RPS 2306E4

The Optimal Shoulder for Reducing Speed Related and Lane Departure Crashes

Research Proposal

PREPARED BY:

CENTER FOR ADVANCED TRANSPORTATION EDUCATION AND RESEARCH (CATER)

UNIVERSITY OF NEVADA RENO

University of Nevada, Reno

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The Optimal Shoulder for Reducing Speed-Related and Lane Departure Crashes

Principal Investigator (PI):

Seri Park, Ph.D., PTP
University of Nevada, Reno, MS 258 Reno, NV 89557
Tel: 775-682-6744; E-mail: serip@unr.edu

Key Members:

Hao Xu, Ph.D., P.E.
University of Nevada, Reno
E-mail: haox@unr.edu

Aobo Wang, Ph.D.
University of Nevada, Reno
E-mail: aobow@unr.edu

1. Problem Description

Speed-related and lane departure crashes significantly contribute to highway fatalities in both Nevada and the United States. Between 2016 and 2020 in Nevada, there were 496 fatalities due to speeding and 583 due to lane departure, ranking as the second and fourth leading causes of traffic fatalities in the state, respectively [1]. Recent trends indicate an increase in lane departure crashes, notably the fatal rollover accidents on US-95 MM10 to MM69 in Nye County, where newly constructed and flattened road conditions prevail, underscoring the urgent need for safety enhancements. To effectively address such crash-prone highway segments in Nevada, it is imperative to conduct a comprehensive study on the causes of speed-related and lane departure crashes and identify optimal countermeasures for strategic intervention.

Deploying enhanced shoulders has been identified as a proven approach to reducing both the number and severity of speed-related and roadway departure crashes [2]. However, to achieve effective implementation of this strategy in Nevada, it is essential to address three important issues.

1. Intellectual questions have been raised regarding the contributing factors to the recent increase in crash occurrences in Nevada, especially at locations where roadway conditions appear to be less hazardous from the road condition perspective (e.g., US-95 MM10 to MM69). A thorough study is necessary to examine potentially influencing factors such as roadway and roadside conditions, traffic operational characteristics, and driver behavioral responses.
2. Crash countermeasures pertaining to road shoulders encompass a diverse array of options, including widening paved or stable shoulders, improving the traversability and recoverability of shoulder slopes, and implementing high-friction surfaces, Safety Edge, rumble strips, and barriers. However, selecting suitable and effective treatments for specific roadway segments in Nevada presents a challenge. Consequently, in-depth reviews and explorations tailored to the Nevada context are needed to evaluate and examine the potential for safety enhancements and relevant impacts.
3. One of transportation agencies' major tasks is to select optimal road shoulder designs that effectively mitigate crash risks and minimize economic costs and environmental impacts. Policy recommendations must be based on inclusive evaluations concerning Nevada's specific scenarios. Such an approach can practically facilitate future developments by the Nevada Department of Transportation (NDOT), ensuring that the chosen solutions are both efficient and contextually appropriate.

This proposed research aims to conduct studies on the aforementioned three aspects, with a focus on identifying the optimal shoulder designs suited to Nevada's specific conditions and needs. The outcome will include policy recommendations intended to advocate for the adoption of safer shoulder configurations.

2. Background Summary

Road shoulders (including roadside slopes), defined as the graded or surfaced areas adjacent to travel lanes, are pivotal in ensuring traffic safety by providing a stable and clear recovery area for vehicles in case of lane departure. Proper design of shoulders and slopes can significantly increase the likelihood of safe recovery when a driver inadvertently leaves the lane, whether to avoid a crash or an object ahead. In the context of reducing speed-related and lane departure crashes, the enhancement of shoulders and slopes entails considering a range of factors, such as the width and type of the shoulder, the configuration of the slope and the entire clear zone, the characteristics of the pavement edge, and the application of roadside safety treatments such as rumble stripes, signage, delineation, and protective barriers.

The influence of road shoulder design on traffic safety is extensively documented in prior research, with relevant countermeasures recommended in authoritative resources such as the Highway Safety Manuals (HSM) [3] and the Manual for Selecting Safety Improvements on High-Risk Rural Roads [4]. However, determining the optimal shoulder design in practice remains a multifaceted challenge, characterized by the following key aspects:

1. **Data-Driven Risk Identification**: Employing a data-centric approach is crucial for identifying high-risk segments prone to speed-related and lane departure crashes. Data collection for traffic and road conditions and safety performance analyses should be adopted to preemptively discover and rank hazardous roadway segments.
2. **Comprehensive Countermeasure Studies**: Inclusive research is required to select appropriate crash countermeasures for Nevada, considering their effectiveness in improving safety and practical applicability within the state's specific context.
3. **Economic and Environmental Considerations**: A systematic approach that accounts for economic and environmental impacts is essential for implementing cost-effective and sustainable road shoulder enhancements.

Literature review

Investigating the correlation between speed-related and lane departure crashes and various roadway features is the foundation of risk identification and ranking. While statistical analyses of crash data have indicated that factors such as shoulder width, lateral clearance, and side slope condition significantly influence roadway departure crashes [5 6], these studies often lack detailed insights explaining crash occurrences on specific road segments, particularly when roadway conditions and designs that meet or are beyond standards. The Highway Safety Manual introduces a concept of "roadside hazard rating" which, beyond shoulder width and type, includes all other safety considerations concerning roadside design. However, this rating is subjective and may vary based on the assessor's judgment. When facing specific safety risk management tasks, transportation agencies need to establish their standards for performance data collection and safety assessment.

In addition to roadway and road shoulder configurations, the incidence of speed-related and lane departure crashes is closely linked to traffic operational and safety characteristics. Actions such as speeding and passing maneuvers often lead to "harmful events" such as overturning or encroachment into opposing lanes [7], which may not always be captured in traditional crash statistics. The quality and comprehensiveness of the data collected are paramount in ensuring accurate evaluations and effective safety interventions. The process of collecting data on roadway geometric and traffic operational characteristics is typically resource intensive, hence in practice, there may be only limited and untimely updated measurements available for safety assessment. In recent years, Light Detection and Ranging (LiDAR)-based data collection methods present a significant advancement, markedly enhancing the accuracy and detail of the collected roadway and traffic data while potentially reducing the associated costs [8]. With the emergence of advanced vehicle trajectory data sources offering broad spatial coverage and high-resolution waypoints, a more nuanced safety surrogate evaluation becomes possible without the necessity of installing sensors along roadways. These vehicle trajectory data sources boast a penetration rate of up to 5% of total traffic and a precision within 10 feet [9], enabling detailed analysis of speed-related and lane departure behaviors, even on rural highways in Nevada. For instance, the research team has procured a dataset encompassing abundant high-resolution vehicle trajectories captured in two weeks in March 2023. The team's preliminary analysis focusing on a segment of US-95 near MM52 in Nye County revealed over 5,000 trajectories in total, with 367 northbound trajectories identified as executing passing maneuvers in the opposing traffic lane. This is an example of the extent of data granularity that can provide a unique opportunity to understand and mitigate potential risks more effectively.

Widening shoulders and implementing paved shoulders have been empirically validated as effective measures for improving roadside safety [10 11]. However, subsequent research has revealed that the safety benefits of incrementally wider shoulders may diminish beyond initial extensions [12]. This finding underscores the need for context-specific studies to ascertain the optimal shoulder width under certain roadway conditions. Regarding recoverable slope configurations, a noteworthy study by the National Cooperative Highway Research Program (NCHRP) has thoroughly investigated the effects of various slope configurations on traffic traversability using vehicle dynamics simulation [13]. While this NCHRP study pioneered a simulation-based approach for slope safety evaluation, it primarily utilized default driver behavior models. The importance of driver behavioral factors, especially in response to roadside design features, has been highlighted in several studies employing driver simulators. Incorporating realistic driver behavior into vehicle dynamics simulations could significantly enhance the accuracy of safety improvement predictions for specific shoulder and slope configurations [14 15 16]. Additionally, other roadside treatments such as rumble strips, delineators, protective barriers, and Safety Edge have been shown to mitigate speed-related and lane departure crashes, as evidenced by their successful deployments in other states [17 18 19].

Economic and environmental considerations play a crucial role in determining the feasibility, cost-effectiveness, and sustainability of deploying and maintaining shoulder enhancements. Assessments of life-cycle costs and benefits have been conducted in multiple states across the United States, highlighting the necessity for comprehensive investigations particularly considering local practices [20 21]. In the context of Nevada, environmental considerations assume a unique dimension due to specific factors such as environmentally sensitive areas, impacts on water, drainage systems, and desert ecological concerns. These factors not only influence the feasibility of shoulder enhancements but may also carry safety implications [22].

NDOT's practices

Within the framework of the Nevada Highway Safety Improvement Program (HSIP), crash countermeasures such as rumble strips, shoulder widening, slope flattening, and high-friction surface treatments are acknowledged [23]. In the 2020 annual report of Nevada HSIP, a roadway rehabilitation project for US-95 in Nye County with shoulder widening and slope flattening was presented, aiming to reduce lane departure crashes. Despite these efforts, speed-related and lane departure risks persist notably in this road segment, indicating the urgent need for thorough research to uncover underlying causes and devise effective solutions.

The NDOT Road Design Guide [24] outlines specific requirements for road design elements, including shoulder width, roadside slope configuration, and rumble strips. It also stipulates guidelines for slope flattening and guardrail installations, vital components that must be factored into economic assessments for proposed roadside design enhancements. Additionally, the implementation of Safety Edge is detailed in the NDOT Plan Preparation Guide [25]. These guidelines, as reflected in NDOT's road design directives, suggest that traffic safety considerations, while recognized, may not be the primary focus in the development and improvement of roadway designs. This observation underscores the importance of integrating more comprehensive traffic safety considerations into the road design process, especially in high-risk areas.

Gaps in current research and practices

This proposed research aims to address three gaps identified through the literature review.

1. An in-depth research effort is needed to discover safety risks associated with speeding and lane departure, especially for US-95 in Nye County. As traditional data regarding traffic safety and road conditions may not inclusively reflect the full spectrum of safety hazards, new data collection techniques, and emerging data sources, such as employing LiDAR sensors and high-resolution vehicle trajectory data to analyze roadway and traffic operational characteristics.
2. The effectiveness of crash countermeasures is not comprehensively explored in the Nevada context. Vehicle dynamics and driver behavior simulation studies are an effective approach to validating the countermeasures that have not been implemented in Nevada or indicate unsatisfactory performance after the implementation.
3. There are no established methods to assess the economic and environmental impacts of diverse roadside configurations considering Nevada-specific conditions and requirements. Knowledge gathering and surveys are needed through close collaboration between various NDOT divisions such as Stormwater, Hydraulics, Materials, Landscape and Aesthetics, Construction and Maintenance, local authorities, and contractors.

3. Proposed Research

The proposed research project consists of three phases, aiming to facilitate NDOT's practices in the determination of optimal shoulder design for reducing speed-related and lane departure crashes. The primary contents of this research include:

1. Conduct a comprehensive information and current practice survey to synthesize established research findings and state-of-the-art countermeasures regarding speed-related and lane departure crashes.
2. Perform inclusive data collection and analyses using LiDAR sensors and high-resolution trajectories. Details in terms of roadway and shoulder characteristics, traffic operational profiles, and roadside terrain conditions will be gathered and thoroughly investigated. The focus of the data collection and analyses will be US-95 in Nye County.
3. Leverage vehicle dynamics simulation, i.e., CarSim, to evaluate the effectiveness of potential crash countermeasures, such as shoulder widening and slope flattening. A diver simulator will also be used to explore driver behaviors in response to various roadside configurations. The drivers' behavioral factors will be introduced into vehicle dynamics simulation to improve the accuracy of the evaluation.
4. Work closely with relevant NDOT divisions, local agencies, and key stakeholders or contractors to synthesize economic and environmental considerations and requirements regarding shoulder enhancements. Methods will be developed to incorporate the economic and environmental implications into the determination of the optimal shoulder configuration.

Task 0. Project management (Lead - Park)

The team will collaborate with NDOT and project stakeholders in Nevada to assemble a technical advisory committee (TAC). The TAC will guide the strategic development of the project and provide expert advice on technological matters. The team will maintain close coordination with the TAC to ensure quality and standards compliance. Potential members of the TAC will include representatives from various entities, not limited to:

1. NDOT Divisions such as Traffic Safety Engineering, Design, Environment Program, Construction, and Maintenance & Asset Management
2. Stakeholders in Nevada traffic safety, such as the Nevada Department of Public Safety Office of Traffic Safety
3. Local agencies such as Nye County
4. Other key stakeholders such as Local Technical Assistance Program Center

Task 0 Deliverables

Periodic progress meeting minutes and technical memoranda

Task 1. Synthesis of Critical Resources and State of Practice (Leads - Wang & Park)

The objective of Task 1 is to conduct a complete review of research or technical literature, technologies, and data sources regarding speed-related and lane departure crashes, particularly synthesizing the effect of road shoulder features and potential enhancements. Through the preliminary literature review conducted while developing this proposal, the team has identified important topics of Task 1 as follows:

1. Safety analysis and risk assessment in terms of speed-related and lane departure crashes;
2. Influence of road shoulder features on traffic safety, especially regarding driver behavior and vehicle dynamics;
3. Effectiveness of road shoulder enhancements on 1) keeping vehicles in their travel lane, 2) reducing the potential for severe crashes when vehicles do leave their travel lanes, and 3) minimizing the severity of a lane departure crash if it occurs; and
4. Economic and environmental effects of road shoulder enhancements and methods for comprehensive evaluation and determination of the condition-specific optimal road shoulder.

Task 1 Deliverables

Synthesis documents of the comprehensive literature review

Task 2. Field Data Collection and Analytics (Leads – Xu & Wang)

In Task 2, the team will utilize advanced data collection methods and analytical techniques to conduct an in-depth exploration of roadway features and traffic safety elements. This task is divided into three components:

- Task 2.1: Analyzing NDOT mobile LiDAR data to gain a detailed understanding of roadway features
- Task 2.2: Mining high-resolution vehicle telemetric trajectory data to identify risk-prone locations
- Task 2.3: Employing roadside LiDAR sensors to examine driver's behavior and associated traffic safety characteristics (e.g., passing maneuver characteristics and variation of speed)

Details regarding the three components are presented in Table 1. The team has developed data processing and analysis tools to conduct Task 2. Figure 1 presents the result of the team's preliminary study on the vehicle trajectory data, illustrating a heatmap for passing maneuvers of the northbound traffic on US-95 near MM52 Nye County. Figure 2 shows examples of the team's LiDAR data collection platform, sample cloud points of NDOT mobile LiDAR, and vehicle movement visualization derived from roadside LiDAR.

The locations of roadside LiDAR data collection will be mainly on US-95 according to historical crash data and risks identified using vehicle telemetric trajectories. The specific distribution of data collection sites along US-95 and other in-state highways will be determined and adjusted during the project, informed by inputs from the TAC and results from data reviews.

Table 1: Research Plans of Task 2

	Task 2.1	Task 2.2	Task 2.3
Task Description	The team will process mobile LiDAR data collected by NDOT to extract information about roadway features.	The team will conduct data mining using high-resolution vehicle trajectory data sets (the penetration rate is about 5%) to identify specific locations that are prone to risks based on vehicle maneuvers related to speeding and lane departure crashes.	The team will employ roadside LiDAR data collection platforms to gather 72 continuous hours of data at up to 10 locations to reveal traffic safety characteristics.
Task Objectives	This task aims to obtain a detailed and comprehensive understanding of roadway features in an automated manner.	This task aims to explore the use of emerging vehicle trajectory data to achieve statewide traffic safety assessment, especially for rural highways, without performing ad-hoc data collection and sensor installation.	This task aims to capture the high-fidelity movement of each vehicle along a 600-foot segment at each data collection site to discover exhaustive vehicle movement profiles in "free flow", "following", and "passing" scenarios.
Anticipated Information and Measurements	• Lane and shoulder widths • Configuration of slopes and clear zones • Roadside obstacles within the range of the NDOT mobile LiDAR data • Roadway geometrics such as horizontal and longitudinal curves	• Vehicle travel speed profile on specific roadway segments • Characteristics of vehicle passing maneuvers, e.g., passing speed and duration. • Temporal and spatial distributions of vehicle speeding and passing maneuvers. • Lane departure and hard-braking events	• Speed and lane position profiles of each vehicle • Relative distances and speed profiles between each vehicle and surrounding vehicles (front, rear, and side) • Profiles of the distance between each vehicle and the lane boundaries, rumble strips, and shoulder boundaries

Task 2 Deliverables

Interim reports or technical memoranda regarding field data collection and analytics.

Task 3. Traffic Safety Evaluation (Leads - Park & Xu)

In Task 3, The team will conduct further analyses regarding the effects of roadway characteristics including geometric elements (e.g., shoulder width, side slope), and vehicle movements on traffic safety using the data collected through advanced techniques in Task 2 and NDOT crash data. The scope of analysis will focus on rural two-lane highways with two specific crash types, heads-on and lane departure

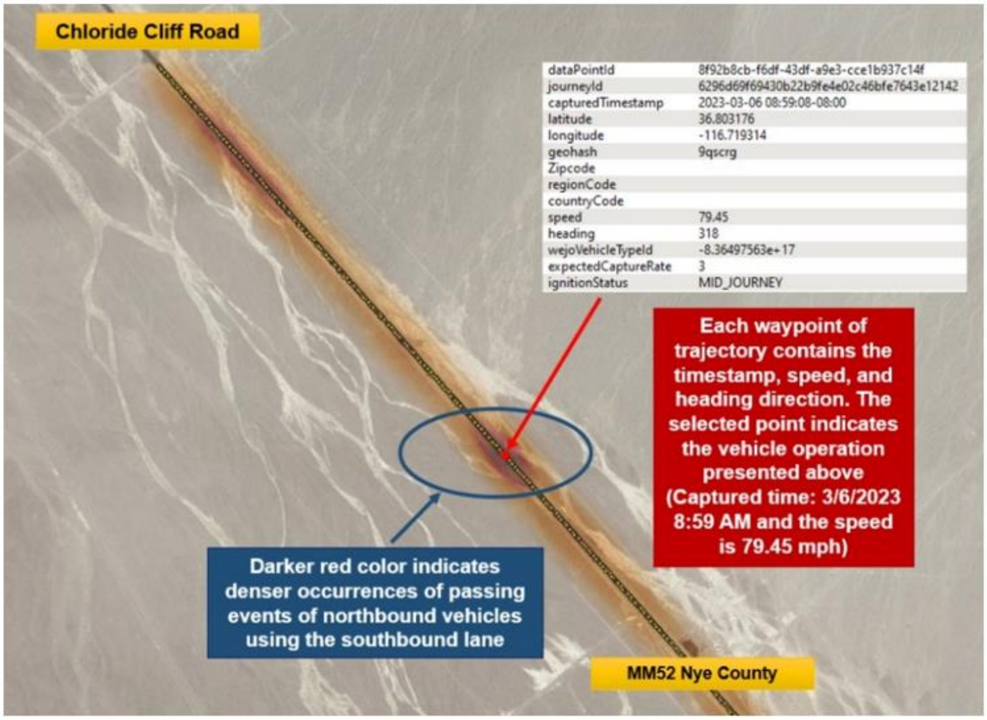

Figure 1: Spatial Distribution Heatmap of Northbound Traffic Passing Events near US-95 MM52 Nye County

crashes. Three different crash severity levels – all types and Types K & A (fatal and major injuries) – will also be reviewed. This traffic safety evaluation in Task 3 aims to comprehensively explore the relationship between road shoulder configurations, crash risks, and potential crash severity levels involving speeding and lane departure. This approach also aligns with the FHWA's Safe System Approach [26]. The findings can facilitate the development of more informed guidelines to screen hazardous roadway segments and conditions in terms of speed-related and lane departure crashes.

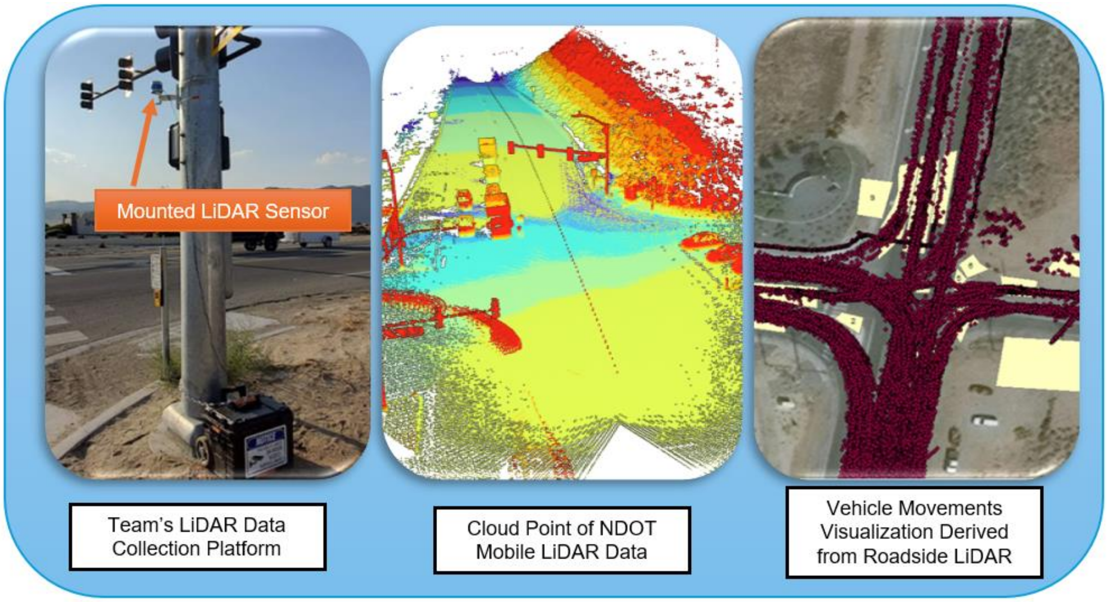

Figure 2: LiDAR Data Collection Platform Developed by the Team (left), A Sample of Mobile LiDAR Cloud Points (Middle), and Traffic Movements Captured by LIDAR (right)

Task 3 Deliverables

Traffic safety evaluation findings

Task 4. Simulation-Based Vehicle Dynamic and Driver Response Analyses for Countermeasures (Leads - Park & Wang)

In Task 4, to assess potential countermeasures across diverse scenarios, the team will use two major simulators: the RDS-100 Driving Simulator for driver behavior simulation and the CarSim software suite for vehicle dynamics simulation. The RDS-100 Driving Simulator will allow for quantitative analyses of driver behaviors under speeding and/or lane departure circumstances, and CarSim will simulate vehicle dynamics in response to given vehicle operational status, driver behavioral factors, and roadside configurations. The simulated vehicle dynamics changes derived from CarSim will reflect potential crash likelihood, type, and severity. Figure 3 illustrates this simulation-based approach.

Task 4 is dedicated to identifying the key factors that contribute to the effectiveness of crash countermeasures suitable for implementation in Nevada, with a specific focus on the unique context of the state. To achieve this, the team will utilize the detailed roadway and environmental data gathered in Task 2, which will be instrumental in developing high-fidelity simulation scenarios that accurately reflect Nevada's specific road and driving conditions. Furthermore, the team will conduct comprehensive statistical analyses of driver behaviors, using a sufficiently representative sample of Nevada drivers participating in the proposed driver simulator studies.

Task 4 Deliverables

Countermeasure evaluation reports

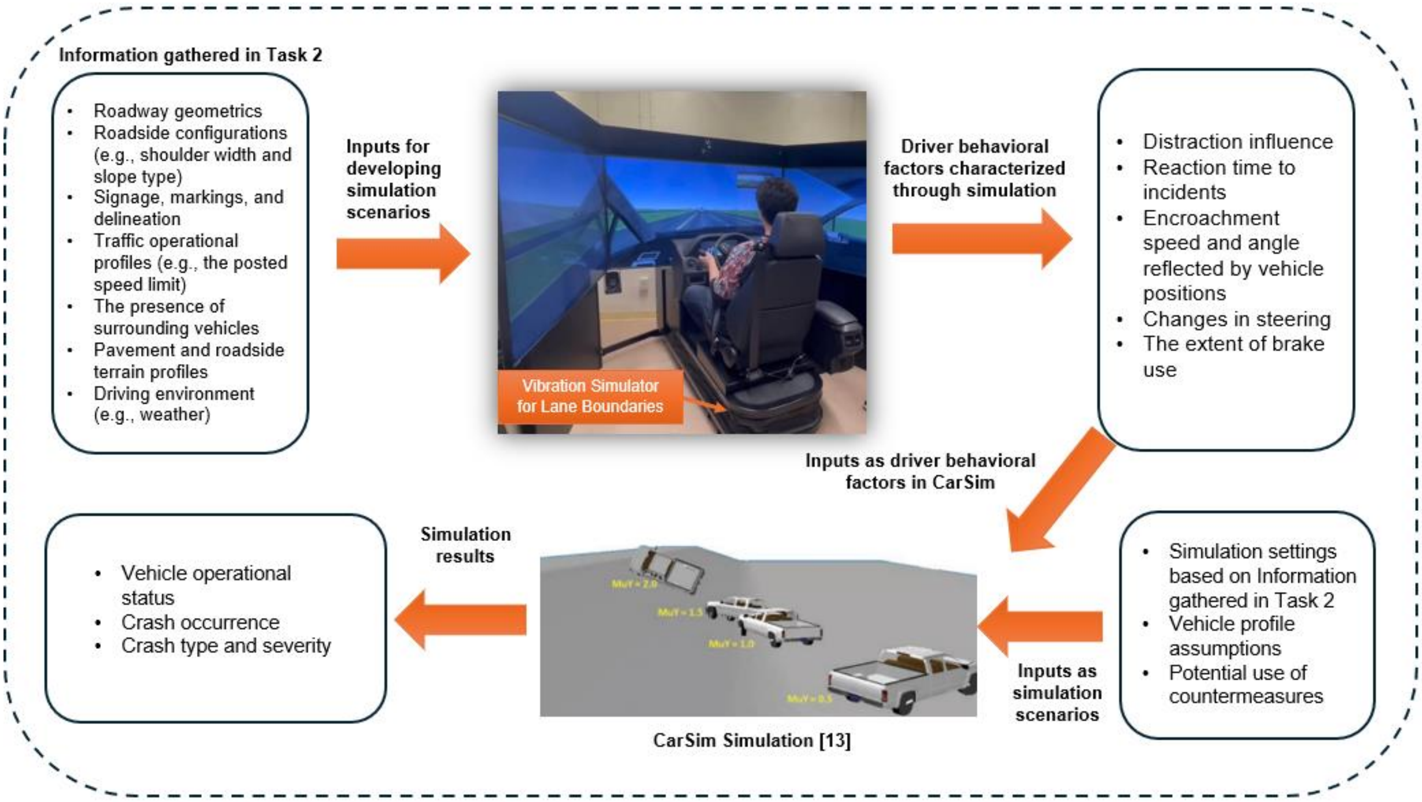

Figure 3: Simulation-based Research Approach to Countermeasure Effectiveness Evaluation Considering Vehicle Dynamics and Driver Behavior

Task 5. Economic and Environmental Assessments (Leads - Xu & Park)

This task will focus on capturing the economic and environmental impacts of the shoulder configurations. Acknowledging the importance of Benefit-Cost Analysis in economic analysis, the team will review several tools that have been widely used by federal and state agencies, such as BAC.net developed by the FHWA and Cal-B/C model. Furthermore, the team will study various economic aspects of safety enhancement by applying the Nevada Project Safety Process (PSP) - an Excel spreadsheet-based tool that utilizes the economic appraisal process outlined in the HSM to quantify the safety benefits of projects.

In addition to the economic analysis, the team will also carefully examine the environmental impacts and footprints of shoulder configurations. As the project progresses, the team also plans to coordinate with the NV Department of Conservation and Natural Resources to gain a better understanding of the state's environmentally sensitive issues and concerns related to roadway construction and maintenance.

Task 5 Deliverables

Economic and environmental assessment methodologies and findings

Task 6. Policy Recommendations (Leads - Park & Xu)

In Task 6, the team will develop policy recommendations for implementing and maintaining optimal shoulder configurations. The recommended shoulder enhancements will be based on the effectiveness evaluation performance in Task 4 with economic and environmental considerations identified in Task 5.

Task 6 Deliverables

Policy recommendation reports

Task 7. Final Report and Future Research Roadmap (Leads - Park & Xu)

The team will deliver a final research report that documents all the study findings, data analytics, developed methodologies, and policy recommendations. Furthermore, the team will propose a research roadmap to facilitate future research development regarding potential road shoulder enhancements and traffic safety improvements.

Task 7 Deliverables

A final research report and research roadmaps.

4. Urgency and Anticipated Benefits

The urgency of conducting the proposed research is emphasized by the immediate need for informed interventions to reduce crash risks on Nevada's roadways, particularly on US-95, which witnessed a notable surge in fatal crashes within a brief period in 2023. The proposed research is designed to undertake exhaustive data collection, conduct thorough analyses, and evaluate countermeasures comprehensively, ultimately aiming to develop policy recommendations that will facilitate the practice of NDOT to take prompt and effective actions. Moreover, this research project represents a pioneering effort to incorporate traffic safety considerations more integrally into roadway and roadside design. The formulation of evidence-based recommendations for roadside configuration enhancements aligns with the objectives of the 2021-2025 Nevada Strategic Highway Safety Plan, particularly in addressing the critical issue of lane departure and speed-related crashes.

The anticipated benefits of this research can be divided into two aspects: 1) crash mitigation benefits and 2) resource savings by applying cost-effective construction of the optimal shoulder configuration. The National Highway Traffic Safety Administration (NHTSA) estimates that each fatality can result in an average discounted lifetime cost of $1.6 million in economic costs, and $11.3 million when quality-of-life valuations are considered [27]. A comprehensive determination of the optimal roadside configuration will be developed through this research considering economic performance. As a result, construction and maintenance costs will be optimized.

5. Implementation Plan

The proposed research falls under Stage 1 of research deployment. The research outcomes include experimental design using state-of-art simulators and sensors; data collection and analysis; and assessment of environmental and economic impacts to identify any potential implementation barriers/challenges.

The implementation plan for this research project is strategically divided into near-term and long-term actions. In the near term, the primary focus will be on promptly providing policy recommendations specifically tailored for segments of US-95 in Nye County, where a significant frequency of crashes has been observed. To achieve this, the team will expedite data collection and analysis processes to swiftly identify potential countermeasures that can be implemented to enhance road safety in these high-risk areas.

For long-term implementation, the plan includes the dissemination of research findings and methodologies through a series of educational and informational initiatives, such as workshop sessions, webinars, and training programs. These efforts will be aimed at applying the insights and strategies developed through this research across statewide roadways in Nevada. The goal is to ensure that the knowledge gained from this study extends beyond the immediate scope of US-95, contributing to broader traffic safety improvements throughout Nevada and other states in the United States.

6. Project Schedule and Budget

The proposed research will be completed in 30 months, and the proposed budget is $375,279. A project schedule has been proposed to assist in meeting all project milestones and deliverables on time, as shown in Table 2. Appendix A presents the budget itemization and justification.

Table 2: Project Schedule

Research Tasks		Timeline in Months																												
		2024						2025												2026										
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	30
PHASE I		■	■	■	■	■	■	■	■	■	■	■	■																	
Task 1	Synthesis of Critical Resources and State of Practice	■	■	■	■	■	■	■																						
Task 2	Field Data Collection and Analytics		■	■	■	■	■	■	■	■	■																			
Task 3	Traffic Safety Evaluation					■	■	■	■	■	■	■	■																	
PHASE II														■	■	■	■	■	■	■	■	■	■							
Task 4	Simulation-Based Vehicle Dynamics and Driver Response Analyses for													■	■	■	■	■	■	■										
Task 5	Economic and Environmental Assessments																			■	■	■	■							
PHASE III																								■	■	■	■	■	■	■
Task 6	Policy Recommendations																							■	■	■	■			
Task 7	Final Report and Research Roadmap																										■	■	■	■
	Deliverables	A			Q			T	Q		T		T/I				Q			T	Q		T		Q		T		D/Q	T/F
	Calendar Month:	*Jul.*	*Aug.*	*Sept.*	*Oct.*	*Nov.*	*Dec.*	*Jan.*	*Feb.*	*Mar.*	*Apr.*	*May*	*Jun.*	*Jul.*	*Aug.*	*Sept.*	*Oct.*	*Nov.*	*Dec.*	*Jan.*	*Feb.*	*Mar.*	*Apr.*	*May*	*Jun.*	*Jul.*	*Aug.*	*Sept.*	*Oct.*	*Nov.*

A	: Amplified Work Plan	I	: Interim Report
Q	: Quarterly Report	D	: Draft Final Guide & Report
T	: Technical Memorandum	F	: Final Guide & Report

7. Facilities and Expertise

The project team comprises four professional researchers: Dr. Seri Park (PI), Dr. Hao Xu, Dr. Aobo Wang, and Mr. Trevor Whitley. Additional support will be provided by UNR graduate students who work as research assistants. This research team possesses unmatched expertise and experience that equip them to pursue the proposed research. Dr. Seri Park is a recognized expert and has over 20 years of combined teaching, research, and professional experience with a major focus on traffic safety and driver behavioral studies. Dr. Hao Xu is one of the worldwide top experts applying LiDAR sensing technologies in traffic data collection. Dr. Aobo Wang has in-depth expertise in traffic simulation development and statistical analysis. The resumes of key team members are attached as Appendix B. The team has all the needed facilities to perform this research, such as a self-developed LiDAR data collection platform, Artificial Intelligence (AI) based data processing software, an advanced driver simulator, and a vehicle dynamics simulation software suite, CarSim. More information regarding the research facilities is presented in Appendix C.

8. Project Champion, Coordination, and Involvement

In developing this research proposal, the team reached out to the three project champions. The team has also established coordination with potential project stakeholders, such as the Office of Traffic Safety of the Nevada Department of Public Safety. As a local research team in Nevada, project involvement will be facilitated by close collaborations.

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Appendix A: Budget Itemization and Justification

Project Title: The Optimal Shoulder for Reducing Speed-Related and Lane Departure Crashes

Project Duration: 30 Months

Name and Position	Monthly Salary	Wage	Fringe Benefit	Total Year 1
Dr. Seri Park, PI	~$333.34	$4,000	96	$4,096
Dr. Hao Xu, Co-PI	~$333.34	$4,000	96	$4,096
Aobo Wang, Co-PI	~$1,666.67	$10,000	$3,380	$13,380
Trevor Whitley, Research Scientist	~$1,666.67	$10,000	$3,380	$13,380
Graduate Assistant I	$2,500	$30,000	$5,280	$35,280
Graduate Assistant II	$2,500	$30,000	$5,280	$35,280
Year 1 Totals		**$88,000**	**$17,512**	**$105,512**
Name and Position	**Monthly Salary**	**Wage**	**Fringe Benefit**	**Total Year 2**
Dr. Seri Park, PI	~$333.34	$4,000	96	$4,096
Dr. Hao Xu, Co-PI	~$333.34	$4,000	96	$4,096
Aobo Wang, Co-PI	~$1,666.67	$10,000	$3,380	$13,380
Trevor Whitley, Research Scientist	~$1,666.67	$10,000	$3,380	$13,380
Graduate Assistant I	$2,500	$12,500	$2,200	$14,700
Graduate Assistant II	$2,500	$12,500	$2,200	$14,700
Year 2 Totals		**$53,000**	**$11,352**	**$64,352**
Name and Position	**Monthly Salary**	**Wage**	**Fringe Benefit**	**Total Year 3**
Dr. Seri Park, PI	~$333.34	$2,000	$48	$2,048
Dr. Hao Xu, Co-PI	~$333.34	$2,000	$48	$2,048
Aobo Wang, Co-PI	~$1,666.67	$5,000	$1,690	$6,690
Trevor Whitley, Research Scientist	~$1,666.67	$5,000	$1,690	$6,690
Year 3 Totals		**$14,000**	**$3,476**	**$17,476**
	Year 1	**Year 2**	**Year 3**	**Year 4**
A. Personnel and Fringe	$105,512	$64,352	$17,476	
B. Travel	$12,000			
C. Operating Costs (Materials & Supplies)	$4,000			
D. Final Report Preparation & Submission				
E. Equipment	$40,000			
F. Other Costs				
F.1. Internet Service	$1,400			
F.2. CarSim Software		$14,500		
G. Subcontract (1st $25,000)				
H. Subtotal of Direct Costs	$162,912	$78,852	$17,476	
I. Total Indirect Cost (47%)	$57,769	$37,060	$8,214	
J. Student Tuition and Fees	$8,520	$4,476	$ -0-	
K. Subcontract (w/o Indirect Cost)				
L. TOTAL PROJECT COST PER YEAR	$229,201	$120,388	$25,690	
TOTAL PROJECT COST	**$375,279**			

Budget Justification

The University of Nevada, Reno is on an 8-month academic and 4-month summer calendar schedule.

A. Personnel: $155,000

Principal Investigator. $10,000. The commitment of PI (Seri Park) is for 0.25 summer months in Years 1-2 and 0.12 summer months in Year 3. Based on a salary of $137,731 (assuming an 11% COLA in Year 1, $124,082 is the current base), the project-related salary is $4,000 in Years 1-2 and $2,000 in Year 3. Total PI salary requested for the project: **$10,000** ($4,000+$4,000+$2,000).

Co-Principal Investigator. $10,000. The commitment of Co-PI (Hao Xu) is for 0.25 summer months in Years 1-2 and 0.12 summer months in Year 3. Based on a salary of $137,316 (assuming an 11% COLA in Year 1, $123,708 in the current base), the project-related salary is $4,000 in Years 1-2 and $2,000 in Year 3. Total Co-PI salary requested for the project: **$10,000** ($4,000+$4,000+$2,000).

Research Scientist. $25,000. The commitment of Researcher (Aobo Wang) is for 1 summer month in Years 1-2 and 0.5 summer months in Year 3. Based on a salary of $86,763 (assuming an 11% COLA in Year 1, $78,165 currently), the project-related salary is $10,000 in Years 1-2, and $5,000 in Year 3. Total salary requested for the project: **$25,000** ($10,000+$10,000+$5,000).

Research Scientist. $25,000. The commitment of Researcher (Trevor Whitley) is for 0.8 summer months in Years 1-2 and 0.4 summer months in Year 3. Based on a salary of $105,672 (assuming an 11% COLA in Year 1, $95,200 currently), the project-related salary is $10,000 in Years 1-2, and $5,000 in Year 3. Total salary requested for the project: **$25,000** ($10,000+$10,000+$5,000).

Graduate Assistants. $85,000. Two graduate assistants will each commit approximately 20 hours per week for 17 months at a wage of $2,500 per month or $42,500 for the project. Total wages for two graduate assistants: **$85,000** ($42,500 x 2 graduate assistants).

Fringe: $32,340

Fringe rates for the University of Nevada, Reno are based on approved DHHS rates. The rate for the PI and Co-PI as overload without retirement is 2.4% (**$480**). The rate for research scientists is 33.8% of requested salaries (**$16,900**). The rate for graduate assistants is 17.6% of requested wages (**$14,960**).

B. Travel: $12,000

Domestic. Travel is requested for the project team to attend field sites in Nevada related to the project to disseminate research findings. The cost for a typical 9-day trip (for example) to Goldfield, NV is approximately $2,000/person: transportation/mileage ($397), lodging ($1,072 for 8 nights, $134/night), and per diem ($531 for 9 days, $59/day). Estimated six trips (4 trips for the LiDAR team and 2 for field observation) at $2,000 each is **$12,000** ($2,000/trip x 6 trips) for the project period. *Travel costs are based on current GSA rates.*

C. Operating Costs: $4,000

Materials and Supplies. $4,000. Costs include necessary lab supplies and consumable materials for the project duration. The estimated total is **$4,000** for the project period. *Estimated costs are based on vendor and historical costs.*

E. Equipment: $40,000

Costs include two trailers to be purchased during Task 2 of the project at $20,000 per trailer. The estimated total for two trailers is **$40,000** ($20,000/trailer x 2 trailers) for the project period. *Equipment costs are excluded from the F&A base.*

F. Other Costs: $15,900

F.1. Internet Service. $1,400. Costs include internet service during field data collection during Task 2. The estimated total for internet service is **$1,400** for the project period.

F.2. CarSim Software. $14,500. Costs include CarSim software licensing during Task 4 of the project. The estimated total for software licensing is **$14,500** for the project period.

H. Subtotal of Direct Costs: $259,240

I. Indirect Costs: $103,043

The University of Nevada, Reno has an approved, federally negotiated facilities and administrative cost rate for on-campus research of 47.0% on Modified Total Direct Costs (MTDC), excluding equipment and tuition costs. MTDC base is $219,240.

J. Student Tuition and Fees: $12,996

Tuition is required on all assistantships at UNR. Considering an average course load of 12 credits per year (6 per semester), the estimated tuition rate is $355/credit in Year 1 and $373/credit in Year 2.

- Graduate Assistant I: $4,260 in Year 1 (12 credits) and $2,238 in Year 2 (6 credits)
- Graduate Assistant II: $4,260 in Year 1 (12 credits) and $2,238 in Year 2 (6 credits)

Total tuition cost is **$12,996** [($4,260+2,238) x 2 graduate assistants]. *Tuition cost per credit is projected to increase by 5% annually. Tuition costs are excluded from the F&A base.*

Total Funding Request: $375,279

Appendix B: Team Member Resumes

Seri Park Ph.D., PTP

Associate Professor

Civil and Environmental Engineering
University of Nevada, Reno

Center for Advanced Transportation Education and Research (CATER)

Education

Ph.D., University of California, Irvine – 2004

Professional Affiliations

Transportation Research Board (TRB)

Institute of Transportation Engineers (ITE)

Women's Transportation Seminar (WTS)

American Society of Civil Engineers (ASCE)

American Statistical Association (ASA)

Dr. Seri Park is a certified Professional Transportation Planner. Dr. Park offers highly specialized knowledge in the areas of traffic safety, traffic operations and control, and targeted group survey development and analysis that are major components in this project's success. Dr. Park's expertise in traffic engineering and transportation planning derives from a versatile career as both an academic researcher and a professional engineer. Dr. Park is also actively involved in regional safety and operational committees, serving as a former member of Pennsylvania State Transportation Innovation Council (STIC), and as the current member Pennsylvania DOT Safety Technical Advisory Group (TAG) and the Delaware Valley Regional Planning Commission's (DVRPC) Regional Safety Task Force.

Research Experience (selected)

"Collaborative Research: IRES Track I: Future Mobility for Smart City," National Science Foundation (2022-2025)

"Integrating Freight and Active Transportation into Policies, Programs, Plans and Project Development," National Cooperative Highway Research Program Synthesis Topic 53-17 (2021-Present)

"Understanding Young Drivers' Distracted Driving Behavior", National Motorist Association (2021-2023)

"Assessing Roadway Flood Inundation Factors," Pennsylvania Department of Transportation (2021- 2022)

"Synthesis 573: Practices for Integrated Flood Prediction and Response Systems," Transportation Research Board of the National Academies (2019-2021)

Strategic Highway Research Program (SHRP) 2 Education Connection: Integration of SHRP2 Modules within the Civil Engineering Curriculum at Rowan University, Temple University, Villanova University, and West Virginia University, Federal Highway Administration (2017- 2018)

"Synthesis 523: Integration of Roadway Safety Data from State and Local Sources," Transportation Research Board of the National Academies (2016 – 2018)

"Pilot a Solution to Fix Non-Compliant Edge Line Rumble Strips for Bicycle Safety," Pennsylvania DOT (2016 – 2017)

"Synthesis 486: States Practices for Local Road Safety," Transportation Research Board of the National Academies (2014-2015)

Hao Xu Ph.D., P.E.

Associate Professor

Civil and Environmental Engineering
University of Nevada, Reno

Center for Advanced Transportation Education and Research (CATER)

Dr. Hao Xu's research areas include roadside LiDAR sensing networks, algorithms for processing high-density city cloud points, edge- and cloud-based data processing, all-traffic trajectory generation from roadside LiDAR data, and GIS-based traffic information extraction from LiDAR trajectory data. His research group is a worldwide leader in roadside LiDAR sensing and trajectory data applications in traffic. Dr. Xu and his collaborators are applying the roadside LiDAR technologies and all-traffic trajectory data for connected-autonomous vehicle applications, real-time traffic signal control systems, and performance evaluation of multimodal traffic safety and mobility. He has published 90 research papers, and his research team has received more than $6 million in funding and multiple research and paper awards.

Education

Ph.D., Texas Tech University – 2010

Professional Affiliations

Institute of Electrical and Electronics Engineers (IEEE)

Institute of Transportation Engineers (ITE)

Transportation Research Board (TRB)

American Society of Civil Engineers (ASCE)

Nevada Strategic Highway Safety Plan Intersection CEA Committee

Nevada Strategic Highway Safety Plan Pedestrian CEA Committee

Nevada Traffic Records Coordinating Committee

Research Experience (selected)

"Automatic Road Feature Extraction from State-Owned Mobile LiDAR Data for Traffic Safety Analysis and Prediction," research sponsored by U.S. Department of Transportation

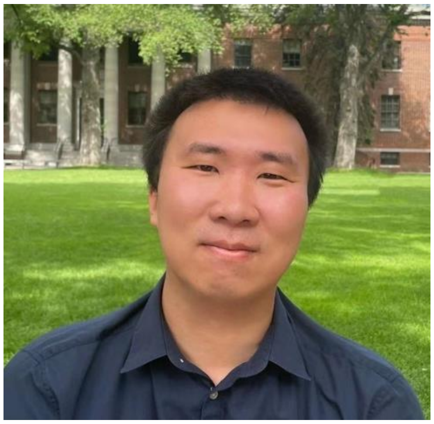
"Proof-of-Concept Research of Roadside LiDAR Sensing Multimode Traffic, Nevada Department of Transportation," research sponsored by Nevada Department of transportation

"A novel optimization-based method to develop representative driving cycle in various driving conditions," published research, 2022, Energy

"Headway Data Extraction and HCM Capacity Function Calibration for Roundabouts with Roadside LiDAR Trajectory Data," published research, 2022, Transportation Research Record

"Metro passenger's path choice model estimation with travel time correlations derived from smart card data," published research, 2021, Transportation Planning and Technology

"Real-time Queue Length Detection with Roadside LiDAR Trajectory Data," published research, 2020, Sensors



Dr. Aobo Wang is a key member of the Center of Advanced Transportation Education and Research (CATER) at the University of Nevada Reno. Dr. Wang had in-depth knowledge regarding traffic simulation, vehicle trajectory data analytics, and human behavioral studies. He has participated in several research projects, including one NDOT-sponsored research, and authored or co-authored over 20 publications. He currently provides referee services to Transportation Research Record: Journal of the Transportation Research Board, IEEE Transaction on Intelligent Transportation Systems, ASCE Journal of Transportation Engineering, Journal of Advanced Transportation, etc. He is currently a member of the TRB Traffic Signal System Committee (ACP25).

Aobo Wang Ph.D.

Research Scientist

Civil and Environmental Engineering
University of Nevada, Reno

Center for Advanced Transportation Education and Research (CATER)

Education

Ph.D., University of Nevada Reno – 2020

Professional Affiliations

Transportation Research Board (TRB)

Institute of Traffic Engineers (ITE)

American Society of Civil Engineers (ASCE)

World Conference on Transport Research Society (WCTR)

Institute of Electrical and Electronics Engineers (IEEE)

Research Experience

“Freeway and Arterial Performance Analysis with High-Resolution Vehicle Trajectory Data”, Nevada Department of Transportation (2023-2026)

“Developing a Quality of Signal Timing Performance Measure Methodology for Arterial Operations”, Nevada Department of Transportation (2017-2020)

“Signal Timing - 6”, RTC Washoe (2020-2022)

“Signal Timing - 5”, RTC Washoe (2018-2020)

“Carson Street Signal Re-timing Project”, City of Carson City (2018-2019)

"Transportation Technical Support Service", RTC Washoe (2016-2018, 2019-2021 & 2021-2023)

Appendix C: Team's Research Highlights

1. LiDAR-based Applications for Detailed and Inclusive Traffic Data

The UNR team will use a self-developed LiDAR data collection platform and data processing software to gather and analyze detailed vehicle trajectories and speeds, including the vehicle's offset from the shoulder and within the lane (lane marking) with high-resolution high-accuracy LiDAR trajectory data.

The application of UNR's advanced roadside sensing solution aims to gather comprehensive behavior data of all road users. The high-frequency, high-accuracy trajectory data collected is pivotal for various studies, including safety behavior analysis, near-crash analysis, proactive safety measures, evaluation of safety countermeasures, making evidence-based decisions, and improving connected and autonomous systems. LiDAR sensors, which operate by emitting pulsed lasers, are instrumental in measuring the positions of objects with stability and reliability, performing optimally in different environmental conditions, both day and night. For data collection, the LiDAR sensor is strategically placed on portable trailers, streetlights, or utility poles, utilizing available infrastructure. It is connected to a cabinet at the pole/trailer's base, housing a processing unit with a hard drive, powered by lithium batteries that can last 3-5 days continuously.

Technology Used - 32-Channel Velodyne LiDAR Sensors:

The technology in use includes 32-channel Velodyne LiDAR sensors. These sensors generate a point cloud of the surrounding environment using 32 vertically distributed lasers that rotate 360 degrees, pulsing at a frequency of 10 hertz. Each laser pulse results in accurate spatial measurements, recorded as a Cartesian vector originating from the sensor. The raw LiDAR data visualizes a point cloud outlining the landscape, including buildings, trees, the ground, and crucially, the movements of various road users like vehicles, bicycles, and pedestrians.

Post-Processing through UNR's AI Software:

The collected cloud points are post-processed using UNR's artificial intelligence (AI) software, which performs several steps to derive the desired traffic movement or trajectory data. Initially, the software filters out background points (such as trees and buildings). Following this, road users are classified like vehicles, pedestrians, or bicyclists. The software then tracks the movements of these road users as they move through the traffic landscape within the sensor's detection range. This enables the conversion of trajectory points into georeferenced points, which are then uploaded to GIS software for further processing and analysis. The frequency of point collection is 10 hertz, meaning a road user's movements are tracked every 0.1 seconds. The primary focus of this study is to analyze traffic patterns and safety concerns for all road users and to identify potential countermeasures.

Details of Traffic Data Analysis:

The traffic data derived from these trajectories include:

1. Speed profiles of each vehicle along a 600-ft segment at each data collection site (72-hour data for each site).

2. Vehicle lane position profiles for each vehicle along the same segment, providing insights into the occurrences of passing events.
3. Relative distances and speed profiles between each vehicle and surrounding vehicles (front, rear, and side) along the 600-ft segment. This analysis reveals the relative positions of vehicles during following or passing maneuvers.
4. Profiles of the distance between each vehicle and the lane boundaries, rumble strips, and shoulder boundaries along the 600-ft segment at each data collection site. This data sheds light on how vehicle trajectories align with current lane markings and shoulder/roadside designs.

Data Analytics using Mobile LiDAR Data:

The team will extract the detailed geometry features including slope & shoulder widths, and clear zone. We will obtain raw mobile LiDAR data from NDOT, UNR team will process the data to gather detailed information about the roadway features.

The mobile LiDAR project involves examining detailed geometry features of roads, such as slopes and shoulder widths. This data will be obtained from raw mobile LiDAR data provided by NDOT. The team will process this data to extract detailed information about roadway features. This infrastructure data is crucial for safety analysis and offers insights into how roadway features impact proactive behavior for roadway safety improvements. The data also assists in recommending modifications to enhance road safety.

NDOT's Mobile LiDAR Data:

NDOT collects mobile LiDAR data on all its routes and functionally classified roads, primarily in the Northbound or Eastbound directions. This data undergoes post-processing with GPS corrections and precise ephemeris files to ensure accuracy. The begin/end frame numbers of the data are adjusted to accurately reflect the start and end points of the routes. The GPS corrections further fine-tune the mileage and linear referencing to achieve the most accurate length and position. The mobile LiDAR data comprises high-quality 3D cloud points of traveled ways and roadsides, accurately geolocated to the WGS_1984_UTM_Zone_11N GIS coordinates. Roadway and roadside surfaces are represented with high accuracy (4 centimeters), and high-density 3D points, containing detailed information like depth, laser reflection intensity, and geolocation.

Project Methodology - Detailing Road Features:

The project team will collaborate with NDOT to access their high-resolution, high-accuracy mobile LiDAR data collected along the study US95 segment and other selected high-speed two-lane, two-way road segments. The objective is to extract details of the existing lane, shoulder, and roadside geometry, including stripping details such as lane width, shoulder width, the elevation difference between the shoulder edge and the fore slope, lane foreslope, shoulder slope, and fore slope grades, as well as roadside obstacles within the range of the NDOT mobile LiDAR data, horizontal curve data, and longitudinal road grades.

Data Conversion and Analysis Steps:

Converting the LAS LiDAR data into GIS raster format significantly enhances data processing efficiency and operation. This conversion compresses the LAS data into high-resolution grids, retaining only each grid's elevation and laser reflection intensity information. Each geolocated LAS file is then converted into two geolocated raster layers: one for elevation and the other for reflection intensity. Using these converted grid data and selected algorithms, the team will perform several steps to extract road features:

1. Split the centerline GIS into short segments (e.g., 100 ft).
2. Apply segmentation technology to the related two-channel LiDAR image for each centerline segment, differentiating road surface objects. Then, use classification methods to recognize each object's classification.
3. Identify the existence of road features and calculate the corresponding values listed above.
4. Integrate the identified road features for each centerline segment and create separate GIS layers for each extracted data element.

2. Big Data Mining of Vehicle Trajectories for Risk Identification

Over the past 15 years, vehicle trajectory data, also known as probe-vehicle data, have been used by a growing number of state departments of transportation in traffic studies. These vehicle trajectory data are sourced from cell phones, mobile applications with location-based services (LBS), and on-board GPS devices like automatic vehicle locating (AVL) systems in transit vehicles and taxis. In the last two years, an emerging trajectory data source called “connected vehicle data” has been launched in the U.S. that provides high-resolution trajectories crowdsourced directly from vehicles (i.e., trajectories are collected through telematics of individual vehicles). High-resolution trajectories can be redistributed by traffic data companies after removing privacy information. Compared to earlier sources, connected-vehicle data has three major advantages:

1. **First-hand data for vehicle trips**. A connected vehicle trajectory indicates a complete trip with “key on” and “key off” tags, reflecting more accurate and detailed traffic performance compared to aggregated probe-vehicle data. Besides timestamp, location coordinates, and speed, the connected-vehicle trajectory also includes vehicle status information such as vehicle type, fuel type, passenger occupancy, and harsh breaking.
2. **Large sample size**. Connected-vehicle data providers report that their data penetration rate can be around 5% across the U.S., which is sufficient for measuring performance. Research has shown that problematic arterial operations can be identified using trajectory data with a penetration rate of about 1%.
3. **High temporal and spatial resolutions.** Connected-vehicle trajectories have a stable time granularity of 3 seconds per data point, while the INRIX platform’s probe-vehicle data usually have time intervals between two consecutive trajectory waypoints ranging from 1 second to 10 minutes. Connected-vehicle trajectories also have geographic precision of under **10 feet** more than 95% of the time.

Figure C-1 presents a sample of a waypoint of a vehicle telemetric trajectory. The unique journey IDs represent individual trips. Each waypoint indicates a timestamp, the location presented by latitude and longitude, instant speed measured from the vehicle onboard system, heading direction, vehicle type, model, and vehicle year. Figure C-2 shows the distribution of waypoints on a highway segment in Las Vegas. The lane positions of individual trajectories can be accurately identified.


```
"dataPointId": "044862f9-88f9-4abe-bde0-dded07c567d2",
"journeyId": "02c4aee2350d42a9b8da1accfab10727f851a80b",
"capturedTimestamp": "2022-03-07T01:30:03.000-0800",
"latitude": 39.510527,
"longitude": -119.960526,
"Zipcode": "89439",
"speed": 70.86,
"heading": 262.0,
"ignitionStatus": "MID_JOURNEY",
"make": "GMC",
"model": "Sierra Limited",
"vehicleYear": "2022.0",
"bodyClass_NHTSA": "Pickup",
"fuelTypePrimary_NHTSA": "Diesel",
"fuelTypeSecondary_NHTSA": null,
"PowerTrain": "ICE",
"year": "2022",
"month": "03",
"day": "07",
"hour": "01",
"minute": "30",
"second": "03"
```


Figure C-1: Sample Waypoint of Vehicle Telemetric Trajectories

Figure C-2: Lane Positions of Waypoints

Although Such vehicle trajectories are sampled data of the total traffic (5% penetration), this data source can provide abundant information regarding speeding and lane departure because of excellent speed record details and spatial precision, especially considering rural highways where agencies may not have enough resources to perform data collection on a timely basis.

3. Advanced Simulator for Exploring Drivers' Behavioral Factors in Traffic Crashes

The team will leverage RDS-1000 Simulator in this research, as shown in Figure C-3, which features real-vehicle equipment, including a real steering wheel with control-loaded steering, real accelerator, and brake pedals, along with a fully customizable virtual dashboard. The RDS-1000 features a quarter-cab design with a standard 210° horizontal field-of-view.

The RDS-1000 cab is a quarter of a mock Ford Fusion dash assembly. It includes three large monitors for the forward scene, as well as a virtual dashboard for the speedometer and other in-vehicle information. A surround sound system, along with base-shaker under the seat, is also included.

Figure C-3: RDS-1000 Driving Simulator

The simulation environment of the RDS-1000 simulator is developed using a software suite that allows for various modifications. Road environment, pavement conditions, weather, lane boundaries, and the presence of surrounding vehicles can be customized by the team. Figure C-4 presents three typical simulation settings – 1) city scene, 2) night driving scene, and 3) freeway scene.

City Scene

Night Driving Scene

FREEWAY SCENE

Figure C-4: Typical Simulation Settings

The RDS-1000 simulator can capture significantly board and detailed data regarding driving maneuvers. Table C-1 lists the data categories that can be measured through driving simulation.

Table C-1: Data Measurements Obtained through Driving Simulation

Variable	Description
Acceleration	value in m/s/s. Negative values are decelerations.
Lateral Acceleration	value in m/s/s
Accelerator Pedal	This is the angle of the pedal position
Brake Pedal Force	brake force
Gear	Gear
Heading	a value in degrees (deg) representing the heading of the vehicle. a value of 0 is North.
Heading Error	Angle (deg) between road path and current heading
Headway Distance	a value in meters (m). This is the headway distance between the center of gravity of the vehicle to the center of gravity of the vehicle ahead.
Headway Time	a value in seconds (s). This is the headway time between the center of gravity of the vehicle to the center of gravity of the vehicle ahead.
Lane Number	an integer value of the lane the vehicle is in. Lane numbers start from the center line and go out. Positive lane numbers are the positive direction of the road.
Lane Offset	a value in meters (m) of the position of the vehicle from the center of the lane. Positive numbers are to the right of the lane and negative are to the left.
Road Offset	a value in meters (m) of the position of the vehicle from the center line. Positive numbers are to the right of the center line and negative are to the left.
Steering Wheel Position	a value in radians (rad) describing the steering wheel position.
Tailway Distance	a value in meters (m). This is the tailway distance between the center of gravity of the vehicle to the center of gravity of the vehicle behind.
Tailway Time	a value in seconds (s). This is the tailway time between the center of gravity of the vehicle to the center of gravity of the vehicle behind.
Velocity	a value in m/s
Lateral Velocity	a value in m/s
Vertical Velocity	a value in m/s
X Position	X position in meters
Y Position	Y position in meters
Z Position	Z position in meters
Roll	Roll in degrees
Pitch	Pitch in degrees
Yaw	Yaw in degrees