ignored in the calculation of the length-of-need. However, this deficiency in RDF method happens when the length of the hazard (like fixed-object) is less than the clear zone length. This topic will be discussed further in section 5.3.2.

Another part of the previous studies is related to the condition assessment of barriers. As one of the most recent efforts in this part, the Pennsylvania Department of Transportation (PennDOT 2017) conducted a field survey to present a uniform statewide condition evaluation for shoulder and barrier in Pennsylvania. Their study defined different types and severities for damages to present new inspection checklists for the field surveys. However, no methodwas mentioned for optimization of the improvement activities.NCHRP report 656 (2010) might be the most comprehensive study regarding the guardrail condition assessment. The report 656 almost pointed out all the possible damages of guardrails and rated them based on the frequency and severity of the damages; however, optimization was not considered in the study. Moreover, the research only focused on guardrails, and the other types of barriers like cable systems or concrete barriers were not considered in the evaluation.

As one of the studies which included optimization, Wiebelhaus et al. (2013) proposed a benefit-cost analysis using the Roadside Safety Analysis Program (RSAP).The study was done on 68 W-Beam guardrail systems in Kansas with a specific focus for the improvement of low-height guardrails and the guardrails with failed end-treatments (such as blunt-end or turned-down terminals).

The most related work to the proposed project is an ongoing project by Wyoming Technology Transfer Center (WYT^2/LTAP 2017) in Wind River Indian Reservation (WRIR), Wyoming. The ongoing project considered the geometric features (height, and offset) as well as the hardware parameters(deflection damages, panel condition, posts condition, soil erosion, and the end-treatment condition) to evaluate six different barrier segments in WRIR. Figure 6 shows the summary of assessment on one of the sites based on the developed BCI.Figure 6 shows an average score equal to 1.83 for a sample barrier segment. This means that the barrier is in the category of high-severity damages.Based on the previous studies (AASHTO 2011; Julin et al. 2016; Schmidt et al. 2015; Albuquerque et al. 2015), geometric features (height, offset, and the length) are as the primary parameters in the service time of barriers. The reason of including the hardware condition in the WRIR project was the small number of sites. However, considering the same procedure for a statewide project would not be recommended due to the considerable costs and time needed to investigate all the hardware damages in each panel of the barrier system. Besides the time-consuming and expensive procedure, damage and repair can happen anytime before and after the inventory is taken, so, it is almost impossible to provide an up-to-date data for the hardware condition of barriers. Note that all the sites involved in the WRIR project were among the low-volume rural highways (AADT<400 veh/day) and the project will be done in less than two months. Therefore, there would be a negligible chance to observe a significant change in the hardware condition due to the low-chance of crashes in a short-time period in low-volume roads.

	High	Med	Low	None	Sig Coefficient	SCORE (1-4)	Weighted SCORE	AVE SCORE
Height	*				3.0	1	3	**1.83**
Rail Flattening & Crush				*	0.5	4	2	
Deflection								
Vertical			*		1.0	3	3	
Lateral	*				1.0	1	1	
Cable Sag	N/A	N/A	N/A	N/A				
Panels Condition								
Vertical Tear				*	1.0	4	4	
Horizontal Tear				*	0.5	4	2	
Deterioraton				*	1.0	4	4	
Hardware			*		0.5	3	2	
Posts Condition								
Separated From Guardrail				*	0.5	4	2	
Posts Condition		*			2.0	2	4	
Soil Erosion		*			2.0	2	4	
End-Terminal Condition								
End-Post #1 Condiiton	*				3.0	1	3	
End-Post #2 Condiiton	*				3.0	1	3	
Extra Points								
Removal Section				*				
Side Dozing				*				

Figure6. The developed BCI for the Wind River Indian Reservation project.

Simulation modeling and before-after analyses were popularamong researchers who have been conducting studies on barriers.The simulation studies (Atahan 2016; Teng et al. 2016; Hampton and Gabler 2013) mostly focused on predicting the damages caused to vehicles by barriers in collisions.On the other hand, before-after studies (Cafiso et al. 2014; Elvik et al. 2009) concentrated on estimating the benefits of barrier improvements in comparison to the before-improvement period.

5. STUDY TASKS

Thestudy will be performed in the following five tasks:

5.1 Literature Review

The latest studies will be reviewed in this step to consider the recent findings of researchers regarding barrier studies. In addition, other research institutions will be contacted to identify their latest contributions in this area. This step will be helpful in identifying all relevant studies for determining the condition and potential improvements of barriers.

5.2 Data Collection

Data collection of the study will be mostly computer-based with no need for any field survey since WYDOT has already executed a contract to collect the needed data. The required data in this phase is itemized as follows:

- All the data collected and the photographs taken in the WYDOT guardrail project no. HPR1217. According to Trihydro Corporation (2017), 2,350 barrier segments had been measured in a 16-month period from June 2016 to September 2017. Therefore, all the control sites can be selected among the 2,350 locations with no need for additional field data collection. Figure 7 illustrates the locations inventoried in WYDOT project no. HPR1217
- Annual average daily traffic (AADT) of the sites.
- Speed limit data at the sites.
- Costs of purchasing, installing, and repairing the barriers in Wyoming.
- Crash statistics at all sites (with a focus on the crashes involved with barriers).
- Age of barriers and any available record regarding previous improvements in each site.

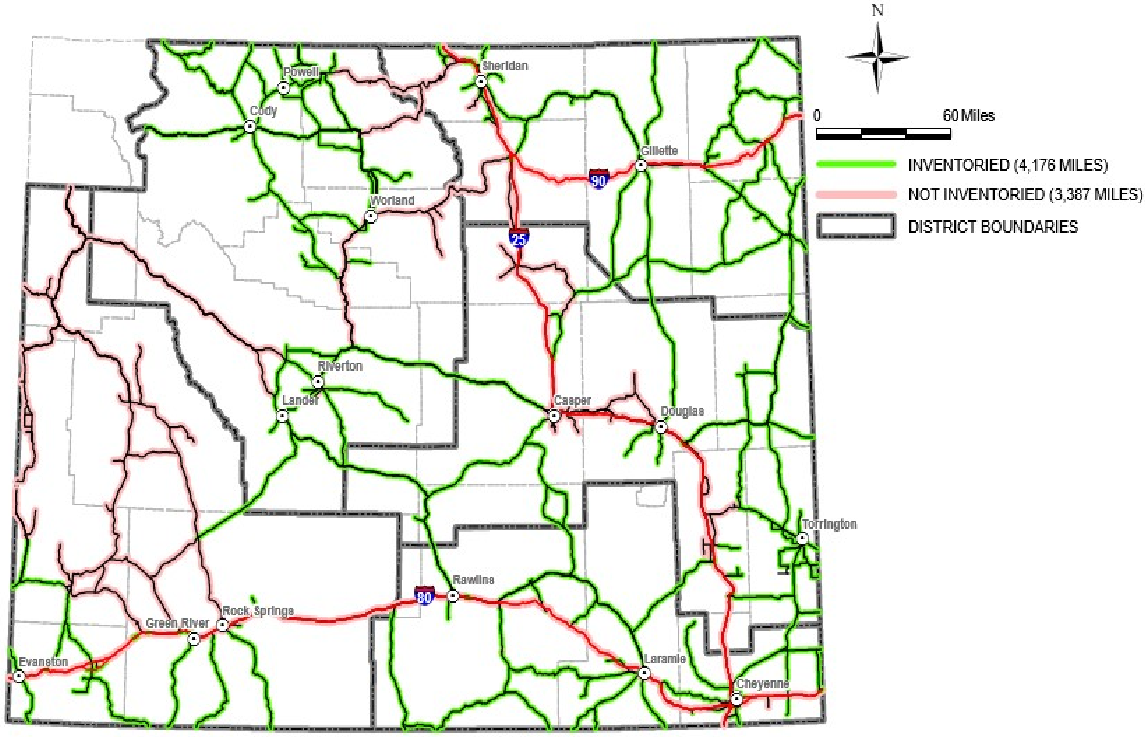

Figure 7. 2017 Inventory progress in WYDOT project no. HPR1217 (Trihydro Corporation 2017).

- Road geometric features (radius of the curve, grade rate, etc.) at each site.
- Any other available information regarding the barrier segments in Wyoming from previous studies.

5.3 Data Analysis

This part focuses on the analysis of data. The following paragraphs explain the stepwise procedure of data analysis in the study:

5.3.1 Considering the Impact of Barriers Reaction

This stepseeks to identify the performance (reaction) of various barrier types in crashes. The results in this part would introduce the risk posed by each type of barriers in crashes to find the most hazardous barrier types. The summary report provided by Trihydro Corporation (2017) showed that three types of W (Corrugated) Beam, Box Beam, and the W (Corrugated) Corten Beam include 97% of barriers in Wyoming while the bridge transitions, End Anchorage WY-BET, and types I, C, A were the most popular end-treatments with a percentage about 83% of the whole network.The combinations of these types (barriers/end treatments) will be investigated by implementing two techniques.

The first technique for evaluating barriers reaction will consider crash data involving barriers. The effect of various barrier types will be reviewed considering control sites with similar situations (traffic volume, geometry, etc.) but different types of barrier systems. For example, a site with a cable system would be compared to a second site with a W-Beam guardrail system.A quick review over the available crash data provided in Critical Analysis Reporting Environment (CARE) package shows that it is possible to obtain the needed information such as the type of barrier, location, severity, weather, and the vehicles speed of crashes involved with barrier systems. As an example of the provided data by CARE, the crashes in 24 miles of I-80 (milepost 336-360) in Wyoming were collected for a span of 10 years from 2004 to 2014. Based on CARE, barrier systems were involved in 17% of the total 476 crashes in this segment. None of the crashes involved with barrier systems concluded a fatal crash. However, all the six fatal crashes in this segment occurred on the roadside. Figure 8, and 9 show the analysis done on this segment.

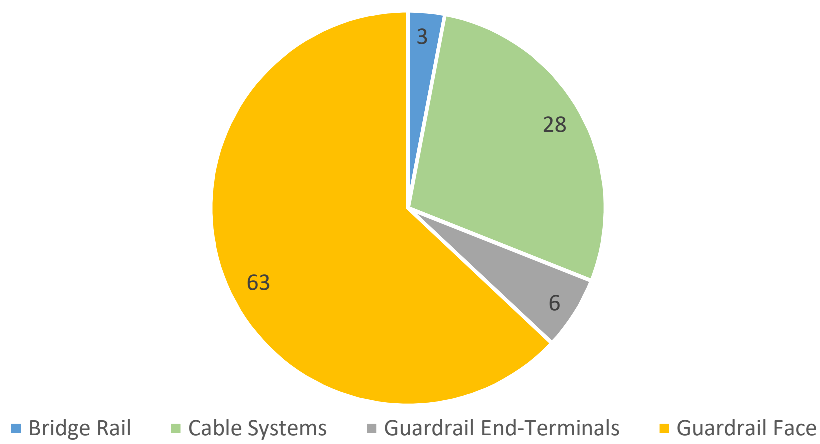

Figure 8. Percentage distribution of crashes among different types of barriers collected using CARE on a 24-mile segment of I-80 in Wyoming.

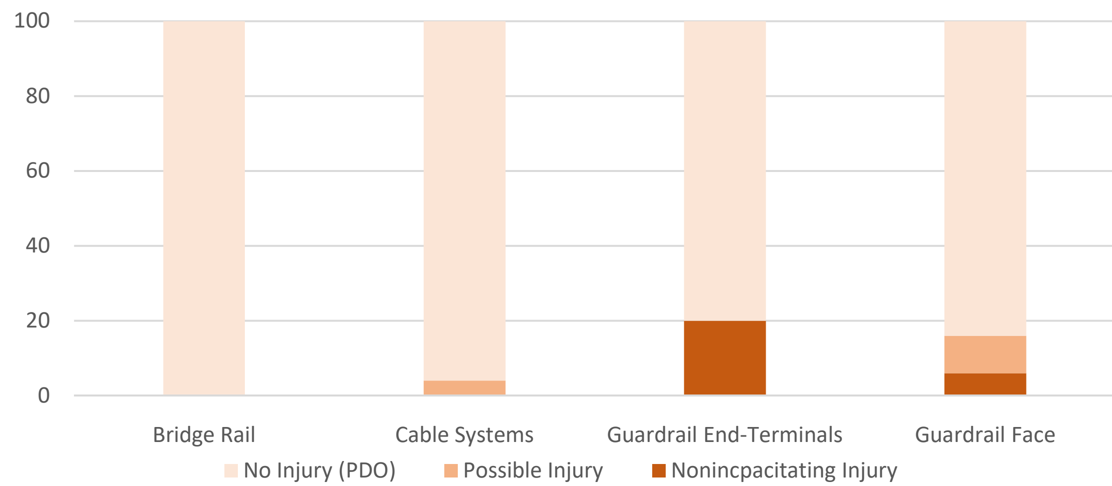

Figure 9. Crash statistics collected using CARE on a 24-mile segment of I-80 in Wyoming.

Note that the purpose of these figures is only demonstrating an example of the available data by CARE and the analysis cannot be considered as a representative of the statewide statistics. Based on Figure 8, guardrail systems were involved in 69% (considering all the end-terminal and the guardrail face crashes) of the barrier crashes. Also, based on the crash-severity demonstrated in Figure 9, the guardrail systems included the highest severity of crashes as well, especially when the crash happened at the end portion (end-terminals) of guardrails.

The secondtechnique includesgathering previousfindingsfrom simulation and field tests doneon barriers in different environments with various vehicle speed, collision angle, barrier type, and vehicle type.Based on an initial literature search review, many studies (MwRSF 2017; Kwon et al. 2016; Atahan et al. 2017; Atahan 2016; Teng et al. 2016; Hampton and Gabler 2013) have run simulations for barriers which proved to be a powerful tool to predict barriers performance due to crashes.The simulation software LS-DYNA has been used extensively due to its high ability in modeling barriers; however, the simulation procedure follows a fairly complicated analysis and it is vital to include actual crash tests for developing effective models and results. Therefore, the research team will secure information on barriers performance by reviewing previous valid simulation and field test efforts. In the cases with a need for more information, the study team will communicate with institutions involved in testing barriers to verify test results. Midwest Roadside Safety in Nebraska and the Texas Transportation Institute (TTI) are two of the institutions involved in testing barriers (Rosenbaugh et al. 2017; Meyer et al. 2017; Abu-Odeh et al. 2014; Arrington et al. 2011). They will be contacted as needed to secure information and to verify test results of barriers in Wyoming.

Figure 10 shows a general view of the LS-DYNA environment for the barriers modeling.

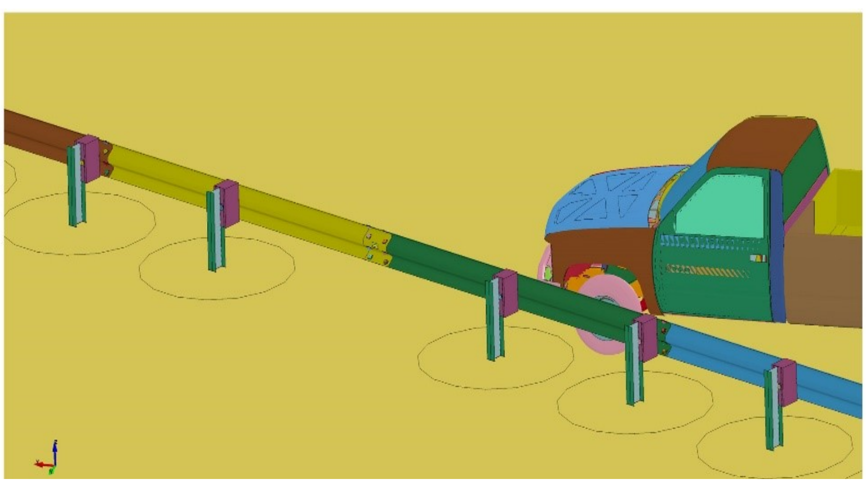

Figure 10. A general view of the LS-DYNA environment (Hampton and Gabler 2013).

5.3.2 Considering the Impact of the Geometric Features

Height, length, offset (from the roadway), slope, and post spacing of barriers are the main geometric features that should be upgraded based on the recent design guidelines.Height is one of the most important variables regarding the safety. An inappropriate barrier height leads the vehicles to climb, override, or penetrate the guardrail (Wiebelhaus et al. 2013).The previous studies (AASHTO 2011; NCHRP 2010; Julin et al. 2017) have presented anappropriate range of height and post spacing for the different types of barriers. Therefore, a comparison between the existing measurements and the recommended values would clarify any existing error in terms of barrier height and post spacing. As another perspective regarding the height consideration in the study, slope and the offset also play a key role when the vehicles leave the road since the height of the bumper-barrier interaction woulddifferbased on the rate of slope and the offset width due to the suspension reactions in the roadside. In fact, the bumper path would not follow a constant line and it is deviating in every moment on the slope. To make the point clearer, Figure 11 and Table1 illustrate thebumper path and the bumper trajectory data, respectively.

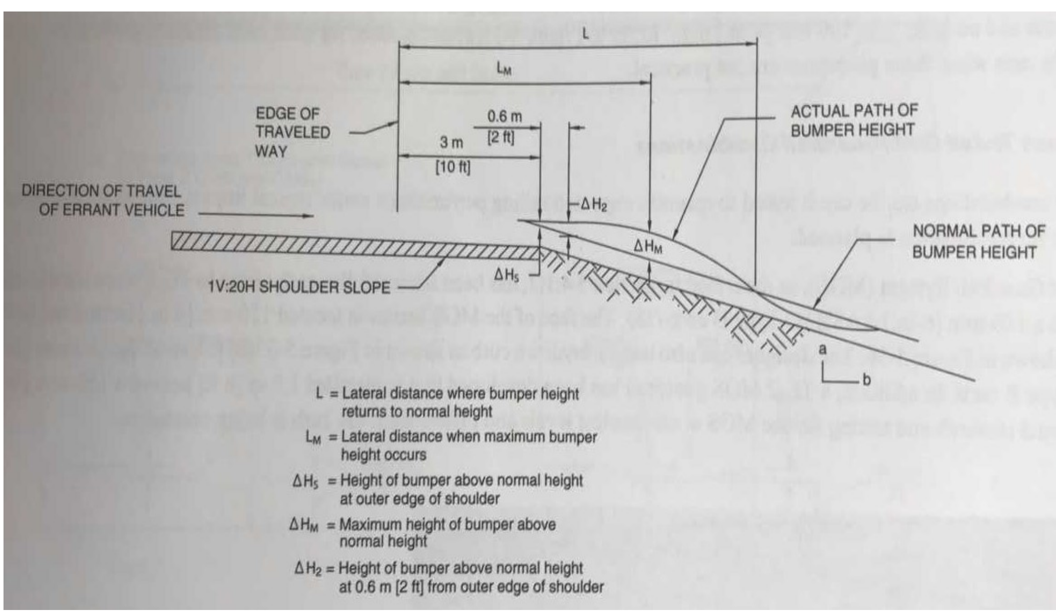

Figure 11. Path of bumper height on slopes (AASHTO 2011).

Table 1. Example bumper trajectory data (AASHTO 2011).

Encroachment Angle (deg)	Embankment Slope (V:H)	L (ft)	Delta H_S (in.)	Delta H_2 (in.)	Delta H_M (in.)	Delta L_m (ft)
25	1:6	30	4	4.8	6.9	20
25	1:4	35	4	4.8	7.9	23
25	1:3	40	4	4.8	7.9	23
25	1:2	40	4	4.8	7.9	23
15	1:6	23	1.9	2.8	4.5	16
15	1:4	26	1.9	2.8	6.9	18
15	1:3	28	1.9	2.8	8.3	20
15	1:2	33	1.9	2.8	8.8	25

The existing slopes and offsets will be compared to the given information in Table 1 to consider their effect on the height in the barrier assessment.

The length-of-need might be one of the most effective parameters regarding the cost of barriers (for example, the unit price of the typical MGS, and Box Beam are equal to $22.23, and $41.96 per ft, respectively according to WYDOT website). The influence of length-of-need will be appliedto another variable in the barrier evaluation as well as the optimization of improvements. As an easy and practical method, the effect of length can be included comparing the change ratio between the current AADT and speed limit of the sites,and the values during the design time (or the last improvement). However, for the cases with no information regarding the background of the design, the required length will be calculated (based on the most recent AADT and speed limit) and compared to the existing length to find the difference.TheRDG (AASHTO 2011)presents a popular method to calculate the required length of barriers. Figure 12 shows the geometric parameters involved in the method.

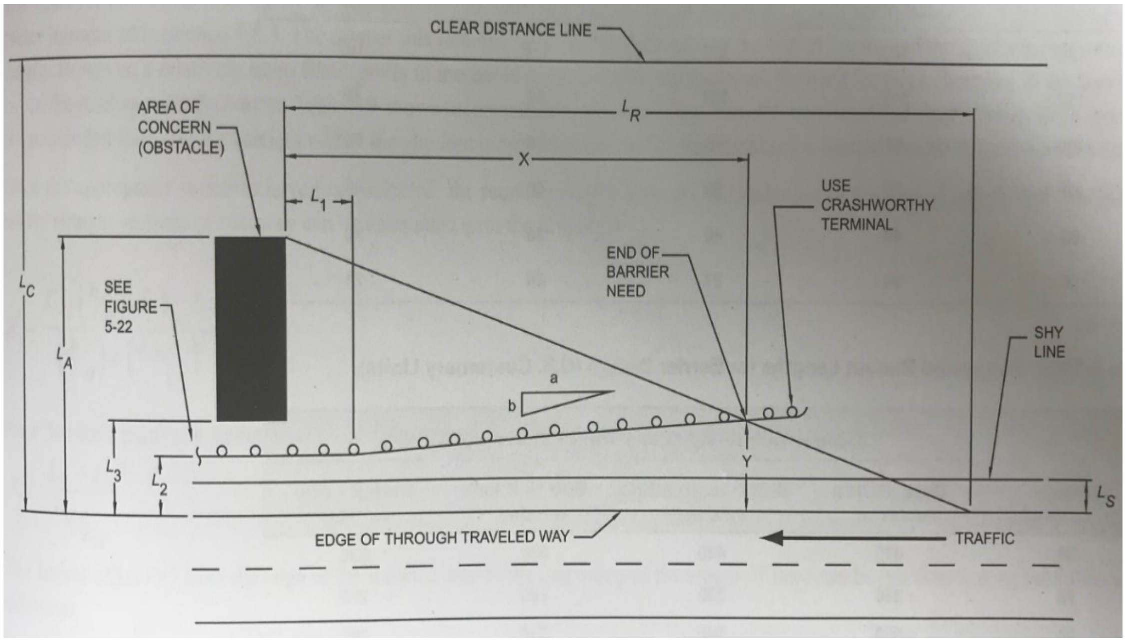

Figure 12. Variables involved in barrier design (AASHTO 2011).

Among the variables of Figure 12, L_A, and L_R, have the key role in the method. L_A (the lateral extentof the area of concern) is the distance from the edge of the pavement to the far side of the fixed object or the steep sideslope (like steeper than 1V:3H) to the outside edge of the clear zone (when the fixed object extends beyond the clear zone). L_R (the runout length) is the distance from the fixed-object being shielded to the point where the vehicles depart from the road. L_A, and $L_C$will be collected using Google Earth software while the RDG (AASHTO 2011) estimates the required L_R based on the ADT and speed limit as presented in Table 2.As the last step, these variables will be used in equation 1, and 2 to calculate the length-of-need when there is a flared installation or a parallel (tangent) installation, respectively.

$$X = \frac{\mathrm{LA} + \left(\frac{\mathrm{b}}{\mathrm{a}}\right)(L1) - L2}{\left(\frac{\mathrm{b}}{\mathrm{a}}\right) + \left(\frac{LA}{LR}\right)} \quad Equation\ 1$$

$$X = \frac{\mathrm{LA} - L2}{\left(\frac{LA}{LR}\right)} \quad Equation\ 2$$

Table 2. Recommended runout lengths for barrier design (AASHTO 2011).

Design Speed (mph)	Runout Length Given Traffic Volume (ADT) (ft)			
	Over 10,000 veh/day	5,000 to 10,000 veh/day	1,000 to 5,000 veh/day	Under 1,000 veh/day
80	470	430	380	330
70	360	330	290	250
60	300	250	210	200
50	230	190	160	150
40	160	130	110	100
30	110	90	80	70

5.3.3Developingthe Barrier Condition Index (BCI)

The collected data (from the previous tasks) will be used to develop the BCI. Therefore, the main structure of the BCI includes the height, offset, slope, length, post spacing, and the type of barriers (and the end-treatments).The effect of these variableswill be utilized to compare the crash statistics of the barrier segments and their control sites. Note that the control sites must havesimilar conditionsregarding traffic volume, geometry, general driver behavior and the weather.

Finally, a two-way ANOVA will be conducted in this step for the investigation of effective parameters of barriers condition on highway safety. These parameters will build the main structure of the BCI; however, each parameter will receive a different weighted coefficient based on the significance levels (p-value) in ANOVA. Basically, the independent variables (in this study such as height, and length) with a significant level less than 0.05are considered as the variables with effective impact on the dependent variables (in this study such as safety).Finally, the average of (weighted) scores will present the BCI in each barrier segment.

5.3.4Investigating the Hazardous Barrier Segments

Two analyses will be completed in this step. First, the barrier segments will be ranked based on the BCIs extracted in the evaluation to investigate the barrier segments which increase the severityrisk of crashes.

The next step will be done using the traditional "Rate Quality Control (RQC)," and the "Crash Severity (CS)" methods of finding hazardous locations to identify the most dangerous segments in the study. Equations 3, and 4 illustrates the formulas required for the RQC, and CS methods, respectively.

$$R_c = R_a + K\,(R_a / M)^{0.5} + (1 / 2M) \qquad \text{Equation. 3}$$

R_c= Critical rate for asegment
R_a= Average accident rate for all segments
M = Average exposure (100 million vehicles miles of travel on a segment)
K = A probability factor determined for the desired level of significance (usually = 1.645)

$$EPDO = 541.74(F) + 29.18(A) + 2.5\,(B) + 6.06(C) + PDO \qquad \text{Equation. 4}$$

EPDO = Number of equivalent PDO (property damage only) collisions
F, A, B, C = Fatal, Type A, B, and C crash injuries

RQC method defines a critical rate (Rc) based on Equation 3to introduce the sites with a higher crash rate than R_c as hazardous sites. The CS method also converts all the various types of crash injuries to an equivalent PDO rate for comparing the sites. Afterward, the studywill considerthe results ofthe BCI (as a representative of barrier condition), RQC (as a representative of crash frequency), CS (as a representative of crash severity), and the barrier reaction (as a representative of barrier type-section 5.3.1)analyses to present a risk ranking for the sites.

5.3.5 Developing Crash Modification Factors (CMFs)

As another task of the study, CMFs will be developed. The primary objective of developing CMFs is to find a view of benefits for each type of improvement and the analysis will be useful to present a beneficial optimization.The study makes a comparison between the barrier segments and their control sites to present the CMFs of any improvement regarding the geometric features and type of barrier systems in Wyoming. Therefore, CMF models will be presented for the height, offset, slope, length, post spacing, type of barrier (and the end-treatment), and different combinations of these variables (such as the CMF for improving both the height and length together).

5.3.6Optimization of Improvements

This section covers the estimation of benefits and costs to optimize the barrier improvement program. Recommendations will be presented to improve the type, height, offset, slope, and the length of barriers.

The first phase of the optimization will be conducted based on the existing data provided until the end of September 2017 (roadways shown in green in Figure 7). The second phase will be implemented when the rest of the data has been collected statewide on all barriers.

5.3.6.1 Optimization Based on the Available Data

The developed CMFs and analytical models in the previous steps will identify the sites which pose a high riskofcrashes. Also, it will provide a prediction of benefits based ondecreasing the severity of crashes at each site. The CMFs calculated in the previous parts will be used to estimate the benefits of each type of improvement. Then, the benefits will be converted toa unified cost value based on the cost estimations ofFHWA (FHWA 2009). Table 3 shows the estimated costsby FHWAin 2009. Note that Equation 4 is also consistent with Table 3.

Table 3.Comprehensive Costs of crashes (FHWA 2009).

Injury Severity of Crash	Average Economic Cost
Death	$4,008,900
Incapacitating Injury (A)	$216,000
Non-incapacitating Injury (B)	$79,000
Possible Injury (C)	$44,900
No Injury (PDO)	$7,400

The cost of improvement will also be estimated using previous studies in Wyoming, valid databases (like WYDOT website), and brochure of barrier manufactures. As it was already mentioned in the methodology, the optimization will be done using dynamic programming technique (DPT).

5.3.6.2 Optimization Based on the Future Collected Data

When the rest of the statewide data is available, the second phase of optimization will be performed considering all the barrier segments. As it is clear in Figure 7, phase two mostly includes the interstate highways in Wyoming. This data will be valuable in the project due to the higher speed limit and ADT on interstates in comparison to the collected data in the first phase. In fact, it is possible that the barrier segments from the second phase include a considerable portion of the improvements. Moreover, a comparison between the results of the first phase and the second phase may also reveal interesting findings. For example, the effect of thespeed limit and the ADT on the severity and frequency of crashes involved with barriers can be studied in this part.

5.3.7 Summary

As a summary of the data analysis in this project, Figure 13 shows the stepwise procedure from the beginning to get the final optimization plan.

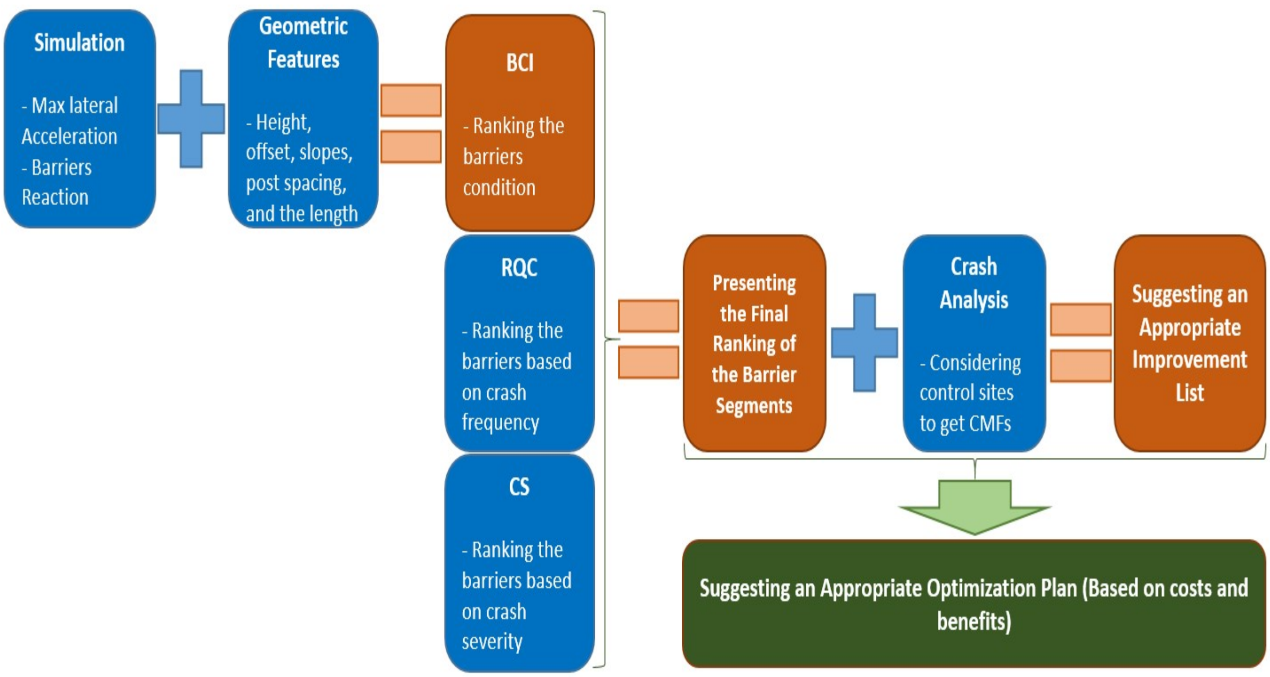

Figure 13. The procedure of data analysis in the project.

Based on Figure 13, the results of the simulation and the geometric feature phases will provide the required information for developing the BCI. Then, the barrier segments will be ranked based on RQC and CS analyses. These rankings will be combined with the BCI ranking to present the final ranking of the barriers segments. In another phase of the study, the crash analysis will (by considering CMFs) investigate the safety effects and benefits of improvements.

Therefore, appropriate improvements will be recommended at each segment, and finally, the improvement phase will be optimized based on different levels of budget.

5.4 Preparation of the Final Report

As the final step, the results will be organized in an appropriate format and summarized in a final report for the Wyoming DOT.

5.5 Technology Transfer and Implementation Plan

The research team will present the findings of this study to the WYDOT RAC as well as any interested party at WYDOT. Also, the research team will submit the findings for publications in various Journals and possibly at the Transportation Research Board.

6. TIMELINE

It is expected that this study will be performed in 26 months. Figure 14 demonstrates the predicated timeline for the project starting from March 1, 2018 and ending in May 1, 2020. In the timeline, the duration of tasks 1-5 were considered as 3, 8.5, 21, 5.5 and 4 months, respectively.

7. BUDGET

The tasks of this proposal will be performed by one faculty member, a post doc, and a part time graduate student. The overall budget breakdown of the study is shown in Table 4.

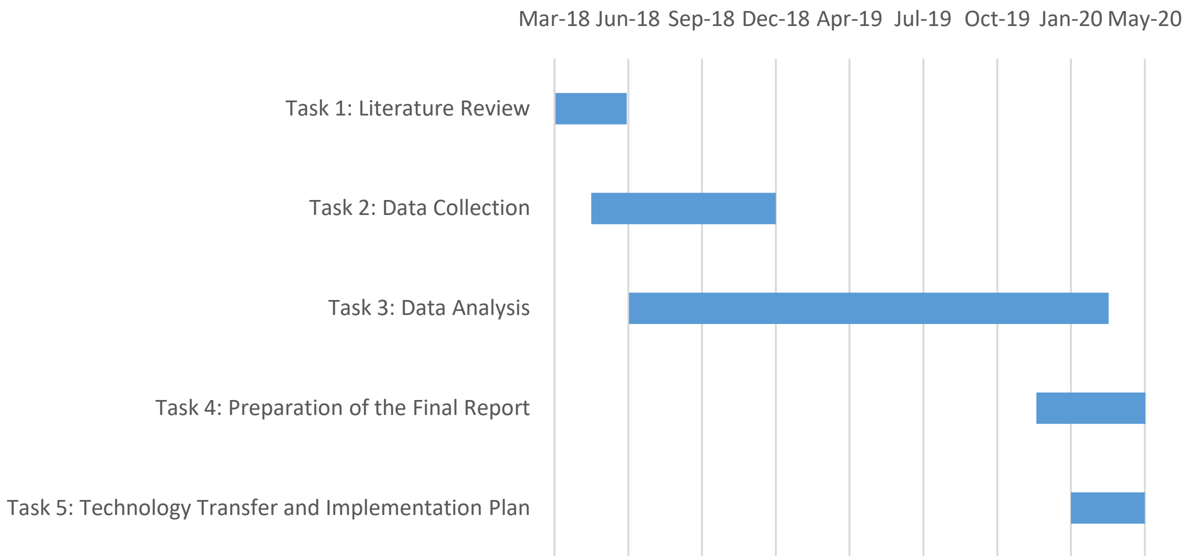

Figure 14. The proposed timeline for the study.

Table 4. Budget breakdown.

Project Title: Developing a New Barrier Condition Index (BCI) to Optimize Barrier Improvements in Wyoming			
University of Wyoming			
Categories	Year 1	Year 2	**Total**
Center Director Salary			
Faculty Salaries	$14,200	$16,100	$30,300
Post Doc	$25,200	$28,300	$53,500
Faculty/Post doc Fringe Benefits (43.3%)	$17,060	$19,225	$36,285
Student Salaries	$5,000	$3,000	$8,000
Student Fringe Benefits (3.9%)	$195	$117	$312
Total Personnel Salaries	$44,400	$47,400	$91,800
Total Fringe Benefits	$17,255	$19,342	$36,597
TOTAL Salaries & Fringe Benefits	**$61,655**	**$66,742**	**$128,397**
Travel	$3,500	$4,000	$7,500
Equipment			$0
Supplies	$500	$2,000	$2,500
Contractual			
Software	$600	$600	
Other Direct Costs (Specify)*	$6,064	$6,064	$12,128
TOTAL Direct Costs	**$72,319**	**$79,406**	**$151,725**
F&A (Indirect) Costs	$13,251	$14,668	$27,919
TOTAL COSTS	**$85,570**	**$94,075**	**$179,645**
*Other Direct Cost includes Graduate Student Tuition, Fees and Insurance			

8. DELIVERABLES

The research team will provide WYDOT with the following at the conclusion of this study:

- A final report summarizing all steps followed in the study, data analysis, conclusions, and recommendations.
- A detail data base showing the ranking of all barriers in the state..
- A comprehensivecost-effective strategy to maintain/upgrade barriers on the interstate/state highway system in Wyoming. This strategy will be developedbased on the proposed analysis as well as by working closely with WYDOT personnel.

9. REFERENCES

Abu-Odeh, A., Bligh, R., Mason, M., and Menges, W. (2014). "Development and Evaluation of a MASH TL-3 31-Inch W-Beam Median Barrier." *Texas Transportation Institute*.

Albuquerque, F., Stolle, C., Sicking, D., Faller, R., Lechtenberg, K., and Emerson, E. (2015). "Optimization of Guardrail Length-of-Need for Interstate Highways." *94th Annual Meeting of TRB*, Washington DC.

American Association of State Highway and Transportation Officials. (2011). "Roadside Design Guide."

Arrington, R., Bligh, R., and Menges, W. (2014). "MASH Test 3-11 on the 5-Inch Cast In Place Deck Barrier Anchors." *Texas Transportation Institute*.

Atahan, A. (2016). "Crashworthiness analysis of a bridge rail-to-guardrail transition." *International journal of crashworthiness, Taylor & Francis*, 21 (5). P.p 423-434.

Atahan, A., Hiekmann, J., Himpe, J., and Marra, J. (2017). "Development of a continuous motorcycle protection barrier system using computer simulation and full-scale crash testing." *Journal of Accident Analysis and Prevention*, Elsevier, https://doi.org/10.1016/j.aap.2017.04.005

Elvik, R., Vaa, T., Hoye, A., and Sorensen, M. (2009). "The Handbook of Road Safety Measures: Second Edition." *Emerald Group Publishing Limited*.

Federal Highway Administration (2008). "W-Beam Guardrail Repair. A Guide for Highway and Street Maintenance Personnel."

Federal Highway Administration. (1994).“Memorandum on Action: Traffic Barrier Safety Policy and Guidance,” Washington, D.C., September 29, 1994.

Federal Highway Administration.(2009). “Highway Safety Improvement Program Manual, Federal Highway Administration, Report No. FHWA-SA-09-029.”

Federal Highway Administration. (2010). “Licensed Drivers, Vehicle Registrations, and Resident Population.”www.fhwa.dot.gov/policyinformation/statistics/2010

Hampton, C., and Gabler, H. (2013). “Development of a Missing Post Repair Guideline for Longitudinal Barrier Crash Safety.” *Journal of Transportation Engineering*, (139) 6.

Henn, H. (1998). “Crash Tests and the Head Injury Criterion.” *Teaching Mathematics and its Applications*, 17 (4).

Jalayer, M., and Zhou, H. (2016). “Overview of Safety Countermeasures for Roadway Departure Crashes.” *ITE Journal*, 86 (2): 39-46.

Julin, R., Pajouh, M., Stolle, C., and Reid, J. (2017). “Maximum Mounting Height for Midwest Guardrail System (MGS).” *96th Annual Meeting of TRB*, Washington DC.

Kwon, O., Baek, SR., Yoon, J., and Lim, J. (2016). “A Study on Crash Analysis of Vehicle and Guardrail using a LS-DYNA Program.” *The Journal of the Institute of Internet, Broadcasting and Communication*, 16 (3), p.p 179-186.

Mackay, M. (2007). “The increasing importance of the biomechanics of impact trauma.” *Sadhana*, 32 (4), pp 397-408.

Meyer, D., Lechtenberg, K., Faller, R., Bielenberg, R., Rosenbaugh, S., and Reid, J. (2017). “MASH Test No. 3-10 of a Non-Proprietary, High-Tension, Cable Median Barrier for Use in 6H:1V V-Ditch (Test No. MWP-8).” *Midwest Roadside Safety Facility*.

Midwest Roadside Safety Facility. (2017). https://mwrsf.unl.edu/index.html

Molan, A., and Ksaibati, K. (2017). “Barrier Condition Assessment in Wind River Indian Reservation, Wyoming (Draft).” *Wyoming Technology Transfer Center*, University of Wyoming, Laramie, Wyoming.

National Cooperative Highway Research Program. (2010). “Report 656: Criteria for Restoration of Longitudinal Barriers.”

National Highway Traffic Administration. (2012). “A Compilation of Motor Vehicle Crash Data from the Fatality Analysis Reporting System and the General Estimates System.”

National Highway Traffic Safety Administration. (1993). “Report 350: Recommended Procedures for the Safety Performance Evaluation of Highway Features.”

National Highway Traffic Safety Administration. (2009). “An Examination of Driver Distraction as Recorded in NHTSA Databases.”

Pennsylvania Department of Transportation. (2017). “Shoulder and Guardrail Condition Survey Field Manual.”

Rosenbaugh, S., Hartwell, Bielenberg, R., Faller, R., Holloway, J., and Lechtenberg, K. (2017). "Evaluation of Floorpan Tearing and Cable Splices for Cable Barrier Systems." *Midwest Roadside Safety Facility*.

Schmidt, J., Weiland, N., Reid, J., and Faller, R. (2015). "Minimum Effective Length for the Midwest Guardrail System." *94th Annual Meeting of TRB*, Washington DC.

Teng, T., Liang, C., Hsu, C., Shih, C., and Tran, T. (2016). "Effect of Soil Properties on Safety Performance of W-beam Guardrail." *International Conference on Advanced Material Science and Environmental Engineering (AMSEE 2016)*

Trihydro Corporation. (2017). "WYDOT Guardrail Inventory – 2016-2017 Field Season Summary Project No. HPR1216 – Statewide."

Wiebelhaus, M., Lechtenberg, K., Sicking, D., Faller, D., and Rosenbaugh, S. (2013). "Cost-Effective Treatment of Existing Guardrail Systems." *MwRSF Research Report No. TRP-03-254-13*.

Wyoming Department of Transportation. (2011). "Setting Speed Limits on Local Roads in Wyoming.

Wyoming Department of Transportation. (2016). "2016 Weighted Average Bid Prices."