Evaluating the Safety Effects of Sinusoidal Centerline Rumble Strips

A proposal prepared for the

Montana Department of Transportation
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PROBLEM STATEMENT

Centerline rumble strips are a low-cost safety countermeasure that have been proven to help reduce the frequency of high-severity crossover crashes, as well as total crash frequency, on both rural and suburban roadways. This is done by providing drivers with an audible and tactile feedback that they are departing the travel lane and are in danger of crossing over into the opposing travel lane. However, the audible feedback provided to the driver can significantly contribute to overall traffic noise and negatively affect nearby residents. One alternative to reduce the noise produced by conventional centerline rumble strips is the installation of sinusoidal centerline rumble strips. Sinusoidal rumble strips are created using a single continuous milled pattern into the pavement that follows a sinusoidal wave, unlike conventional rumble strips, which are milled patterns in the pavement. The sinusoidal pattern has been shown to reduce the overall noise produced when vehicles traverse the rumble strip. While the sinusoidal pattern offers similar in-vehicle audible and tactile feedback as conventional rumble strips, the safety performance of sinusoidal centerline rumble strips has not been documented.

As a part of two unique projects, the Montana Department of Transportation (MDT) intends to install sinusoidal centerline rumble strips on over 600 miles of rural roadway during 2021. The purpose of this project is to evaluate the safety effectiveness of the installation of sinusoidal centerline rumble strips using an observational before-after study and compare these safety impacts with the installation of conventional centerline rumble strips. The results will help MDT select the most appropriate countermeasure (conventional vs. sinusoidal rumble strips) for a given situation, improving the overall safety management process.

BACKGROUND SUMMARY

There were more than 6.75 million reported crashes in the United States in 2019, resulting in 36,000 fatalities and 2.74 million injuries on the highway and street system (NHTSA, 2020). The Federal Highway Administration (FHWA) estimates that approximately one-half of all traffic fatalities are the result of a roadway departure, which is defined as an event in which the “vehicle crosses an edgeline, centerline, or otherwise leaves the traveled way” (FHWA, 2020). Among the roadway departure fatalities, approximately 27 percent are head-on collisions. The principal characteristics of head-on roadway departure crashes are that they occur on high-speed, undivided rural highways.

Mitigating roadway departure crashes involves a multi-stage strategic approach, including the following objectives:

1. Keep vehicles in the intended travel lane;
2. Reduce the potential for a crash when vehicles depart the travel lane or the roadway; and
3. Minimize crash severity if a roadway departure event occurs.

A principal safety strategy associated with keeping vehicles in the intended travel lane is to install rumble strips. FHWA indicates that shoulder and centerline rumble strips are both proven safety countermeasures on two-lane rural highways (FHWA, 2017). Torbic et al. (2009) completed a multi-state safety evaluation of centerline rumble strips and found they are associated with a 40 percent reduction in total crashes and a 64 percent reduction in fatal + injury target (head-on and opposite direction sideswipe) crashes on urban two-lane roads. On rural two-lane roadways, the safety benefits included a 9 percent reduction in total crashes, 12 percent reduction in fatal + injury crashes, 30 percent reduction in total target crashes, and a 44 percent reduction in fatal + injury target crashes. Collectively, these results indicate that centerline rumble strips are effective in reducing total, severe, and target crashes on undivided two-lane roadways.

Rumble strips are intended to provide an adequate level of in-vehicle noise and vibration to warn a driver that the vehicle may be departing the intended travel lane. Donnell et al. (2009) completed a series of field studies to document the levels of in-vehicle noise generated by different rumble strip patterns. An unintended consequence of providing adequate in-vehicle noise and vibration levels to alert a drowsy or fatigued driver of an impending travel lane departure is that some rumble strip patterns may produce high-levels of exterior vehicle noise. As such, transportation agencies have studied alternative patterns to mitigate this exterior noise.

Sinusoidal rumble strips were first developed in Europe and evaluated in the Netherlands, Sweden, and Britain before being investigated in the United States by the California Department of Transportation (Caltrans) (Caltrans, 2012). Preliminary pilot testing by Caltrans intended to develop a sinusoidal pattern that generated quieter exterior noise levels relative to milled rumble strip patterns. The Minnesota Department of

Transportation (MnDOT) also evaluated exterior vehicle noise from several sinusoidal rumble strip patterns (Terhaar et al., 2016) and recommended a sinusoidal pattern that is 14-inches wide and $^{1}/_{16}$- to $^{1}/_{2}$-inch deep for installation. Mathew et al. (2018) evaluated three sinusoidal rumble strip patterns in Indiana and recommended that a 12-inch wavelength produced the desirable decrease in exterior noise while still maintaining adequate lane departure warning to the driver. The recommended pattern is shown in Figure 1.

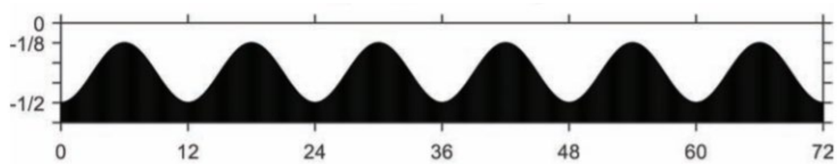


Figure 1. Sinusoidal rumble strip example from Indiana (Mathew et al., 2018).
[Pattern depth is on vertical axis and wavelength is on horizontal axis, in inches]

Sinusoidal rumble strips are milled into the pavement like conventional, milled rumble strips, but use a continuous cut that follows a sinusoidal wave. The safety effects of sinusoidal rumble strips have not been documented to date. The objectives of this study are to evaluate the safety benefits of sinusoidal centerline rumble strips. This will include the development of at least 10 crash modification factors (CMFs) for rural undivided highways in Montana. Among the CMFs to be developed are the following:

- Total crash frequency (all crash types and severity levels)
- Fatal + injury crash frequency (all crash types)
- Frequency of following “target” crash types:
  - Single vehicle run-off the road (SVROR)
  - Off road left
  - Head-on
  - Sideswipe opposite direction crashes
- Fatal + injury crash frequency of following “target” crash types:
  - Single vehicle run-off the road (SVROR)
  - Off road left
  - Head-on
  - Sideswipe opposite direction crashes

The Empirical Bayes (EB) observational before-after study design will be used to develop the CMFs. A novel matching method is proposed to confirm that the reference group sites identified for the EB analysis are similar to the sites treated with the sinusoidal centerline rumble strips. The analysis results will be disaggregated by season (fall, winter, spring, and summer) to determine if the effectiveness of the rumble strips differs throughout the year. In addition, further disaggregate analyses will be undertaken to determine if the safety effects vary based on roadway features, such as the degree (or radius) of horizontal curve. The research team also proposes to develop a benefit-cost ratio for the sinusoidal centerline rumble strips, to illustrate the relationship between safety benefits and construction costs. The team will also compare the safety performance of sinusoidal centerline rumble strips with that of conventional centerline rumble strips to provide guidance on which is the most effective from a safety management perspective.

BENEFITS AND BUSINESS CASE

This research is expected to quantify the safety effects of installing sinusoidal centerline rumble strips on undivided rural highways in Montana. In addition, the crash modification factors developed for the sinusoidal centerline pattern will be compared to a parallel evaluation of centerline rumble strips. These results will provide MDT with quantitative information to determine the impacts of centerline rumble strips countermeasure implementation on undivided rural highways in Montana, and to determine if the safety effects from the different patterns differ. If the safety performance does differ, MDT will be well-positioned to identify the tradeoffs associated with deploying a specific pattern relative to site-specific conditions. For example, research suggests that the sinusoidal pattern produces lower exterior noise levels than the traditional, milled centerline rumble strip pattern. If the safety effects are similar, MDT may consider noise propagation with safety performance tradeoffs when determining which centerline pattern to install at specific sites. If the safety effects between the patterns differ, the MDT will be able to use the results to inform policy decisions concerning centerline rumble strip countermeasure deployments by understanding the safety benefits associated with each pattern.

The disaggregate analyses proposed for this research will also inform decisions concerning where to deploy sinusoidal or traditional centerline rumble strips on undivided highways in Montana. For example, the research plan proposes to consider the impact that degree of curvature, shoulder width, and other site-specific safety countermeasures have on the safety effects of centerline rumble strip implementation. If certain site-specific conditions indicate that the rumble strips are more effective in such instances, this will enable MDT to prioritize their implementation. Similarly, the CMFs developed for certain crash types will enable MDT to identify whether sinusoidal centerline rumble strips offer improved safety performance for a high frequency of certain crash types relative to other crash types. This information will help MDT to most efficiently allocate limited resources when deploying centerline rumble strips throughout the state.

OBJECTIVES

The objectives of this research project are as follows:

- Quantify the safety performance of sinusoidal centerline rumble strips through the development of a suite of crash modification factors that provide an index of their safety effectiveness. Multiple CMFs will be developed to consider different crash severities (all crashes and fatal + injury crashes only), as well as different target crash types that are most likely to be influenced by the installation of centerline rumble strips (singe vehicle run-off the road, off road left, head-on, and sideswipe opposite direction crashes). CMFs will also be considered that are a function of other roadway characteristics, such as horizontal curvature, if applicable.
- Compare the safety effectiveness of sinusoidal centerline rumble strips to that of conventional centerline rumble strips to determine if any significant differences exist and the conditions under which they provide greater safety benefits.
- Provide a cost-benefit analysis of the installation of sinusoidal centerline rumble strips to help MDT improve decision-making regarding widespread implementation of centerline rumble strips.

RESEARCH PLAN

OVERVIEW OF THE RESEACH TEAM AND APPROACH

Dr. Eric Donnell, P.E., Professor of Civil Engineering, will serve as the project Principal Investigator (PI). He will be supported by Dr. Vikash Gayah, Associate Professor of Civil Engineering. Collectively, the research team has the requisite knowledge and skills needed to successfully complete the sinusoidal centerline rumble strips (SCLRS) safety evaluation, develop high-quality CMFs for inclusion in the FHWA CMF Clearinghouse, and perform a benefit-cost analysis of the safety treatment.

Several key distinctions of our team include the following:

- Research team led Montana DOT project entitled “Speed Limits Set Lower than Engineering Recommendations,” which was identified as a “Sweet Sixteen” high-value research project in maintenance and safety by the American Association of State Highway and Transportation Officials’ Research Advisory Committee.
- Co-principal author of Volume 1, Part B: Roadway Safety Management Process in the first edition of the *Highway Safety Manual* (NCHRP Project 17-34), which describes the safety management process, including methods to perform safety effectiveness evaluations.
- Estimated safety effectiveness of several safety countermeasures using the EB method as well as other state-of-the-art safety evaluation methods. Examples of safety countermeasure evaluations performed by the research team using the EB method include adaptive traffic signal control (PennDOT); shoulder, centerline, and edgeline rumble strips (NCHRP); SafetyEdge paving technique (FHWA); and horizonal curve pavement marking warnings (FHWA).
- Members of the research team are currently participating in a national-level study to estimate CMFs for various ITS strategies as a part of NCHRP Project 17-95.
- Co-principal author of NCHRP Report 641, *Guidance for the Design and Application of Shoulder and Centerline Rumble Strips*, which includes numerous multi-state EB evaluations of various rumble strip types.
- Have used roadway inventory and crash data from more than 10 state transportation agencies, including Montana.

Figure 2 is an overview of the proposed technical approach. Section 3 of the proposal describes the objectives, research approach, and deliverables associated with each of the 10 tasks shown in Figure 2.

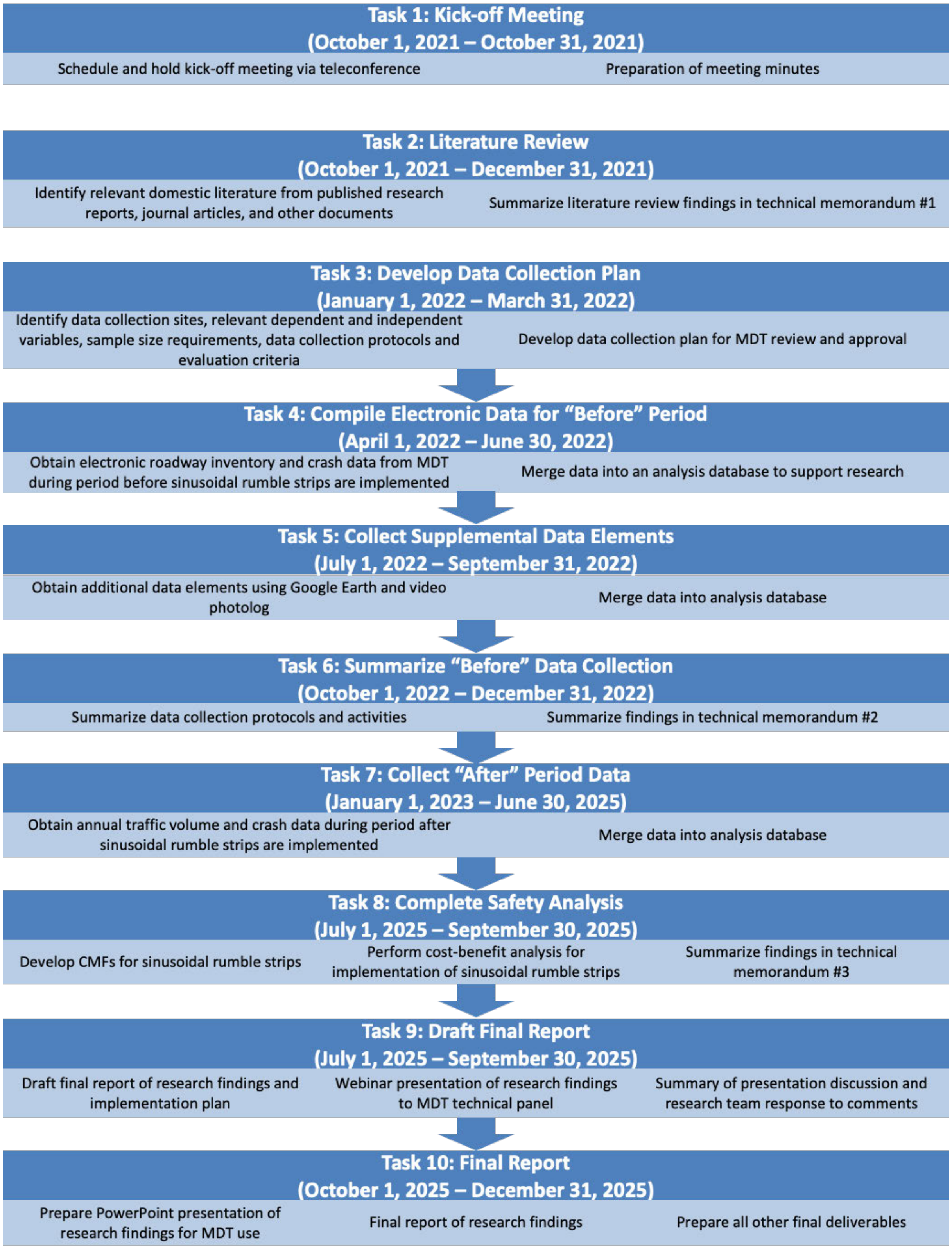


Figure 2. Overview of project research approach.

PROPOSED TASKS

This section of the proposal describes the objectives, research approach, and deliverables for each proposed project task.

Task 1: Kick-off Meeting

Objective

The objective of this task is to work in consultation with the Montana Department of Transportation technical panel to develop a meeting agenda and conduct a meeting with the technical panel and research team.

Research Approach

Within two weeks of the contract award, a kick-off meeting with the MDT technical panel, research team, and other interested personnel will occur. The proposed project Principal Investigator (Dr. Donnell) and Co-Principal Investigator (Dr. Gayah) will coordinate the meeting, which is assumed will be held virtually. The project PI will deliver a briefing describing the planned research approach, planned deliverables, and project schedule. Briefing materials will be provided prior to the call, including an agenda and presentation documents. Questions that the technical panel has concerning the research approach, planned deliverables, and project schedule will be discussed during the meeting.

One week after the kick-off meeting, the PI will distribute meeting minutes, including responses to issues raised concerning the proposed scope of work, to the MDT technical panel for review and comment. A one-week review period will be provided to MDT to comment on the research team’s response to issues related to the project scope of work, deliverables, and planned schedule. A final set of meeting minutes and any changes to the scope of work will be delivered to MDT, the research team, and others in attendance at the meeting no later than two weeks after the kick-off meeting.

Deliverables and Schedule

- Schedule a project kick-off meeting no later than two weeks after the project notice-to-proceed date.
- Prepare and distribute a draft meeting agenda at least two days prior to the kick-off meeting.
- Deliver draft meeting minutes to MDT technical panel no later than one week after the kick-off meeting, including responses to issues raised regarding the research approach, deliverables, or schedule.
- Deliver final meeting minutes to MDT technical panel, research team members, and others in attendance at kick-off meeting no later than two weeks after the meeting.

Task 2: Literature Review

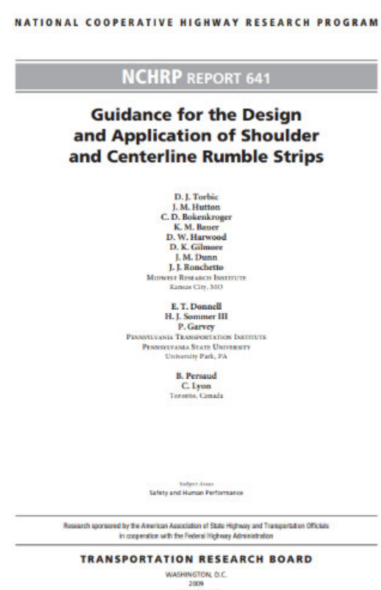
Objective

The objective of Task 2 is to review extant literature and current state and local transportation agency practices related to rumble strip use, particularly focused on sinusoidal rumble strips. Since sinusoidal centerline rumble strips were developed in Europe, relevant international literature will also be identified.

Approach

The research team has completed multiple studies related to the safety performance of roadway segments with rumble strips. Examples of these include the following:

- Development of Safety Performance Functions (SPFs) for different roadway types in Pennsylvania that include estimation of CMFs for shoulder and centerline rumble strips using cross-sectional modeling approaches.
- Co-authorship of *NCHRP Report 641: Guidance for the Design and Application of Shoulder and Centerline Rumble Strips.*
- Development of 321 CMFs for rumble strips that are currently included in the *FHWA CMF Clearinghouse*, of which over 260 are rated 3 stars or higher.


NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

NCHRP REPORT 641

Guidance for the Design and Application of Shoulder and Centerline Rumble Strips

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Subject Areas
Safety and Human Performance

Research sponsored by the American Association of State Highway and Transportation Officials in cooperation with the Federal Highway Administration

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WASHINGTON, D.C.
2009
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As a result of these efforts, the research team is very familiar with the extant research literature, state and local transportation agency practices, and international practices related to rumble strip application and use.

Both centerline and shoulder (or edgeline) rumble strips are proven and effective low-cost safety countermeasures. Based on the multi-state safety evaluation of shoulder rumble strips in NCHRP Report 641, shoulder rumble strips have been shown to reduce single-vehicle run-off-road total crashes by 15 percent and single-vehicle run-off-road fatal + injury crashes by 29 percent on two-lane rural highways.

Similarly, NCHRP Report 641 reported several safety benefits associated with centerline rumble strips on two-lane rural highways. These include: (1) 9 percent reduction in total crashes, (2) 12 percent reduction in fatal + injury crashes, (3) 30 percent reduction in head-on and opposite direction crashes, (4) 44 percent reduction in head-on and opposite direction fatal + injury crashes. Published research related to the safety effectiveness of sinusoidal centerline rumble strips is limited.

The purpose of the Task 2 literature review is to identify relevant literature related to application and safety effectiveness of sinusoidal centerline rumble strips, and to review the safety evaluation literature associated with observational before-after study designs. The results of this review will be used to inform the remaining tasks and as a comparison for the results of this research project. In addition to reviewing the rumble strips safety literature, the research team will also review and document various safety evaluation methods, focused on the Empirical Bayes observational before-after methodology. As is described in Task 3 below, the research team proposes that the EB process be used to evaluate the effectiveness of sinusoidal centerline rumble strips. However, the team also proposes to compare the results of the EB evaluation to some enhancements to the traditional EB process, which will be documented in the literature review.

To complete the Task 2 objectives, our team will identify and review domestic and international literature related to rumble strip evaluations. Our team will use the extensive library systems at Penn State, the 10th largest research library in North America, to identify published research reports and journal articles to be included in the literature review. The library consists of 38 individual libraries spread throughout the Commonwealth of Pennsylvania. Fifteen of these are located on the University Park campus near the Larson Transportation Institute, including the Engineering Library, Donald W. Hamer Maps Library, Penn State Law Library, and Architecture and Landscape Architecture Library. The entire library maintains an active collection of over 5.3 million physical titles and over 440,000 electronic titles. This includes most relevant journals that cover topics in transportation engineering, transportation science, and safety. The interlibrary loan program will also identify and borrow any title not currently available within the library system. Our team will review the Transportation Research Board's (TRB) *Research in Progress* (RIP) and *A Transportation Research Database* (TRID) to identify ongoing research related to rumble strip application and safety performance, which was not identified through the university library systems. The research team will also review safety rumble strip studies cited in the *CMF Clearinghouse*.

Deliverable

- A summary of the literature review will be included in a Task Report. This Task Report will be submitted to MDT for review no later than two months after the notice to proceed date. Note that the literature review will be continuously updated throughout the project to incorporate new findings on the safety effectiveness of sinusoidal centerline rumble strips. Any new findings after the completion of Task 2 will be incorporated into the Draft Final Report as a part of Task 9.

Task 3: Develop Data Collection and Analysis Plan

Objective

The objective of this task is to develop a data collection and analysis plan to assess the safety performance of sinusoidal centerline rumble strips that are to be implemented on MDT roadways during 2021.

Approach

The safety analysis proposes to use an Empirical Bayes before-after study design to evaluate the safety effectiveness of sinusoidal centerline rumble strips. The research team assumes that the date and locations where sinusoidal centerline rumble strips were installed during the 2021 construction season will be supplied to the research team by MDT. In outlining the research approach in this section, the proposed dependent and independent variables, Measures of Effectiveness (MoEs), data collection procedures/methodology, anticipated sample sizes, and proposed statistical techniques are described below.

<u>Dependent and Independent Variables</u>

A series of crash-based dependent variables will be considered for the safety evaluation. The dependent variables for both treatment (sites with sinusoidal centerline rumble strips) and reference sites (similar sites without sinusoidal centerline rumble strips) will include, at a minimum:

- Total crashes (all crash types and severity levels)
- All fatal + injury crashes for all crash types
- Total and fatal + injury crashes of the following “target” crash types:
    - Single vehicle run-off the road
    - Off road left
    - Head-on
    - Sideswipe opposite direction crashes

The data collection and analysis plan considers a process to develop 10 CMFs for sinusoidal centerline and conventional centerline rumble strips. To identify candidate crash types, electronic crash data will be used. The crash severity field will be used to identify fatal, injury, and property damage only (PDO) crashes. It is anticipated that the injury category may include subcategories, such as serious or other injury (based on review of online crash summary data on Montana DOT website). For all CMFs related to fatal plus injury categories, the fatal and serious injury categories in the crash severity field will be used. For the crash type CMFs proposed, it is anticipated that the electronic crash data will include a crash type field. This field will be used to identify the target crash types, including: single-vehicle run-off-road, off-road left, head-on, and sideswipe opposite direction crashes.

It is anticipated that three years of data both before and after the installation of the sinusoidal centerline rumble strips will be requested for both treatment and reference group sites, so the before period will include the period between 2018 and 2020 (inclusive) while the after period will cover the period between 2022 and 2024 (inclusive). The 2021 construction year will be excluded from the evaluation period.

The following variables will potentially be used as independent variables in the present study:

- Traffic volume (average annual daily traffic, veh/day);
- Segment length (miles);
- Proportion of commercial vehicle traffic (veh/day);
- Lane width (feet);
- Shoulder width (feet);
- Shoulder type (paved, stabilized, unpaved);
- Horizontal curve radius and length;
- Length of preceding tangent;
- Posted speed limit;
- Density of access points along roadway segment;
- Roadside hazard rating (1 = clear roadside; 7 = roadside hazards present near roadway); and
- Presence of other safety countermeasures at treatment and reference group sites.

Table 1 provides a summary of these data elements and anticipated sources of data collection. All crash and roadway data that MDT can provide based on electronic data systems will be determined by the research team, and these data will be requested by the research team and evaluated for their reliability and feasibility for use in this project. Note that the research team has prior experience working with electronic data available in Montana through the previous *Speed Limits Set Below Engineering Recommendations* research project and is thus well positioned to maximize the use of the existing electronic data. Candidate independent variables listed above, but not available from MDT, will be collected using tools such as Google Earth or available video photologs (e.g., Google Maps Street View). Based on prior experience, the research team envisions needing to manually collect data on roadside hazard rating, horizontal curvature, access density, and presence of other safety countermeasures.

Table 1. Proposed data collection elements, information sources, and collection periods.

Data Description	Elements	Information Source(s)	Collection Period (Before/After)
Crash Data	Crash type Severity Crash sequence Date of crash Crash location (e.g., route/milepost)	Electronic crash reporting system	Before and after periods
Traffic Data	Average annual daily traffic Posted speed limit	Electronic roadway inventory files	Before and after periods
Roadway Cross-section Data	Lane width Shoulder type and width Pavement surface type	Electronic roadway inventory files	Before period only (no change during analysis period)
Horizontal Alignment Data	Curve presence Radius and length of curve (if available)	Google Earth	Before period only (no change during analysis period)
Roadside Hazard Rating	Subjective roadside hazard rating (on a scale of 1 to 7)	Video photolog review	Before period only (no change during analysis period)
Treatment Installation Dates	Dates of sinusoidal rumble strip installation	MDT	Before period
Presence of Other Safety Improvements at Treatment and Comparison Sites	Shoulder rumble strip presence Traffic control devices Others as identified during vehicle review	Video photolog review	Before and after periods
Access Density	Number of driveways on each roadway segment	Google Earth	Before and after periods

Measures of Effectiveness

The primary MoE for this study will be the estimated change in crash frequency by severity or crash type. This estimate will produce a crash modification factor that can be used to determine how installing the sinusoidal centerline rumble strips will affect safety performance. In addition to the 10 CMFs requested by MDT (total and fatal + injury CMFs for all crashes and each of the target crash types), the research team anticipates further disaggregation of the CMFs. In this case, it is anticipated that the disaggregation will be completed based on site characteristics, such as the presence or radius horizontal curvature, or the presence of other safety countermeasures at each site (e.g., presence of shoulder rumble strips). Seasonal safety performance will also be considered. As a part of this task, the research team will prepare a preliminary plan for the types of CMFs that might be estimated; however, a final determination will be made during Task 8 upon obtaining and analyzing crash data during the "after" period.

Determination of Anticipated Sample Sizes

It is vital to ensure that enough data are collected such that the expected CMF can be detected with appropriate statistical significance in an observational before-after study. Even though in the planning stage for data collection the expected change in safety is unknown, it is still possible to make a rough determination, using appropriate assumptions, of how many sites are required based on the best available information about the expected change in safety and likely crash rates for similar untreated locations. For example, the methodology in Hauer (2008) can be used to obtain a "back-of-the-envelope" calculation for the sample size, given assumptions about the estimated safety effectiveness level, length of the after period, and crash rates before countermeasure installation.

As a demonstration, the research team applied the methodology in Hauer (2008) to determine the minimum average crash rates required on the roadways being considered for sinusoidal centerline rumble strip installation to obtain CMFs that are statistically significant at the 95% confidence level. This is necessary to help ensure that the CMF receives the highest possible star rating in the CMF Clearinghouse. For these calculations, the research team assumed:

- Sinusoidal rumble strips will be installed on 620 miles of roadway;
- Crash data are available for five years in the "before" period (i.e., before sinusoidal rumble strips are installed) and three years in the "after" period (i.e., after sinusoidal rumble strips are installed); and
- The safety effectiveness of sinusoidal centerline rumble strips is similar to that of conventional centerline rumble strips as reported in NCHRP Report 641.

The results are provided in Table 2. Based on known crash rates from other states (Minnesota, Pennsylvania, and Washington) obtained from NCHRP Report 641, the research team expects that these minimum crash rates will be exceeded in Montana. As a part of this task, however, the research team will refine these estimates based on actual crash rate information from Montana to provide a better understanding of the potential to obtain statistically significant CMFs as a part of this project.

Table 2. Preliminary estimate of minimum crash rates needed for statistically significant CMF results.

Crash Type	Assumed CMF Value*	Minimum Crash Rate (Crashes/Year/Mile)
Total crash frequency	0.91	0.27
Fatal + injury crash frequency	0.88	0.15
Total single-vehicle run-off-road (SVROR), off-road left, head-on, and sideswipe opposite direction crashes	0.70	0.02
Fatal and injury SVROR, off-road left, head-on, and sideswipe opposite direction crashes.	0.56	0.01

** Values obtained from NCHRP Report 641*

Data Analysis

To develop CMFs for this project, the research team proposes to use the EB before-after approach (Hauer 1997), which is accepted as the state-of-the-art in observational before-after studies in road safety. The proposed EB analysis properly accounts for regression-to-the-mean, differences in traffic volume, and crash trends (time series effects) between the periods before and after sinusoidal centerline rumble strip installation.

The EB approach is comprised of three basic steps, each defined as follows:

- *Step 1*: Predict what the safety performance of roadway with sinusoidal centerline rumble strips would have been in the after period had they not been installed.
- *Step 2:* Estimate what the actual safety performance was in the after period with the installation of sinusoidal centerline rumble strips.
- *Step 3:* Compare the results of *Step 1* and *Step 2*.

Step 1

In approaching *Step 1*, a reference group is used to account for the effects of traffic volume changes and temporal effects on safety due to the variations in weather, demographics, and crash reporting. This is done through the estimation of safety performance functions, which relate crashes of different types and severities to traffic flow and other relevant factors for a reference group of sites. This will enable the simultaneous accounting for temporal and possible regression-to-the-mean effects, as well as those related to changes in traffic volume. The reference group sites are those that do not have sinusoidal centerline rumble strips installed during the evaluation period – the reference group is used to estimate SPFs.

The research team will consider two methods for the identification of the set of reference group sites. The first will be all sites with similar functional classifications and number of lanes as the treatment sites (e.g., all two-lane rural roads, if sinusoidal centerline rumble strips are to be installed only on two-lane rural roads). This will be used to maximize the set of reference group sites considered. In the second method, the research team will apply an advanced statistical method (the propensity score matching approach) to identify a subset of reference sites that are as similar as possible to the set of treatment sites with respect to the independent variables considered (e.g., traffic volumes, geometric and roadside design, horizontal curvature, etc.). The propensity scores approach specifically seeks to emulate a randomized experiment that is similar to what would have been done in a clinical trial, in which the treatment and control groups are nearly identical. This is done by estimating a propensity score model that predicts the probability a given site receives treatment based on its features, then “matches” individual treatment sites to sites in the reference group based on these propensity scores. While the result is a new reference group that uses fewer overall sites in the CMF estimation, the reduced reference group minimizes the potential for bias in the CMF estimation that may be caused by the reference and treatment groups being too different. The research team has applied this propensity score approach to estimate the safety effectiveness of horizontal curvature, bus traffic, lane width on urban roads, intersection lighting, intersection forms, and rumble strips (Guadamuz et al., 2020; Li and Donnell, 2020; Wood and Donnell, 2016; Gooch, Wood and Donnell, 2016; Wood, Gooch, and Donnell, 2015; Sasidharan and Donnell, 2013).

Data required for SPF development include crash, traffic volume, and geometric data. Negative binomial regression will be used to fit the SPF parameters from the reference group. Other count regression modeling methods, such as panel data models, will be considered, if they offer an improved fit to the data.

The general functional form of the negative binomial regression model is:

$$ln\lambda_i = \beta X_i + \varepsilon_i \quad (1)$$

where λ_i = expected number of crashes at location i; β = vector of estimable regression parameters; X_i = vector of geometric design, traffic volume, and other site-specific data for location i; and ε_i = gamma-distributed error term.

The mean-variance relationship for the negative binomial distribution is:

$$Var(\lambda_i) = E(\lambda_i)[1 + \alpha E(\lambda_i)] \quad (2)$$

where $Var(\lambda_i)$ = variance of reported crashes y occurring at location i; $E(\lambda_i)$ = expected crash frequency at location i; and α = overdispersion parameter.

Equation 3 shows the general form of an SPF for roadway segments that is consistent with Equation 1.

$$N_{i,SPF} = AADT_i^{\beta_{AADT}} \times \exp(\beta_0 + \sum x_{ij}\beta_j) \quad (3)$$

where $N_{i,SPF}$ = predicted crash frequency for roadway segment i using an SPF created from the reference group [crashes/year]; β_{AADT} = estimated coefficient for traffic volume; $AADT_i$ = traffic volume on segment i; and β_j = estimated coefficient for other variables x_{ij} that describe segment i.

Step 2

The expected number of crashes on segment i had no treatment been applied, $N_{i,EB}$, uses an SPF of the type shown in Equation 3 to first estimate the number of crashes that would be expected in each year of the before period at locations with traffic volumes and other characteristics similar to a treatment site being analyzed. An EB adjustment is then applied to the SPF prediction to incorporate reported crash frequency in the prediction of crash frequency at each location. This EB adjustment is shown in Equation 4 (Hauer, 1997).

$$N_{i,EB} = w_i \times N_{i,SPF} + (1 - w_i) \times N_{i,obs} \quad (4)$$

where $N_{i,EB}$ = predicted crash frequency at location i based on EB adjustment [crashes/year]; w_i = adjustment weight for predicted crash frequency at location i; $N_{i,SPF}$ = predicted crash frequency at location i based on the SPF (e.g., Equation 3) [crashes/year]; and $N_{i,obs}$ = reported or observed crash frequency at location i [crashes/year].

The weight (w_i) used for the EB adjustment for any location i is derived using Equation 5 (Hauer, 1997).

$$w_i = \frac{1}{1+\alpha\times\sum_{all\ study\ years} N_{i,SPF}} \quad (5)$$

Thus, Equations 3, 4, and 5 are used to determine N_{EB}^{Before} for the treatment sites in the before period by applying the SPFs generated in *Step 1*.

The SPF is then used to calculate the predicted crash frequency using the SPF, N_{SPF}^{After}, for all treated sites in the after period. Finally, the EB adjusted expected crash frequency in the after period, N_{EB}^{After}, is calculated using Equation 6 and the adjustment factor, r, from Equation 7.

$$N_{EB}^{After} = N_{EB}^{Before} \times r \quad (6)$$

$$r = \frac{\sum_{after\ years} N_{SPF}^{After}}{\sum_{before\ years} N_{SPF}^{Before}} \quad (7)$$

where r = adjustment factor for differences in duration and traffic volume between before and after periods; and N_{EB}^{After} = EB adjusted crash frequency predicted during the after period.

This EB adjusted value obtained from Equation 6 provides the expected crash frequency if no treatment was applied. This expected crash frequency will then be compared with the reported crash frequency after the treatment was applied to assess the safety effects of the sinusoidal centerline rumble strips.

Step 3

An unbiased estimate of the safety effect (θ) of the treatment is obtained using Equations 8 and 9.

$$\theta = \frac{N_{observed}^{After}}{N_{EB}^{After}\left[1+\frac{Var(N_{EB}^{After})}{N_{EB}^{After^2}}\right]} \tag{8}$$

$$Var(N_{EB}^{After}) = \sum_{all\ sites} r^2(1-w)N_{EB}^{After} \tag{9}$$

where θ = unbiased estimate of safety effect of the countermeasure; and $N_{observed}^{After}$ = reported or observed crashes during the after period.

Finally, the standard error associated with this safety effect estimate was computed using Equations 10 and 11.

$$Std\ Error(\theta) = \sqrt{\theta^2\left[\frac{\left(\frac{Var\left(N_{observed}^{After}\right)}{N_{observed}^{After^2}}\right)+\left(\frac{Var\left(N_{EB}^{After}\right)}{N_{EB}^{After^2}}\right)}{\left(1+\frac{Var\left(N_{EB}^{After}\right)}{N_{EB}^{After^2}}\right)^2}\right]} \tag{10}$$

$$Var(N_{observed}^{After}) = \sum_{all\ sites} N_{observed}^{After} \tag{11}$$

The percent change in crashes is $100 \times (1-\theta)$*;* thus, a value of $\theta = 0.70$ with a standard deviation of 0.12 indicates a 30 percent reduction in crashes with a standard deviation of 12%. In this particular example, the CMF is the index of effectiveness.

CMFs will be estimated using this methodology both with the entire set of reference group sites and the reduced reference group obtained using the propensity score matching procedure. Any differences can be used to determine how much more effective the propensity score matching approach is able to capture the safety effects associated with sinusoidal centreline rumble strips.

Dr. Donnell, the proposed project PI, led a project for the FHWA Office of Safety, titled *Development of a Crash Modification for the Safety Edge on Rural Highways*, which employed the EB observational before-after evaluation method that is described above (Donnell et al., 2016). The Penn State research team also applied the EB approach to estimate CMFs for speed limits set lower than engineering recommendations in Montana (Donnell et al., 2016), for horizontal curve pavement marking warnings for Pennsylvania (Donnell et al., 2019), and for installation of adaptive traffic signal control in Pennsylvania (Gayah et al., 2020). Dr. Gayah is also participating in a national-level study to estimate CMFs for various ITS strategies as a part of NCHRP Project 17-95.

The research team will supplement the observational before-after analysis to estimate CMFs for sinusoidal centerline rumble strips with a cross-sectional comparison of the safety performance between application of conventional centerline rumble strips and sinusoidal centerline rumble strips. This cross-sectional comparison will use crash data from MDT on similar roadway segments with conventional centerline rumble strips installed. For this analysis, the research team proposes to apply the propensity scores approach outlined above to "match" sites with conventional and sinusoidal rumble strips to simulate a randomized experiment. A cross-sectional statistical model will then be developed using negative binomial regression to compare the safety performance between sites with conventional centerline rumble strips versus those with sinusoidal centerline rumble strips.

Deliverable

- Develop a draft data collection plan no later than six months after project notice-to-proceed date as a part of a Task Report. The MDT technical panel will then be provided with a 30-day review period.
- A final data collection plan, integrating all MDT technical panel comments on the draft plan, will be submitted to MDT no later than eight months after the project notice-to-proceed date.

Task 4: Compile "Before" Period Crash and Electronic Roadway Inventory Data for Treatment and Reference Group Sites

Objective

The objective of this task is to collect electronic crash and roadway inventory data for both the treatment and reference group sites in the period before sinusoidal centerline rumble strips were implemented.

Approach

As a part of this task, the research team will obtain crash and roadway inventory data for both reference and treatment sites, as well as sites with conventional center rumble strips installed, in the period before sinusoidal centerline rumble strips were installed. The treatment sites will include those that are being proposed for sinusoidal rumble strip installation during the 2021 construction season. Additionally, the set of reference group sites will be determined as a part of this task. As mentioned in the Task 3 description, two reference groups will be considered. The first will be all sites with similar functional classifications and number of lanes as the treatment sites, which will be used to maximize the set of reference group sites considered.

The research team will also consider applying the propensity score matching approach to identify a subset of reference sites that are as similar as possible to the set of treatment sites with respect to the independent variables considered (e.g., traffic volumes, geometric and roadside design, horizontal curvature, etc.). The propensity scores framework is applied in causal inference to improve quasi-experimental studies (Dehejia and Wahba, 2002). The method involves using characteristics of individual observations to predict the likelihood, or propensity, that an observation has been treated with some feature (Rosenbaum and Rubin, 1983). These propensity scores are then used to match treated observations with untreated observations. This mimics a randomized experiment by accounting for the non-random assignment of the treatment to an observation by reducing correlation between the treatment and explanatory variables between two samples (i.e., selection bias) (Guo and Fraser, 2010; Hirano et al., 2003; Holmes, 2014). The propensity score is the probability that an observation will receive the treatment based on known characteristics (Holmes, 2014). In this study, a binary logit model was used to estimate the propensity scores. The functional form that describes the conditional probability is shown in Equation 12:

$$P(RS_i|X_i = x_i) = E(RS_i) = \frac{e^{x_i\beta_i}}{1+e^{x_i\beta_i}} \tag{12}$$

where RS is the presence of sinusoidal centerline rumble strips (1 if present; 0 otherwise); x is a vector of covariates; i is the observation number; and β is the vector of estimated coefficients. When estimating this model, variables should be considered based on their relationship to the treatment and not on statistical significance, as omitted variable bias can arise (Kennedy, 2008; Rubin, 1980).

Treated and untreated observations are matched based on their propensity scores. A nearest-neighbor (NN) 1:1 method is proposed, which identifies the closest propensity score for an untreated observation within a predetermined caliper width (e.g., 20 percent of the standard error of estimated propensity scores) for each observation in the treated sample (Holmes, n.d.). The data are randomly sorted prior to matching to avoid potential bias that can arise from matching curves to adjacent tangents. Upon matching an untreated observation to a treated observation, the untreated observation is removed from the sample, as performing the matching without replacement maximizes the efficiency of the estimators (Dehejia and Wahba, 2002). If an entity is unmatched, it is also removed from the dataset.

The goal of matching on propensity scores is to reduce bias between a set of treated (sites with sinusoidal centerline rumble strips) and untreated (reference group sites) observations. In order to verify that matching has done this effectively, the two matched samples are compared using standardized bias—calculated as shown in Equation 13—which quantifies differences in the distribution of the covariates between a set of treated and untreated data (Rosenbaum and Rubin, 1983).

$$SB = 100\left(\frac{(\bar{x}_T - \bar{x}_{UT})}{\sqrt{\frac{S_T^2+S_{UT}^2}{2}}}\right) \tag{13}$$

where SB is the standardized bias between the treated and untreated samples; $\bar{x}_T$ is the sample mean of the treated group for covariate x; $\bar{x}_{UT}$ is the sample mean of the untreated group for covariate x; S_T^2 is the sample variance of the treated group for covariate x; and S_{UT}^2 is the sample variance of the untreated group for covariate x. Previous research suggests that standardized bias values of less than 10 percent for each covariate is desired upon completion of the matching process (Austin, 2011).

For the treatment and reference groups, as well as the group of sites with conventional centerline rumble strips, the research team will request electronic crash and roadway inventory datafiles from MDT. A minimum period of three years of "before" data will be requested for each treatment and reference location, though up to five years will be obtained if sufficient data are available. The research team will develop an analysis database in which crash data are matched to individual roadway segments using the linear referencing system implemented in Montana. This existing system identifies crash locations on the state roadway networks based on the state route or corridor identification number, reference post (milepost) and offset. These crash data will be reviewed to classify crashes based on their injury severity level (fatal/injury vs. non-fatal/injury) and type. Specifically, the research team will classify crashes based on the "target" crash types outlined in Task 3. The team will first assess if existing classifiers can be used to determine if each crash falls into each of these target crash categories; otherwise, the research team will request detailed crash narratives for the set of crashes identified, which will be used to determine if each crash falls into any of the target crash types.

The research team will also assess the electronic roadway datafiles to identify data elements useful for the analysis and identify additional data elements to be manually collected. The research team will review these additional data collection elements with the MDT technical panel before beginning manual data collection as a part of Task 5.

Task 5: Collect Supplemental Roadway Inventory Data for Treatment and Reference Group Sites

Objective

The objective of this task is to append the existing roadway inventory data obtained from MDT with additional data collection elements that might be useful for the safety analysis.

Approach

In this task, the research team will collect the additional data elements identified in Task 4 (and reviewed with the MDT technical panel) and append these to the analysis database. Data elements will be collected electronically using both Google Earth aerial imagery and Google Maps Street View. Google Earth will be used to collect access density and horizontal curvature information, both of which have been shown to significantly influence both total and target crash frequencies. Specific horizontal curvature information would include length of curve within a segment as well as radius or degree of curvature. Google Maps Street View and/or video photologs available from MDT will be used to collect roadside hazard rating (measured on a 1-7 scale as defined in Zegeer et al. (1986)) and presence of safety countermeasures, such as the presence of shoulder rumble strips or other safety-influencing features of interest. The research team has existing data collection protocols in place that have been applied as a part of prior projects for state agencies, including both the Pennsylvania and Montana Departments of Transportation.

Task 6: Summarize "Before" Period Analysis Data

Objective

The objective of this task is to summarize the data collection activities performed as a part of Tasks 4 and 5.

Approach

In this task, the research team will summarize all data collection activities and protocols performed in Tasks 4 and 5 in a Task Report. This Task Report will include tabular and graphical summaries of the before period analysis data, including information regarding the number, type, and severity of crashes at all treatment and reference group sites, as well as those with conventional centerline rumble strips installed, and descriptive statistics (e.g., minimum, maximum, mean, and standard deviation) of all roadway, roadside, traffic, and other site-specific data.

Deliverable

- A summary of the before period data collection process, as well as a summary of the before period analysis data, will be included in a Task Report. This Task Report will be submitted to MDT for review no later than 15 months after the notice-to-proceed date.

Task 7: Collect and Compile "After" Period Crash and Traffic Volume Data for Treatment and Reference Group Sites Annually

Objective

The objective of this task is to update the analysis database with crash and traffic volume information during the period after sinusoidal centerline rumble strips are installed.

Approach

In this task, the research team will collect crash and traffic volume data for both the treatment and reference group sites during the period after sinusoidal centerline rumble strips are installed. It is anticipated that three years of data will be included in the after period (2022, 2023, and 2024) to obtain the most reliable CMF possible. The research team will also periodically review other data collection elements to identify changes that might have occurred during the after-period data collection. Specifically, the team will look for changes in posted speed limits, presence of other safety countermeasures implemented at sites during the after period, or changes in access density or other features that might affect the safety analysis. It is anticipated that the after-period crash data will be available on or near June 1st in the year following the previous calendar year. For example, it is assumed that the 2022 after-period crash data will be available on or near June 1, 2023.

Task 8: Complete Safety Analysis

Objective

The objective of this task is to estimate final CMFs for sinusoidal centerline rumble strips using the data obtained from the previous tasks.

Approach

In this task, the research team will apply the EB observational before-after study methodology outlined in Task 3 to develop a suite of CMFs for sinusoidal centerline rumble strip application in Montana. At least 10 CMFs will be developed. These include:

- Total crash frequency (all crash types and severity levels)
- Fatal + injury crash frequency
- Frequency of following “target” crash types:
    - Single vehicle run-off the road
    - Off road left
    - Head-on
    - Sideswipe opposite direction crashes
- Fatal + injury crash frequency of following “target” crash types:
    - Single vehicle run-off the road
    - Off road left
    - Head-on
    - Sideswipe opposite direction crashes

The research team will also consider disaggregating CMF results by season (fall, winter, spring, and summer) to determine if the effectiveness of the rumble strips differs throughout the year. In addition, further disaggregate analyses will be undertaken to determine if the safety effects vary based on roadway features, such as the degree (or radius) of horizontal curve. CMFs will be developed using both the larger reference group and the reference group identified using the propensity score approach for comparison. The former would have a larger sample size, while the latter would most closely simulate a randomized experiment and is likely to provide more accurate estimates of the safety impacts of sinusoidal centerline rumble strips.

Using the CMF estimates, the research team will also perform a cost-benefit analysis of sinusoidal centerline rumble strip application. The team will obtain construction cost estimates from MDT and then estimate expected benefits based on the CMFs determined in this task. The research team will estimate safety impacts over an assumed life of the sinusoidal rumble strip installation, apply average crash costs obtained from MDT to estimate the benefits, and convert all future benefits to present-day value. This cost-benefit analysis would help MDT improve its decision-making regarding the widespread implementation of sinusoidal rumble strips throughout the state. In this analysis, both costs and benefits will be converted to present dollar values for a fair comparison.

Additionally, the team will apply cross-sectional analysis methods to compare the safety performance of conventional versus sinusoidal centerline rumble strips to provide MDT with details on which is the most effective from a safety management perspective.

Deliverable

- A summary of the safety analysis, including CMF estimates and benefit-cost analysis, will be provided as a part of a Task Report. This Task Report will be submitted to MDT for review no later than 47 months after the notice to proceed date.

Task 9: Draft Final Report and Presentation

Objectives

The objectives of this task are to: (1) prepare a draft final report of all safety evaluations completed for the research project and (2) develop a PowerPoint presentation that will be used in a webinar debriefing with the MDT technical panel.

Approach

The Task 9 draft final report will provide a comprehensive summary of all project activities. The report will include elements from the Task 2 literature review (updated to reflect the latest literature on the safety effectiveness of sinusoidal centerline rumble strips at the time of final report preparation), Task 4 data collection and analysis plan, results from the Task 6 data collection effort, and Task 8 safety analysis. However, these elements will be woven together to provide a comprehensive report on all project activities. The report will also include recommendations to implement the findings statewide. The MDT technical panel will have 30 days to review and comment on the draft final report.

The research team will also prepare a presentation describing the entire research effort. The presentation will highlight the overall objectives of the project, literature review, research methodologies, research findings, and implementation recommendations. The research team will work with the MDT technical panel to schedule a webinar briefing. During the briefing, the research team will present the findings from the project to the MDT technical panel. Recommendations for field implementation of the findings will be included in the presentation as well.

Deliverables

- Prepare draft final report and submit to MDT no later than 48 months after the notice-to-proceed date of the project.
- Develop and execute a webinar PowerPoint debriefing the project findings no later than 48 months after the notice-to-proceed date.

Task 10: Final Report and Presentation

Objectives

The objectives of this task are to: (1) prepare a final report of all safety evaluations completed for the research project and (2) update the Task 9 PowerPoint presentation.

Approach

The MDT technical panel will be provided with a 30-day review period of the Task 9 draft final report. Once the panel's comments are received by the research team, a teleconference call will be scheduled to review and discuss the comments. The panel's comments will then be integrated into a final report.
Similarly, panel comments on the Task 9 PowerPoint presentation will be solicited in Task 10. The research team will integrate the panel's comments into a final presentation that will then be shared with the technical panel. The technical panel can use the presentation to conduct statewide debriefings on the project after the period of performance concludes.

Deliverables

- Schedule a research team-panel teleconference call to discuss the panel's comments on the draft final report and debriefing presentation.
- Integrate panel comments in final project report, which will be submitted no later than 51 months after the notice-to-proceed date.
- Integrate panel comments in final project presentation, which will be submitted no later than 51 months after the notice-to-proceed date.

INTELLECTUAL PROPERTY

The research team does not envision any intellectual property issues as a part of this project.

MDT AND TECHNICAL PANEL INVOLVEMENT

The Penn State research team anticipates that MDT will provide the following support during the project period of performance:

- Electronic roadway inventory data for all sinusoidal centerline rumble strip and traditional centerline rumble strip treatment sites, as well as the corresponding reference sites, in Montana. The installation dates for both treatments will also be requested.
- Crash data files for all treatment and reference group sites included in the data collection plan (as well as sites with conventional centerline rumble strips installed). It is anticipated that these data will be requested for three to five years before and for three years after rumble strip installation. The project schedule assumes that all before-period crash data will be available when the project begins, and that the after-period data will be available by June of each year after the prior calendar year (e.g., 2022 after-period crash data will be available by June 1, 2023).
- It is anticipated that MDT will review deliverables submitted during Tasks 1, 2, 3, 6, 8, 9, and 10.
- The research team will have annual meetings with the Technical Panel at least once per year to provide updates on the project status. These meetings will be held in a virtual format (via MS Team or similar software). Meeting notes will be provided by the research team for review.

OTHER COLLABORATORS, PARTNERS, AND STAKEHOLDERS

There are several candidate collaborators, partners, and stakeholders that should be considered for this project. These include the following:

1. Montana State Highway Traffic Safety Section: this group will be a valuable stakeholder through collaboration, by supporting safety data requests, reviewing all project deliverables, and creating buy-in and acceptance of the research results among the organization.
2. MDT Research Division: this group will be a valuable collaborator by coordinating interactions between the research team, the MDT Research Review Committee, and the MDT technical staff. The MDT Research Division will also be a valuable partner with the research team in identifying opportunities to implement the research into practice.
3. Montana Design and Construction Professionals: the safety effects of sinusoidal and traditional centerline rumble strips will be determined for this project – sharing the results of the research with these stakeholder groups will inform designers and contractors of the benefits associated with both centerline rumble strip patterns, so that these safety countermeasures may be integrated into planned projects or deployed on existing roads, to mitigate roadway departure crashes.

PRODUCTS

The following products will be developed during the course of this project:

1. Monthly progress reports delivered within 15 days after the conclusion of each month during the project period of performance.
2. Minutes from the Task 1 kick-off meeting and Annual Project meetings will be provided by the research team.
3. Three Task Reports will be provided at the conclusion of the following tasks:
    a. Task 2: Literature Review
    b. Task 3: Develop Data Collection/Analysis Plan
    c. Task 6: Summary of "Before" Period Data
    d. Task 8: Summary of "After" Period Data and Analysis Results
4. Draft Final and Final Report summarizing the entire research effort, findings, and recommendations during Tasks 9 and 10.
5. Presentation of project findings to the technical review panel, delivered through a webinar format at the conclusion of Task 9. This presentation will include a summary of the research effort, findings, and implementation strategies.
6. PowerPoint file of the webinar for MDT use to present to local agencies – this file will be delivered with the Final Report in Task 10.
7. Research project summary report, TRB poster submission, implementation report, and performance measures report after all deliverables in Task 10 have been approved by the project review panel.

IMPLEMENTATION

The Final Report will provide at least 10 crash modification factors for the safety effects of sinusoidal centerline rumble strips, including a comparison of these findings to the CMFs developed for centerline rumble strips on undivided rural highways in Montana. These CMFs will help MDT determine when and where rumble strips may be most effective (location and crash type). The findings will also provide safety data that MDT can use to determine which centerline rumble strip pattern to use when centerline rumble strips are used as a safety countermeasure to mitigate lane departure crashes.

SCHEDULE

Table 3 presents the proposed schedule for this project. In addition to the deliverables shown in this table and the “Research Plan” section, monthly progress reports will be provided to MDT no later than 15 days after the end of each calendar month during the project period of performance.

Table 3. Project Time Schedule.

Task	2021	2022				2023				2024				2025			
	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Task 1: Kick-off Meeting	M																
Task 2: Literature Review	R																
Task 3: Develop Data Collection/Analysis Plan		R															
Task 4: Compile "Before" Period Crash and Electronic Roadway Inventory Data for Treatment and Reference Group Sites																	
Task 5: Collect Supplemental Roadway Inventory Data for Treatment and Reference Group Sites																	
Task 6: Summarize "Before" Period Analysis Data					R/M												
Task 7: Collect and Compile "After" Period Crash and Traffic Volume Data for Treatment and Reference Group Sites Annually									M				M				
Task 8: Complete Safety Analysis																R	
Task 9: Draft Final Report and Presentation																R/M	
Task 10: Final Report																	R
TR – Task Report or other deliverable to be submitted to the project technical panel. M – Meeting with the project technical panel																	

BUDGET

The itemized budget for the entire project appears on the next page in the required format.

The total amount budgeted is $184,731.

One person-month = 160 person-hours. The provision of person-hours and salary rates is solely for purposes of estimation in this proposal. It is understood that the University will not be required to maintain a record by person-hours of effort and rates under a resultant award, because the University's accounting system is not geared toward providing this information. The University operates per 2 CFR 200.430 (h) and (i), and its financial system is based on a percent of effort, not hours worked. The University will not maintain accounting records on a task-by-task basis, but rather for the total project.

Estimated salary costs are based on salary rates for fiscal year 2020-2021. For budgeting in succeeding fiscal years (for the project time occurring after June 30 of any given year), the salaries have been adjusted at the University approved rate of 2.5% per year each July 1. Therefore, the salary costs shown in the tasks will not necessarily correspond to the hourly rate.

Employee Benefit Plan: Fringe benefits are computed using the fixed rates of 34.88% applicable to Category I Salaries, 12.35% applicable to Category II Graduate Assistants, 7.94% applicable to Category III Salaries and Wages, 0.31% applicable to Category IV Student Wages, and 23.88% for Category V, Postdoctoral Scholars and Fellows, for fiscal year 2021 (July 1, 2020, through June 30, 2021). If this proposal is funded, the rates quoted above shall, at the time of funding, be subject to adjustment for any period subsequent to June 30, 2021, if superseding Government approved rates have been established. Fringe benefit rates are negotiated and approved by the Office of Naval Research, Penn State's cognizant federal agency.

Overhead: F&A rates are negotiated and approved by the Office of Naval Research, Penn State's cognizant federal agency. Penn State's current fixed on-campus rate for research is 60.50% of MTDC from July 1, 2020, through June 30, 2021. New awards and new competitive segments with an effective date of July 1, 2021, or later shall be subject to adjustment when superseding Government approved rates are established. Per 2 CFR 200 (Appendix III, Section C.7), the actual F&A rates used will be fixed at the time of the initial award for the duration of the competitive segment.

Graduate Student Tuition Remission: Computed using the approved tuition charges for a one-half (1/2) time graduate assistant of $9,350 for fall semester 2020, $9,350 for spring semester 2021, and $4,675 for summer session 2021. The charges quoted above are increased by one percent (1%) for any project period occurring after summer session 2021, and each summer session thereafter.

Definition of a Year: The University defines the term "year" as the fiscal year (July – June).

Table 2 Detailed Project Budget

Labor Expenses																	
Person	**Role**	**Task 1**	**Task 2**	**Task 3**	**Task 4**	**Task 5**	**Task 6**	**Task 7**	**Task 8**	**Task 9**	**Task 10**	**Total**	**Hourly Wage**	**Total Wages**	**Hourly Benefit**	**Total Benefit**	**Total Cost**
E. Donnell	Principal Investigator	4	16	16	24	16	16	24	40	40	16	**212**	[redacted]				
V. Gayah	Co- Principal Investigator	4	16	24	40	24	24	40	40	40	16	**268**					
Post Doctoral Student	Research	0	120	120	120	80	40	0	0	0	0	**480**					
Graduate student	Research	0	0	0	0	240	0	240	400	80	40	**1000**					
Total:		**8**	**152**	**160**	**184**	**360**	**80**	**304**	**480**	**160**	**72**	**1960**	[redacted]	**$88,162**	[redacted]	**$26,936**	**$115,098**
Indirect Cost @ 60.50%:																	**$69,633**
Fixed Fee @ X%:																	**$0**
Total Labor Cost:																	**$184,731**
Direct Expenses																	
Subcontractor: A																	**$**
Subcontractor: B																	**$**
In State Travel																	**$**
Out of State Travel																	**$**
Expendable Supplies																	**$**
Total Project Cost:																	**$184,731**

Table 4: Task, Meeting, and Deliverable Cost Breakout			
Item	**Labor**	**Travel**	**Total**
Task 1: Kick-off Meeting	$ 1,518.00	$ -	$ 1,518.00
Task 2: Literature Review	$ 12,615.00	$ -	$ 12,615.00
Task 3: Develop Data Collection/Analysis Plan	$ 13,891.00	$ -	$ 13,891.00
Task 4: Compile "Before" Period Crash and Electronic Roadway Inventory Data for Treatment and Reference Group	$ 18,201.00	$ -	$ 18,201.00
Task 5: Collect Supplemental Roadway Inventory Data for Treatment and Reference Group Sites	$ 22,993.00	$ -	$ 22,993.00
Task 6: Prepare Technical Memorandum Summarizing "Before" Period Analysis Data	$ 10,038.00	$ -	$ 10,038.00
Task 7: Collect and Compile "After" Period Crash and Traffic Volume Data for Treatment and Reference Group Sites	$ 27,492.00	$ -	$ 27,492.00
Task 8: Complete Safety Analysis	$ 44,057.00	$ -	$ 44,057.00
Task 9: Draft Final Report and Presentation	$ 23,866.00	$ -	$ 23,866.00
Task 10: Final Report	$ 10,060.00	$ -	$ 10,060.00
Total:	***$ 184,731.00***	***$ -***	**$ 184,731.00**

Table 5: State Fiscal Year (7/1 – 6/30) Breakdown						
Item	**State Fiscal Year**					**Total Cost**
	2022	**2023**	**2024**	**2025**	**2026**	
Salaries	$ 31,731.00	$ 7,196.00	$ 2,763.00	$ 15,853.00	$30,619.00	$ 88,162.00
Benefits	$ 7,944.00	$ 2,510.00	$ 920.00	$ 5,255.00	$10,307.00	$ 26,936.00
In-State Travel	$ -	$ -	$ -	$ -	$ -	$ -
Out of State Travel	$ -	$ -	$ -	$ -	$ -	$ -
Expendable Supplies	$ -	$ -	$ -	$ -	$ -	$ -
Total Direct Costs	$ 39,675.00	$ 9,706.00	$ 3,683.00	$ 21,108.00	$40,926.00	$ 115,098.00
Indirect Cost – 60.50%	$ 24,003.00	$ 5,872.00	$ 2,228.00	$ 12,771.00	$24,759.00	$ 69,633.00
Total Project Cost	***$ 63,678.00***	***$ 15,578.00***	***$ 5,911.00***	***$ 33,879.00***	***$65,685.00***	***$184,731.00***

STAFFING PLAN

This section provides an overview of the staff proposed for this project. Table 4 provides a breakdown of staff hours by task and total distribution of the project person-hours. In addition, qualifications of the project PI (Dr. Eric T. Donnell) and co-PI (Dr. Vikash V. Gayah) are provided. If the project is approved for funding, the Penn State team will hire a post-doctoral scholar and graduate assistant to participate in the project. The post-doctoral scholar will work on the literature review, data collection and analysis plan, and the before-period data collection effort. The graduate research assistant will work on the after-period data collection and analysis tasks.

Eric T. Donnell, Ph.D., P.E.

Eric Donnell is a professor in the Department of Civil and Environmental Engineering at Penn State, and will serve as the project Principal Investigator. He received his Bachelor of Science, Master of Engineering, and Doctor of Philosophy degrees in civil engineering from Penn State. His research interests and teaching responsibilities include: traffic safety, speed management, geometric design of highways and streets, and statistical and econometric modeling of transportation data. Dr. Donnell has 23 years of teaching and research experience.

Dr. Donnell has served as principal or co-principal investigator on research projects totaling more than $20 million in funding from sponsors including US DOT, NCHRP, FHWA, PennDOT, Montana DOT, New York City DOT, and the Department of Defense. He has published more than 70 refereed journal articles and more than 35 research reports on topics related to traffic safety, geometric design of highways and streets, speed management, and other transportation-related topics. Dr. Donnell chairs the Transportation Research Board's (TRB) Design Section and is past chair of the TRB Geometric Design Committee. He is an associate editor of *Accident Analysis*, the leading international journal related to traffic safety. He is also an associate editor of *Transportation Letters: The International Journal of Transportation Research* (in the safety and design areas), and *Transportation Research Record: the Journal of the Transportation Research Board*. He is a licensed professional engineer in the Commonwealth of Pennsylvania.

Total hours committed elsewhere during 51-month project duration	7,140
Percent time committed elsewhere	87.5%
Percent time available for MDT Project	12.5%

Vikash V. Gayah, Ph.D., E.I.

Dr. Vikash V. Gayah is an associate professor in the Department of Civil and Environmental Engineering at Penn State (joined 2012). He received his B.S. and M.S. degrees from the University of Central Florida (2005 and 2006, respectively) and his Ph.D. degree from the University of California, Berkeley (2012). Dr. Gayah's research focuses on urban mobility, traffic operations, traffic flow theory, traffic safety, and public transportation. His research approach includes a combination of analytical models, micro-simulations, and empirical analysis of transportation data.

Dr. Gayah has authored over 65 peer-reviewed journal articles, over 80 refereed conference proceedings, and numerous research reports to sponsors. He has worked on research contracts valued at more than $15 million, sponsored by various State Departments of Transportation (including Pennsylvania, Washington State, Montana, and South Dakota), US Department of Transportation (via the Mineta National Transit Research Consortium, the Mid-Atlantic Universities Transportation Center, and the Center for Integrated Asset Management for Multimodal Transportation Infrastructure Systems), Federal Highway Administration, National Cooperative Highway Research Program, and National Science Foundation. He is a member of the Transportation Research Board's Standing Committee on Access Management (ACP60) and Traffic Flow Theory and Characteristics (ACP50), where he serves as a paper review coordinator and the committee research coordinator.

Total hours committed elsewhere during 51-month project duration	4,600
Percent time committed elsewhere	56.3%
Percent time available for MDT Project	43.7%

Table 4. Staffing Plan and Level of Effort.

Task	Time Period	Personnel (Level of Effort and Percent Time Committed per Task)[a]			
		Donnell	Gayah	Post-doctoral Scholar (to be named)	Data Collection and Analysis Support (graduate student to be named)
1	10/1/2021-10/31/21	4 (2.5%)	4 (2.5%)		
2	10/1/21-12/31/21	16 (3.3%)	16 (3.3%)	120 (25%)	
3	1/1/22-3/31/22	16 (3.3%)	24 (5%)	120 (25%)	
4	4/1/22-6/30/22	24 (5%)	40 (8.3%)	120 (25%)	
5	7/1/22-9/30/22	16 (3.3%)	24 (5%)	80 (16.7%)	240 (50%)
6	10/1/22-12/31/22	16 (3.3%)	24 (5.0%)	40 (8.3%)	
7	1/1/23-6/30/25	24 (2.5%)	40 4.2%)		400 (41.7%)
8	7/1/25-9/30/25	40 (8.3%)	40 (8.3%)		240 (50%)
9	7/1/25-9/30/25	40 (8.3%)	40 (8.3%)		80 (16.7%)
10	10/1/25-12/31/25	16 (3.3%)	16 (3.3%)		40 (8.3%)
Total Level of Effort		212	268	480	1000
Percent of Total Project Hours per Staff Member[b]		10.8%	13.7%	24.5%	51.0%
Percent Time Committed over Project Period of Performance[c]		2.6%	3.3%	5.9%	12.3%

[a] = Percent time committed per task is the number of hours shown per staff member divided by the number of hours available during the period in which the task is performed. For example, in Task 1, Donnell is committing 4 hours to accomplish the task over a one month period of performance, which is 4 hours divided by 160 available hours = 2.5%

[b] = Percent of total project hours per staff member is the number of hours per staff divided by the total hours committed by all staff to the project. For example, Donnell is committing 212 hours among the 1960 total hours committed by the project team over the project period of performance = 212/1960 = 10.8%

[a] = Percent time committed over project period of performance is the number of hours per staff member divided by the total number of hours available over the 51 month period of performance. For example, Donnell is committing 212 hours to the project and there are 8,160 hours available over the 51 month project period of performance = 212/8160 = 2.6%.

FACILITIES

The Pennsylvania State University is a major research university, ranking nationally among universities in research and development expenditures and in the level of industry-funded research and development. Prominent among the University's programs is the College of Engineering, which has been ranked 15th nationally among graduate programs in engineering. **The Thomas D. Larson Pennsylvania Transportation Institute (LTI)** is an interdisciplinary research unit within Penn State's College of Engineering. Since its inception in 1968, LTI has maintained a threefold mission of research, education, and service. In pursuit of this mission, the institute has aspired to conduct innovative and relevant research directed toward current and future transportation needs, to promote continuing education for transportation professionals, to provide significant interdisciplinary educational and research opportunities for undergraduate and graduate students, and to disseminate research results within and beyond the transportation field. LTI research associates, who typically hold joint appointments with the institute and Penn State's academic colleges and schools, specialize in areas such as architectural, civil, electrical, industrial, and mechanical engineering as well as agriculture, business logistics and management, economics, geography, psychology, and statistics. LTI's energies are directed toward solving problems in three major areas of transportation research: transportation operations; transportation infrastructure; and vehicle systems and safety. The institute has conducted research projects for federal, state, municipal, and industrial sources, including the U.S. Department of Transportation (FHWA, FTA, NCHRP, SHRP, TCRP), U.S. Department of Energy, Department of Defense, National Science Foundation, Pennsylvania Department of Transportation, other state departments of transportation, the Center for Rural Pennsylvania, and a broad range of private-sector entities. The Institute’s external research fund expenditures exceed $10 million annually on contracts valued at more than $30 million.

Headquartered in a research complex on the Penn State University Park Campus, LTI has a number of excellent field facilities and laboratories. In particular, the computer facilities at LTI provide faculty, staff, and students with valuable experience in the use of advanced computer technology in the transportation field. The equipment ranges from portable laptop systems to powerful personal computers for advanced applications, including expert systems, various traffic and transportation software, statistical packages, geographic information systems, and spreadsheet applications, among others. In addition to having access to the institute's extensive microcomputer facilities, LTI researchers have 24-hour access to Penn State's computer laboratories and to the vast library of programs from the University's Information Technology Services. LTI faculty, staff, and students also have convenient access to the considerable holdings of the University Libraries—including a large collection of transportation-related books and journals in the Engineering Library.

The *Transportation Engineering and Management (TEaM) Laboratory* within LTI provides students with state-of-the-art hardware and software for use in academic and research environments. Additionally, the laboratory is equipped with video technology (televisions, digital video players, etc.), printers, and scanners. There are currently 10 workstations equipped with large-capacity network hard drives that contain a multitude of transportation engineering, statistics/econometrics, traffic simulation, and geographic information systems software. Transportation engineering applications include Autodesk's Civil 3D software as well as FHWA's Interactive Highway Safety Design Model (IHSDM), and AASHTO's Roadside Safety Analysis Program (RSAP). Each workstation contains Minitab, SPSS, STATA, Matlab, WinBUGS, and StatTransfer statistical/database management software. A complete set of traffic simulation software is also available, including Synchro, SimTraffic, Highway Capacity Software, PARAMICS, and VISSIM, among others. ArcGIS software is available to compile, map, and publish geographic information.

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APPENDIX A: STAFF RESUMES

ERIC T. DONNELL, PH.D., P.E.

Professor
Department of Civil and Environmental Engineering
The Pennsylvania State University
212 Sackett Building
University Park, PA 16802
Phone: (814) 863-7053
E-mail: etd104@psu.edu

PennState College of Engineering
CIVIL AND ENVIRONMENTAL ENGINEERING

EDUCATION

The Pennsylvania State University, University Park, PA 2003
Doctor of Philosophy, Civil Engineering
Minor: Statistics

The Pennsylvania State University, University Park, PA 1998
Master of Engineering, Civil Engineering

The Pennsylvania State University, University Park, PA 1996
Bachelor of Science, Civil Engineering

PROFESSIONAL REGISTRATION

Professional Engineer, Commonwealth of Pennsylvania License No. PE060273

PROFESSIONAL EXPERIENCE

Director, Center for Integrated Asset Management for Multimodal Transportation Infrastructure System

Thomas D. Larson Pennsylvania Transportation Institute, University Park, PA
2018 – present

Lead Mid-Atlantic regional multi-university consortium in the conduct of research, education, and technology transfer for a U.S. Department of Transportation University Transportation Center. Approximately $14.2 million of federal funding, and equal matching funds, will be disseminated for activities in support of infrastructure asset management over a five-year period. As Director, lead efforts to identify and develop annual activities, prepare federal reporting requirements, and build stakeholder support for Center.

Founded the annual Transportation Asset and Infrastructure Management conference in 2019, which is offered to stakeholders in the mid-Atlantic region. Inaugural conference was attended by 110 participants and has grown by 10 percent annually. In addition, founded the Transportation Infrastructure webinar series, which is held monthly to share research and industry best practices to professionals throughout the mid-Atlantic region.

Director, Thomas D. Larson Pennsylvania Transportation Institute 2016 – present

The Pennsylvania State University, University Park, PA

Responsible for day-to-day management of 56 full-time research, technical and support staff, who support more than 90 active contracts valued at approximately $30 million annually. Duties include developing and implementing the strategic plan for a multi-college research institute, formation of research partnerships, development and delivery of education and outreach programs, fundraising, and alumni relations. Annual research expenditures increased from approximately $7 million to more than $10 million over five-year period.

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Professor, Department of Civil and Environmental Engineering

The Pennsylvania State University, University Park, PA 2015 – present

Served as transportation engineering area coordinator from 2013 through 2018. Responsibilities included managing undergraduate and graduate curriculum offerings, leading graduate student admissions process, and other academic activities among five tenure-track faculty and 20 graduate students in transportation area of Civil Engineering. Also teach undergraduate and graduate courses in transportation design, transportation safety, traffic operations, and roadside safety and design; conduct research on topics related to speed management, traffic safety, and transportation design; perform service and outreach activities to various units at Penn State and professionally.

Director, Transportation Operations Program

Thomas D. Larson Pennsylvania Transportation Institute 2014 – 2015

Coordinate research activities among seven tenure- and non-tenure track faculty in areas of traffic operations, traffic safety, human factors, public policy, and geometric design research. Work with faculty and Thomas D. Larson Pennsylvania Transportation Institute to identify funding to support graduate research assistants.

Associate Professor, Department of Civil and Environmental Engineering

The Pennsylvania State University, University Park, PA 2010 – 2015

Conduct research on topics related to geometric design of highways and streets, traffic safety, speed management, and pavement marking visibility. Teach undergraduate and graduate classes related to transportation engineering, transportation design, traffic safety, roadside design and management, and traffic engineering. Perform service and outreach activities to various units at Penn State and professionally

Assistant Professor, Department of Civil and Environmental Engineering

The Pennsylvania State University, University Park, PA 2004 – 2010

Conduct research on topics related to geometric design of highways and streets, traffic safety, speed management, and pavement marking visibility. Teach undergraduate and graduate classes related to transportation engineering, transportation design, traffic safety, roadside design and management, and traffic engineering.

Associate Engineer, Bellomo-McGee, Inc.

Vienna, VA and State College, PA 2003 – 2004

Performed research in support of Federal Highway Administration Office of Safety Indefinite Delivery-Indefinite Quantity contract. Developed two informational reports and field guides associated with the traffic safety management process, and conducted median cross-section safety evaluation for limited-access rural highways.

Research Assistant, Pennsylvania Transportation Institute
The Pennsylvania State University, University Park, PA 1997 – 2003
Served as laboratory instructor for highway engineering and transportation design courses in Department of Civil and Environmental Engineering. Conducted field studies and statistical analysis related to operational effectiveness of centerline rumble strips; drafted functional specification for Interactive Highway Safety Design Model Policy Review Module; collected field data and performed statistical analysis of median safety for rural freeways/expressways in Pennsylvania.

Research Assistant, The Last Resource, Inc.
Bellefonte, PA 1996 – 1997
Completed computer-aided design drawings in support of roadway lighting study. Assisted with nighttime field data collection for sign visibility study.

Pennsylvania Department of Transportation, Engineering/Scientific/Technical Intern
Roadway Design Unit, Engineering District 3-0, Montoursville, PA 1994 – 1995
Served as construction field inspector for 5-mile, U.S. Route 15 heavy highway construction project. Work activities included quality control for concrete paving operations, quantity tabulations for subbase and base course placement, and confirmation of construction specifications for drainage system. Also, completed geometric design calculations and computer-aided design/drafting for U.S. Route 15 expansion between Buttonwood and Sebring, PA.

SELECT REFEREED PUBLICATIONS (of more than 70)

1. Wu, K., J. Aguero-Valverde, and E. T. Donnell. A Multivariate Random Parameter Crash Frequency Model for Exploring the Associations between Shoulder Rumble Strips on Different Crash Types. *Journal of Safety and Security*, Vol. 13(2), 2021, pp. 158-179.

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5. Gayah, V. G., E. T. Donnell, Z. Yu, and L. Li. Safety and Operational Effects of Setting Speed Limits Lower than Engineering Recommendations. *Accident Analysis and Prevention*, Vol. 121, pp. 43-52, December 2018.

6. Lyon, C., B. N. Persaud, and E. T. Donnell. Effectiveness of the SafetyEdge Treatment on Two-lane Rural Highways. *Transportation Research Record: Journal of the Transportation Research Board*, Vol. 2672, TRB of the National Academies, Washington, DC, March 2018, pp. 1-8.

7. Wood, J.S. and E. T. Donnell. Causal Inference Framework for Generalizable Safety Effect Estimates. *Accident Analysis and Prevention*, Vol. 104, July 2017, pp. 74-87.

8. Wood, J.S. and E. T. Donnell. Safety Evaluation of Continuous Green T Intersections: A Propensity Scores-Genetic Matching-Potential Outcomes Approach. *Accident Analysis and Prevention*, Vol. 93, pp. 1-13, August 2016.

9. Gooch, J. P., V. G. Gayah, and E. T. Donnell. Estimating the Safety Effects of Horizontal Curves on Pennsylvania Two-Lane Rural Roads. *Accident Analysis and Prevention,* Vol. 92, pp. 71-81, July 2016.

10. Wood, J. S., J. P. Gooch, and E. T. Donnell. Estimating the Safety Effects of Lane Widths on Urban Streets in Nebraska Using the Propensity Scores-Potential Outcomes Framework. *Accident Analysis and Prevention*, Vol. 82, September 2015, pp. 180-191.

11. Wood, J. S., E. T. Donnell, and R. J. Porter. Comparison of Safety Effect Estimates Obtained From Empirical Bayes Before-After Study, Propensity Scores-Potential Outcomes Framework, and Regression Model with Cross Sectional Data. *Accident Analysis and Prevention*, Vol. 75, February 2015, pp. 144-154.

12. Sasidharan, L. and E. T. Donnell. Propensity Scores-Potential Outcomes Framework to Incorporate Severity Probabilities in the Highway Safety Manual Crash Prediction Algorithm. *Accident Analysis and Prevention*, Vol. 71, October 2014, pp. 183-193.

13. Sasidharan, L. and E. T. Donnell. Application of Propensity Scores and Potential Outcomes to Estimate Effectiveness of Traffic Safety Countermeasures: Exploratory Analysis using Intersection Lighting Data. *Accident Analysis and Prevention*, Vol. 50, 2013, pp. 539-553.

14. Gross, F. and E. T. Donnell. Case-control and Cross-sectional Methods for Estimating Crash Modification Factors: Comparisons from Roadway Lighting and Lane and Shoulder Width Safety Effect Studies. *Journal of Safety Research,* Vol. 42, No. 2, April 2011, pp. 117-129.

15. Karwa, V., A. B. Slavkovic, and E. T. Donnell. Causal Inference in Transportation Safety Studies: Comparison of Potential Outcomes and Causal Diagrams. *Annals of Applied Statistics,* Institute of Mathematical Statistics, Vol. 5, No. 2B, 2011, pp. 1428-1455.

SELECT FUNDED RESEARCH PROJECTS (as Principal or co-Principal Investigator, of 37 total projects)

1. *Safety Effects of Adaptive Traffic Signal Control (co-PI).* Pennsylvania Department of Transportation, Work Order #013, April 2019 – March 2020, $74,000.

2. *Safety Performance of Part-time Shoulder Use on Freeways (PI).* National Cooperative Highway Research Program (NCHRP 17-89) via Kittelson & Associates. July 2018 – July 2020, $45,000.

3. *Safety Performance Functions for Urban and Suburban Collectors (PI).* Pennsylvania Department of Transportation, Work Order #007, May 2018 – February 2019, $74,000.

4. *Speed Limits Set Lower than Engineering Recommendations (PI).* Montana Department of Transportation, September 2014 – June 2016, $145,000.

5. *70 mph Speed Limit Study (PI).* Pennsylvania Department of Transportation, December 2014 – June 2016, $143,000.

6. *Regionalized Safety Performance Functions (PI).* Pennsylvania Department of Transportation, April 2015 – January 2016, $122,000.

7. *Crash Modification Factors (co-PI).* Pennsylvania Department of Transportation, March 2014 – September 2014, $75,000.

8. *Safety Performance Functions (co-PI).* Pennsylvania Department of Transportation, August 2012 – October 2013, $500,000.

9. *Development of Crash Modification Factors for the Continuous Green T-intersection (PI).* Federal Highway Administration, February 2013 – January 2016, $64,000.

10. *Reducing Roadway Departure Crashes at Horizontal Curve Sections on Two-lane Rural Highways (PI).* Federal Highway Administration, February 2013 – August 2018 (with University of Utah and Vanasse Hangen Brustlin, Inc.), $665,000

11. *Development of a Crash Modification Factor for Application of Safety Edge$_{SM}$ on Two-lane Rural Highways* (PI). Federal Highway Administration, August 2011 – December 2016 (with Persaud & Lyon, Inc. and Vanasse Hangen Brustlin, Inc.), $112,500.

12. *Guidance for the Design and Application of Shoulder and Centerline Rumble Strips* (PI). National Cooperative Highway Research Program and Midwest Research Institute, January 2005 – August 2008, $202,000.

13. *Guidelines for Roadway Lighting Based on Safety Benefits and Costs* (PI). National Cooperative Highway Research Program and Rensselaer Polytechnic Institute. January 2005 – May 2009, $190,000.

14. *Prepare Parts IV and V of the Highway Safety Manual* (PI). National Cooperative Highway Research Program and Kittelson & Associates, Inc., June 2005 – December 2006, $21,000.

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6. Donnell, E. T., V. G. Gayah, Z. Yu, L. Li, and A. DePrator. *Speed Limits Set Lower than Engineering Recommendations*. Report No. FHWA/MT-16-008/8225-01, Montana Department of Transportation, Helena, MT, August 2016.

7. Donnell, E. T., B. Hamadeh, and L. Li. *70 mph Study*. Report No. FHWA-PA-2016-009-PSU WO 13, Pennsylvania Department of Transportation, Harrisburg, PA, June 2016, 145 pp.

8. Donnell, E., J. Wood, and K. Eccles. *Safety Evaluation of Continuous Green T Intersections*. Report No. FHWA-HRT-16-036, Federal Highway Administration, Washington, DC, April 2016, 86 pp.

9. Donnell, E. T., V. G. Gayah, and L. Li. *Regionalized Safety Performance Functions*. Report No. FHWA-PA-2016-001 PSU WO 17, Pennsylvania Department of Transportation, Harrisburg, PA, January 2016, 195 pp.

10. Donnell, E. T., V. Gayah, and P. Jovanis. Safety Performance Functions. Report No. FHWA-PA-2014-007 PSU WO 1, Pennsylvania Department of Transportation, Harrisburg, PA, October 2014, 81 pp.

11. Gayah, V. V. and E. T. Donnell. Establishing Crash Modification Factors and Its Use. Report No. FHWA-PA-2015-005-PSU WO 6, Pennsylvania Department of Transportation, Harrisburg, PA, August 2014, 178 pp.

12. Boodlal, L., E. T. Donnell, R. J. Porter, D. Garimella, T. Le, K. Croshaw, S. Himes, P. Kulis, and J. Wood. Factors Influencing Operating Speed and Safety on Rural and Suburban Roads. Report No. FHWA-HRT-15-030, Federal Highway Administration, McLean, VA, May 2015.

13. D. J. Torbic, J. M. Hutton, C. D. Bokenkroger, K. M. Bauer, D. W. Harwood, D. K. Gilmore, J. M. Dunn, J. J. Ronchetto, E. T. Donnell, H. J. Sommer III, P. Garvey, B. Persaud, and C. Lyon. *NCHRP Report 641: Guidance for the Design and Application of Shoulder and Centerline Rumble Strips*. Transportation Research Board of the National Academies, Washington, DC, 2009.

14. Donnell, E., E. Ferguson, W. Kittelson, C. Lyon, J. Mason, C. Monsere, B. Persaud, E. Wemple, and J. Zegeer. *NCHRP 17-34: Parts IV and V of the Highway Safety Manual.* National Research Council, Transportation Research Board, Washington, DC, December 2006, 296 pp.

HONORS AND AWARDS

Eno Transportation Foundation Leadership Fellow, May 2002

Finalist, Milton Pikarsky Award, Best Dissertation, Science and Technology, Council of University Transportation Centers, 2003

"Best Paper Award," Third International Symposium on Geometric Design, for paper titled "Median Design Considerations based on Crash and Cost Analyses," Chicago, IL, 2005

"Best Paper Award," TRB Committee on Geometric Design, for paper titled "Geometric Design, Speed, and Safety," 2012 (Committee AFB10, of 36 papers)

"Best Paper Award," TRB Committee on Geometric Design and Design Section, for paper titled "Superelevation Design for Sharp Horizontal Curves on Steep Grades," 2014 (Committee AFB10, of 37 papers)

"Best Paper Award," TRB Committee on Performance Effects of Geometric Design, for paper titled "Safety Effects of Geometric Design Criteria: Horizontal Curve Reliability Index," 2020 (Committee AKD10, of 56 papers)

"Top Research Project in Traffic Safety," American Association of State Highway and Transportation Officials, for Montana DOT project "Setting Speed Limits Lower than Engineering Recommendations," 2018.

"Award-Winning Sweet Sixteen Projects," American Association of State Highway and Transportation Officials, for PennDOT project "Regionalized Urban/Suburban Collector Road Safety Performance Functions (SPFs)," 2020.

Vikash V. Gayah

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EDUCATION

2012 **University of California, Berkeley**
Ph.D., Civil and Environmental Engineering
Advisor: Carlos F. Daganzo
Minors: City & Regional Planning; Industrial Engineering & Operations Research

2006 **University of Central Florida**
M.S., Civil Engineering
Advisor: Mohammed Abdel-Aty
Minor: Statistics

2005 **University of Central Florida**
B.S., Civil Engineering
Summa Cum Laude with University Honors

RESEARCH INTERESTS

Urban mobility; traffic operations and control; transportation network modeling; traffic flow theory; traffic safety modeling and management; safety data analysis; multimodal transportation operations

RESEARCH AND WORK EXPERIENCE

2012— **The Pennsylvania State University**
2018— *Associate Professor of Civil Engineering*
Department of Civil and Environmental Engineering

2012—2018 *Assistant Professor of Civil Engineering*
Department of Civil and Environmental Engineering

2018— **Vanasse Hangen Brustlin, Inc. (VHB)**
Senior Safety Engineer

AWARDS AND HONORS

2020 **“Sweet Sixteen” High-Value Research Project in Maintenance and Safety**, AASHTO Research Advisory Committee
Regionalized Urban/Suburban Collector Road Safety Performance Functions (SPFs) – for the Pennsylvania DOT

2017 **Fred Burggraf Outstanding Paper Award**, TRB Operations and Preservations Group
Estimating the impacts of bus stops of transit signal priority on intersection pperations: A queueing and variational theory approach

2017 **D. Grant Mickle Outstanding Paper Award**, TRB Operations and Traffic Management Section
Improving street network efficiency by dynamically prohibiting left turns at signalized intersections

2017 **“Sweet Sixteen” High-Value Research Project in Maintenance and Safety**, AASHTO Research Advisory Committee
Speed limits set lower than engineering recommendations – for the Montana DOT

2016 Cambridge Systematics **New Faculty Award**, Council for University Transportation Centers

2013 **Cunard Outstanding Paper Award**, TRB Operations and Traffic Management Section
Inhomogeneous flow patterns in undersaturated road networks: Implications for Macroscopic Fundamental Diagram

2012 **Gordon F. Newell Award** for Excellence in Transportation Science
UC Berkeley Transportation Engineering Faculty

RELEVANT PUBLICATIONS

PEER-REVIEWED JOURNAL PUBLICATIONS

1. Tang, H.**, **Gayah, V.V.** and Donnell, E.T. (2020) Crash Modification Factors for adaptive traffic signal control: An Empirical Bayes before-after study. *Accident Analysis and Prevention*, in press.
2. Guadamuz, R.**, **Gayah, V.V.** and Paleti, R. (2020) Impact of bus routes on crash frequency in metropolitan areas. *Transportation Research Record: Journal of the Transportation Research Board*, 2674(3):305-316.
3. Himes, S.C., **Gayah, V.V.**, Gooch, J.P.*, and Read, S. (2020) Estimating baseline numbers for safety measure target settings in Virginia. *Transportation Research Record: Journal of the Transportation Research Board*, 2674(8):523-535.
4. Tang, H.**, **Gayah, V.V.** and Donnell, E.T. (2019) Evaluating the predictive power of an SPF for two-lane rural roads with random parameters on out-of-sample observations. *Accident Analysis and Prevention*, 132:1-11.
5. **Gayah, V.V**, Donnell, E.T., Yu, Z.* and Li, L.** (2018) Safety and operational impacts of setting speed limits below engineering recommendations. *Accident Analysis and Prevention*, 121:43-52.

6. Gooch, J.P.*, **Gayah, V.V.** and Donnell, E.T. (2018) Comparison of safety performance functions for horizontal curves and tangents on two lane, two way rural roads. *Accident Analysis and Prevention*, 120:28-37.
7. Li, L.**, **Gayah, V.V.** and Donnell, E.T. (2017) Development of regionalized SPFs for two-lane rural roads in Pennsylvania. *Accident Analysis and Prevention*, 108:343-353.
8. Gooch, J.P.*, **Gayah, V.V.** and Donnell, E.T. (2016) Quantifying the safety effects of horizontal curves on two-way, two-lane rural roads. *Accident Analysis and Prevention*, 92:71-81.

RESEARCH REPORTS TO SPONSOR

1. Hamilton, I., Kersavage, K.**, Porter, R.J., Smith, K., Sanchez, J., **Gayah, V.V.** and Eccles, K. (2020) An exploration of pedestrian safety through the integration of HSIS and emerging data sources: Case study in Charlotte, NC. *Final Report for the Federal Highway Administration*.
2. Porter, R.J., Dunn, M., Hamilton, I., Gooch, J.P.* and **Gayah, V.V.** (2019) Safety analysis needs assessment for Transportation Systems Management and Operations. *Report for the Federal Highway Administration*, FHWA-SA-19-041.
3. **Gayah, V.V.**, Guler, S.I. and Donnell, E.T. (2019) Pennsylvania traffic records integration plan. *Final Report for the Pennsylvania Department of Transportation*, FHWA-PA-008-PSU WO 008.
4. Donnell, E.T., **Gayah, V.V.**, Kersavage, K.** and Yu, Z.* (2017) Crash data safety factors evaluation. *Final Report for the Pennsylvania Department of Transportation*, FHWA-PA-2017-004-PSU WO 3.
5. Donnell, E.T., **Gayah, V.V.** and Li, L.** (2016) Regionalized safety performance functions. *Final Report for the Pennsylvania Department of Transportation*, FHWA-PA-2016-001-PSU WO 17.
6. **Gayah, V.V.**, Yu, Z.* and Wood, J.S.** (2015) Estimating uncertainty of bus arrival times and passenger occupancies. *Final Report for the Mineta National Transit Research Consortium*, MNTC Report No. 12-56.
7. Donnell, E.T., **Gayah, V.V.** and Jovanis, P.P. (2014) Safety performance functions. *Final Report for the Pennsylvania Department of Transportation*, FHWA-PA-2014-007-PSU WO 1.
8. **Gayah, V.V.** and Donnell, E.T. (2014) Establishing Crash Modification Factors and their use. *Final Report for the Pennsylvania Department of Transportation*, FHWA-PA-2014-005-PSU WO 6.

FUNDED PROJECTS

THE PENNSYLVANIA STATE UNIVERSITY

1. (PI) Interpretable machine learning methods for road crash frequency prediction, *Penn State Institute for Computational and Data Sciences Seed Grant*, 2021, $24,612.

2. (PI) Quantification of systemic risk factors for pedestrian safety on North Carolina roadways, *North Carolina Department of Transportation*, August 2021 – November 2022, $166,328. **[nationally competitive]** [awarded, not yet started]
3. (PI) Network screening, *Pennsylvania Department of Transportation (subcontract to Kittelson & Associates, Inc.)*, October 2020 – June 2021, $1,702,604 (PSU amount - $19,911).
4. (co-PI) SMART intersections, *Pennsylvania Department of Transportation (subcontract to Kittelson & Associates, Inc.)*, October 2020 – September 2021, approx. $613,295 (PSU amount - $63,300).
5. (PI) Update PennDOT Pub. 638A, *Pennsylvania Department of Transportation (subcontract to Kittelson & Associates, Inc.)*, April 2020 – December 2020, approx. $123,000 (PSU amount - $30,847).
6. (co-PI) Safe Integration of Autonomous Vehicles in Work Zones, *US Department of Transportation (subcontract to HNTB Corporation)*, $8,409,444 (PSU amount – $1,479,408). **[nationally competitive]** [awarded, not yet started]
7. (co-PI) Microsimulation of emergency evacuation of Bear Lake and Wild Basin in Rocky Mountain National Park, *National Park Service*, June 2020 – June 2021, $45,300. **[nationally competitive]**
8. (co-PI) Optimization framework for infrastructure management considering traffic safety costs, *Center for Integrated Asset Management for Multimodal Transportation Infrastructure Systems*, June 2020 – November 2021, $193,983 (PSU amount – $96,983).
9. (co-PI) AI-enabled fiscally constrained life-cycle asset management for infrastructure systems, *Center for Integrated Asset Management for Multimodal Transportation Infrastructure Systems*, January 2020 – May 2021, $245,676 (PSU amount – $122,838).
10. (co-PI) Southeastern Veterans Center Transportation Study, *Pennsylvania Department of Military and Veterans Affairs*, July 2019 – December 2019, $20,721.
11. (PI) Adaptive signals crash modification factors, *Pennsylvania Department of Transportation*, May 2019 – March 2020, $73,460.
12. (PI) Traffic signal control using reinforcement learning, *Institute for CyberScience Seed Grant*, 2019, $22,433.
13. (Collaborating Investigator) AI for identifying and optimizing interactions between transit systems, *Institute for CyberScience Seed Grant*, 2019, $24,993.
14. (PI) Pennsylvania traffic records integration plan, *Pennsylvania Department of Transportation*, September 2018 – July 2019, $92,769.
15. (co-PI) Regionalized urban/suburban collector road SPFs, *Pennsylvania Department of Transportation*, May 2018 – March 2019, $71,434.
16. (PI) CAREER: Multi-scale models of urban congestion dynamics to support advanced congestion management strategies, *National Science Foundation*, May 2018 – April 2023, $500,000. **[nationally competitive]**
17. (PSU co-PI) NCHRP Project 17-89: Safety performance of part-time shoulder use of freeways, *National Cooperative Highway Research Program (subcontract to Kittelson & Associates, Inc.)*, June 2018 – March 2021, $400,000 (PSU amount – $45,880). **[nationally competitive]**

18. (co-PI) Crash data safety factors evaluation, *Pennsylvania Department of Transportation*, April 2017 – December 2017, $73,563.
19. (PSU co-PI) NCHRP Project 17-84: Pedestrian and bicycle safety performance functions for the Highway Safety Manual, *National Cooperative Highway Research Program (subcontract to MRI Global, Inc.)*, March 2017 – February 2019, $500,000 (PSU amount – $105,000). **[nationally competitive]**
20. (co-PI) Financial benefits of proposed access management treatments, *South Dakota Department of Transportation (subcontract to South Dakota State University.)*, December 2016 – February 2021, $99,982 (PSU amount – $45,287). **[nationally competitive]**
21. (co-PI) Regionalized safety performance functions, *Pennsylvania Department of Transportation*, March 2015 – December 2015, $121,755.
22. (co-PI) Speed limits set lower than engineering recommendations, *Montana Department of Transportation*, September 2014 – August 2016, $143,332. **[nationally competitive]**
23. (PI) Establishing Crash Modification Factors and their use, *Pennsylvania Department of Transportation*, March 2014 – September 2014, $74,801.
24. (Collaborating Investigator) A data-driven approach for Intelligent Transportation Systems, *IST Research Seed Grant*, Spring 2014, $8,821.
25. (PI) Estimating uncertainty of bus arrival times and passenger occupancies, *US Department of Transportation* via *Mineta National Transit Research Consortium*, December 2013 – September 2015, $133,115 (PSU amount – $62,898).
26. (PI) How can we maximize efficiency and increase person occupancy at overcrowded park and rides, *Washington State Department of Transportation*, October 2013 – June 2014, $147,513. **[nationally competitive]**
27. (Collaborating Investigator) Impacts assessment of dynamic speed harmonization with queue warning, *Federal Highway Association (subcontract to Kittelson & Associates, Inc.)*, June 2013 – March 2015, $369,750 (PSU amount – $4,382). **[nationally competitive]**
28. (co-PI) Safety performance functions for rural roads in Pennsylvania, *Pennsylvania Department of Transportation*, August 2013 – October 2014, $499,936.
29. (Collaborating Investigator) An examination of active travel and economic behavior, *Social Science Research Institute at Penn State University*, 2013, $2,470.
30. (co-PI) Integration of multimodal transportation services, *US Department of Transportation* via *Mid-Atlantic Universities Transportation Center*, May 2013 – June 2015, $153,301 (PSU amount – $39,985).

VANASSE HANGEN BRUSTLIN, INC. (VHB)

1. NCHRP Project 17-89A HOV/HOT freeway crash prediction method for the Highway Safety Manual, *National Cooperative Highway Research Program*.
2. NCHRP 22-47 Incorporating Driver Behavior and Characteristics into Safety Prediction Methods, *National Cooperative Highway Research Program*.

3. NCHRP Project 17-95 Crash Modification Factors (CMFs) for Intelligent Transportation System (ITS) applications, *National Cooperative Highway Research Program*.
4. NCHRP Project 17-81 Proposed macro-level safety planning analysis chapter for the Highway Safety Manual, *National Cooperative Highway Research Program*.
5. Data-driving models for safety measure baselines, *North Carolina Department of Transportation*.
6. Safety measure target setting for 2020, *Virginia Department of Transportation*.
7. NCHRP Project 17-93 Updating safety performance functions for data-driven safety analysis, *National Cooperative Highway Research Program*.
8. NCHRP Project 17-86 Estimating effectiveness of safety treatments in the absence of crash data, *National Cooperative Highway Research Program*.
9. Safety analysis needs assessment for transportation systems management and operations, *Federal Highway Administration*.
10. Developing new methods for safety measure target setting, *Virginia Department of Transportation*.