Roadway and Driver Factors Associated with Vulnerable Road User Detection During Naturalistic Driving

August 2026

Region 1:
New England University Transportation Center

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In cooperation with U.S. Department of Transportation,
Office of the Assistant Secretary for Research and Technology (OST-R)

Grant #: 69A35523483

TECHNICAL DOCUMENTATION

1. Project No.	2. Government Accession No.	3. Recipient's Catalog No.
161549	01935905	
4. Title and Subtitle Roadway and Driver Factors Associated with Vulnerable Road User Detection During Naturalistic Driving		**5. Report Date** August 2026 **6. Performing Organization Code** N/A
7. Author(s) Niloufar Shirani (0009-0002-2914-9004), Patricia Tice (0000-0001-8037-4771) Elena Orlova (0009-0006-9217-1596), Noah Rothermel (0009-0006-5061-5259),		**8. Performing Organization Report No.** N/A
9. Performing Organization Name and Address New England University Transportation Center 181 Presidents Drive University of Massachusetts - Amherst Amherst, MA 01003		**10. Work Unit No. (TRAIS)** **11. Contract or Grant No.** 69A35523483
12. Sponsoring Agency Name and Address United States Department of Transportation Research and Innovative Technology Administration 1200 New Jersey Avenue, SE Washington, DC 20590		**13. Type of Report and Period Covered** Final Research Report **14. Sponsoring Agency Code** USDOT OST-R

15. Supplementary Notes

Report uploaded and accessible at the NEUTC Website (www.umass.edu/neutc)

16. Abstract

Although physical visibility is often assumed to ensure driver awareness, relatively little naturalistic evidence describes how drivers perceive vulnerable road users (VRUs) across real-world driving contexts. This study examined roadway and driver factors associated with detection of pedestrians, cyclists, and motorcyclists using synchronized multimodal data. Twenty-four participants completed two naturalistic drives over a fixed route representing rural, suburban, campus, and urban environments. Driver gaze was recorded using Tobii Pro Glasses 3, vehicle data using a CANbus/GNSS-IMU logger, and heart rate using a Polar H10 sensor. The synchronized dataset contained 3,526 annotated VRU encounters. Mixed-effects logistic regression identified factors associated with successful detection. Vehicle speed was the strongest factor, with each 1-mph increase associated with an approximately 5% reduction in detection odds (OR = 0.95, $p < 0.001$). VRUs on the right side of the roadway were twice as likely to be detected as those on the left (OR = 2.00, $p < 0.001$), and detection was higher in rural than urban environments (OR = 4.55, $p = 0.019$). Findings support speed management, context-sensitive roadway design, and driver-assistance systems to improve VRU safety.

17. Key Words	18. Distribution Statement		
Vulnerable Road Users, Driver Behavior, Eye Movements, Visual Attention, Traffic Safety	No restrictions.		
19. Security Classif. (of this report)	**20. Security Classif. (of this page)**	**21. No. of Pages**	**22. Price**
Unclassified	Unclassified	8	

Form DOT F 1700.7 (8-72) **Reproduction of completed page authorized.**

About NEUTC

The New England Regional University Transportation Center (NEUTC) is a multidisciplinary consortium committed to addressing the pressing issue of traffic safety. Our objective, in line with the Infrastructure Investment and Jobs Act (IIJA), is to drive transformative research, education, and technology transfer to address critical traffic safety needs in a time when roadway fatalities are distressingly high.

Our research and educational activities at NEUTC are guided by four principal safety themes, each addressing a critical challenge in transportation safety. These themes capture the various integral components of the transportation system, focusing on technology, infrastructure, vehicles, and users with a commitment to community engagement. Our overarching theme is promoting safety, with the common underlying science being the study of behavioral, systemic, environmental, and mobility-driven factors on safety.

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Motivation

Background

The Federal Highway Administration (FHWA) has adopted the Vision Zero initiative, a nationwide commitment to eliminating roadway fatalities through the Safe System approach, which recognizes that transportation system should accommodate human error while minimizing the likelihood of fatal and serious injuries (FHWA 2023). Within this framework, improving the safety of vulnerable road users (VRUs), including pedestrians, cyclists, and motorcyclists, remains a major traffic safety challenge, as these road users continue to be disproportionately represented in traffic fatalities despite continued advances in roadway design and vehicle safety.

Although overall crash rates per vehicle mile traveled have declined substantially over recent decades, fatalities involving VRUs have increased considerably since reaching their lowest level in 2009. Because the vast majority of these crashes involve motor vehicles, improving drivers' ability to detect and appropriately respond to pedestrians and cyclists remains one of the most critical challenges in roadway safety.

Crash investigations frequently report that drivers involved in pedestrian and cyclist collisions claim they "didn't see" the vulnerable road user or that the person "came out of nowhere." These observations are consistent with the well-documented looked-but-failed-to-see (LBFTS) phenomenon, in which drivers fail to respond to hazards that are physically visible because of limitations in visual attention, expectation, or cognitive processing rather than inadequate visibility alone. Research has shown that even highly conspicuous objects may go undetected when drivers' expectations or attentional resources are directed elsewhere, highlighting the distinction between physical visibility and driver detection (Langham et al. 2002).

Current roadway design guidance primarily addresses the geometric aspects of visibility through measures such as stopping sight distance and intersection sight triangles. While these measures are essential for ensuring that a pedestrian or cyclist can be physically visible, they do not explicitly account for how drivers allocate visual attention or how roadway context, competing visual information, and driver expectations influence whether a vulnerable road user is actually detected. Consistent with this, Inman et al. 2013 highlighted that visibility alone does not guarantee conspicuity or driver awareness and has emphasized the need to better understand how roadway environments influence visual attention and object detection (Inman et al. 2013).

Naturalistic driving studies and eye-tracking research have substantially advanced our understanding of driver visual attention and hazard perception. Previous studies have shown that drivers' visual search behavior is influenced by roadway geometry, traffic conditions, speed environment, and the presence of vulnerable road users (Jansen and Varotto 2022). However, relatively few studies have integrated eye-tracking, vehicle telemetry, physiological measurements, participant characteristics, and roadway attributes to examine how roadway and driver factors jointly influence driver detection of vulnerable road users under naturalistic driving conditions.

Research Gap

Although previous studies have substantially improved the understanding of driver visual attention, hazard perception, and vulnerable road user detection, important knowledge gaps remain. Existing studies have largely examined individual aspects of driver behavior, such as gaze allocation, hazard perception, or vehicle operation, in isolation. Relatively few studies have simultaneously integrated synchronized eye-tracking, vehicle telemetry, physiological measurements, participant characteristics, and roadway context to examine how these factors jointly influence vulnerable road user detection under naturalistic driving conditions. Furthermore, limited evidence is available regarding the independent effects of roadway context and driver characteristics on the likelihood of successfully detecting vulnerable road users. Addressing these gaps is essential for developing evidence-based, context-sensitive roadway design and Safe System strategies that improve not only the physical visibility of vulnerable road users but also the likelihood that they are detected by drivers.

Objectives

The objective of this study was to examine driver visual attention and behavioral responses during naturalistic encounters with pedestrians, cyclists, and motorcyclists and to identify roadway and driver factors associated with vulnerable road user detection.

Specifically, this study aimed to:

- Characterize the occurrence and characteristics of “Seen” and “Not Seen” VRU encounters;
- Examine differences in visual attention, vehicle operation, and physiological response during VRU encounters;
- Identify and quantify the associations between roadway and driver factors
- Provide naturalistic evidence to support context-sensitive roadway design and Safe System strategies for improving VRU safety.

Executive Summary

This project examined how drivers visually detect and respond to vulnerable road users (VRUs) under real-world driving conditions, with particular attention to the difference between physical visibility and actual driver detection. The study combined naturalistic eye tracking, vehicle telemetry, roadway context, heart-rate data, and participant characteristics to evaluate when pedestrians, cyclists, and motorcyclists were seen or missed. The central finding is that VRU detection is strongly shaped by the operating environment rather than by visibility alone. Vehicle speed was the strongest measured predictor of detection, roadway context and VRU location also mattered, and descriptive review of the eye-tracking videos suggests that drivers continually devote substantial visual effort to constructing and maintaining a model of the navigable path ahead. Together, the quantitative and qualitative results support a Safe System interpretation: roadway design influences operating speed, visual expectations, and the allocation of driver attention, and therefore influences whether a physically visible VRU is likely to be detected and therefore can be responded to in a safe manner.

Methods

Twenty-four participants with completed two drives over an approximately 18-mile fixed route in Connecticut using their own vehicles while outfitted with eye tracking glasses. The route included rural, suburban, campus, commercial, urban, parking, roundabout, trail-adjacent, and limited-access roadway contexts. Participants first completed an outbound drive while remaining naïve to the study purpose. On the return drive, they provided a stream-of-consciousness narration and verbally identified VRUs and other roadway features. The primary inferential model was therefore restricted to outbound-drive encounters to avoid altering visual-search behavior through the return-drive instructions. The return-drive narratives will become a part of the overall data-stream that may be analyzed later.

Driver gaze was recorded at 100 Hz using Tobii Pro Glasses 3. Vehicle operating and location data were collected through a CANedge1 OBD-II/CANbus logger with GNSS/IMU, and heart rate was recorded at one-second intervals using a Polar H10 sensor. Forward-facing scene video and audio were used to verify roadway conditions and annotate VRU encounters. Questionnaire data included demographics, driving history, and surveys assessing driving-related mindfulness, and aggressive-driving behavior. The synchronized multimodal dataset contained 3,526 annotated VRU encounters across 48 drives.

VRU encounters were classified as Seen or Not Seen based on the spatial and temporal relationship between gaze and the VRU. Mixed-effects logistic regression was used to identify roadway, vehicle, and participant factors independently associated with detection while accounting for repeated encounters within participants and roadway segments. Additional analyses examined segment-level VRU density and operating speed, heart-rate responses, and survey measures. The statistical analysis was complemented by a qualitative visual review of the eye-tracking videos to identify recurring visual search patterns that may help explain how drivers

allocate attention in different roadway contexts. Those qualitative observations are preliminary and should be treated as hypotheses for subsequent quantitative testing rather than as confirmed effects.

Key Results and Findings

- **Speed was the strongest measured predictor of VRU detection.** In the primary mixed-effects model, each 1-mph increase in vehicle speed was associated with an approximately 5% reduction in the odds of detecting a VRU (OR = 0.95, 95% CI: 0.94-0.97, $p < 0.001$). Median speeds during Not Seen encounters were generally higher than during Seen encounters across the route. At the roadway-segment level, higher densities of successfully detected VRU encounters were associated with lower mean operating speeds; a logarithmic model explained 58.2% of the variation in segment mean speed. The relationship is likely a result of self-reinforcing feedback loop patterns: lower speed provides more time and visual opportunity for detection, while repeated experience with VRU activity may also teach drivers to select lower speeds in places where they expect people to be present.
- **VRU location within the roadway scene affected detection.** VRUs on the right side of the roadway were approximately twice as likely to be detected as those on the left after adjustment for speed, roadway context, sidewalk characteristics, parking, and participant variability (OR = 2.00, 95% CI: 1.48-2.71, $p < 0.001$). Overall, 80.1% of right-side encounters were classified as Seen compared with 70.4% of left-side encounters. This asymmetry is consistent with attention being organized around the anticipated vehicle path and likely conflict areas.
- **Roadway context influenced detection.** Rural encounters had significantly higher odds of detection than urban encounters (OR = 4.55, 95% CI: 1.28-16.15, $p = 0.019$), although the smaller number of rural encounters produced a wide confidence interval. Urban, campus, service, and parking environments contained some of the highest VRU densities and, in several segments, elevated miss rates. Segment miss rates ranged from 0% to 49%. These results suggest that visual complexity and competing demands matter; in high-density locations, drivers may not individually register every VRU even while responding appropriately to the overall pedestrian environment.
- **Driver-to-driver variability remained substantial.** After accounting for the measured fixed effects, unexplained variability was greater between participants than between roadway segments. By contrast, sidewalk dimension, on-street parking, and self-reported aggressive-driving score were not significantly associated with detection in the primary model. Heart-rate analyses also found no significant acute response to routine VRU encounters and no significant difference between Seen and Not Seen events. Heart rate alone therefore did not provide a useful marker of detection under the conditions studied.
- **The video review suggests that much of driver gaze is devoted to maintaining a navigable forward corridor.** Across participants and contexts, drivers repeatedly sampled the lane center and roadway boundaries, substituted curbs, pavement edges, parked vehicles, and other continuous features when lane markings were absent, looked

ahead through curves, and searched around lead vehicles to reconstruct portions of the roadway that were occluded. These behaviors point toward a common functional task: drivers continually construct, verify, and project a bounded model of navigable space. A second, wider search pattern was also observed in some drivers, in which the basic roadway model was maintained while attention explored more of the surrounding environment.

- **Preliminary qualitative differences merit further study.** Younger participants appeared, in the videos reviewed to date, to fixate closer to the vehicle and make fewer anticipatory glances than older participants. In some vehicles, heads-up displays occupied the same visual region used for lane-center sampling, raising the possibility that numerical speed information can become embedded in or interrupt the normal roadway-search sequence. Individual events also appeared capable of changing subsequent search behavior; for example, after a near miss, one participant began repeatedly checking crosswalk landing areas. These observations have not yet been quantified and should not be treated as population-level conclusions.

Recommendations

- **Prioritize operating-speed management in places where drivers and VRUs are expected to interact.** The consistent association between higher speed and lower detection supports designing for lower operating speeds rather than relying primarily on posted limits or driver vigilance. Speed management is especially important in urban, campus, mixed-use, and transition environments where visual demand and VRU activity are high.
- **Design for attention, not visibility alone.** Traditional sight-distance criteria are necessary but do not guarantee that a pedestrian or cyclist will be cognitively detected. Roadway design should consider what drivers are required to look at, where visual boundaries guide the eyes, how much competing information is present, and whether VRUs appear where the driver's established search pattern is likely to sample.
- **Training VRU Search Patterns.** Some visual search strategies were more effective at identifying VRU’s in the environment, like scanning landing pads at each high-visibility crosswalk. This is a behavior that can be encouraged using PSA’s and trained in driver education courses.
- **Use context-sensitive roadway cues to make VRU activity expected.** Because speed and visual search appear to reflect learned expectations, environments with substantial pedestrian and bicycle activity should communicate that condition consistently through geometry, crossing placement, edge definition, daylighting, bulb-outs, land-use cues, and other design features. The objective is not simply to make an individual VRU conspicuous at the last moment, but to create a roadway context in which the driver already expects human activity.
- **Consider visual-search behavior in vehicle and driver-assistance technology.** Driver-monitoring systems and advanced driver-assistance systems could benefit from models

that account for roadway context, operating speed, gaze allocation, and likely blind areas in the driver's search pattern. Heads-up-display design should also be evaluated for whether it competes with or alters visual sampling used for lane position and trajectory control.

Future Work

The next phase of research should extend both the quantitative model and the qualitative video findings. Although the initial analysis provided answers to many of our questions, there is sufficient data within the collected data stream to analyze a wide range of behaviors including, but not limited to:

- Fixation patterns around multiple crosswalk types, including high visibility zebra crosswalks, raised crosswalks, Rectangular Rapid Flashing Beacons, and signals.
- Near-miss analysis and scanning and visual search behavior after the miss.
- Construction zones, which were present in nearly every context type throughout the study and staffed at different levels throughout. This allows for both construction and control conditions within the same driver to be analyzed.
- The frequency that speed limit signs are fixated and how that relates to how frequently the driver fixates on their speedometer reading. The data stream also includes several vehicles Heads Up Display, which allows for an separate analysis of how this treatment changes the frequency that the driver sees their current speed.
- Fixation distance can also be extracted from the data stream and correlated to the driver's speed in the moment. This can give an indication of how far ahead in time drivers are typically scanning.
- Heart rate data trends have only lightly been explored in the initial analysis. Further analysis could examine how heart rate relates to speed and how it is impacted by different treatments.
- Merge activities often required a burst of high-frequency glances throughout the field of vision. Measuring fixation changes throughout the study could provide an indication of the level of workload the driving environment imposes.
- Accelerometer data is available for each participant from the eye tracking glasses themselves, along with the x and y coordinates within the view-screen. Both age and gender appear to have some impact on the amount of head movement and range of visual scanning.
- Extensive tagging was performed in the second half of the drive to identify both visual and verbal distraction patterns, which could give an outstanding estimate of how context impacts mind wandering.
- Striping was far more commonly used for lane positioning than was expected and became the resting position for most drivers. However, there were contexts where striping was absent and enclosure scanning within the adjacent land uses largely replaced striping

scanning. This deserves more exploration, both in terms of its design and speed implications.

- Atypical scanning patterns were observed in about 10-15% of the study participants. These scanning patterns were far more varied and wide ranging than typical drivers, which could be an indication of a critical difference in visual processing. A more detailed analysis of the effectiveness of these differing patterns and their relationship with age and the survey instruments used in the study may shed light on how neurotypical and atypical search differs. This could elucidate strategies to compensate for either lack of engagement within the neurotypical population or overstimulation within the atypical population.

The present Seen criterion was deliberately generous (gaze within approximately 7 degrees for at least 200 ms), which makes Not Seen classifications relatively strong but does not establish conscious recognition for every Seen event; future work should distinguish fixation, recognition, and behavioral response more explicitly using tighter focal criteria.

The recurring visual-search patterns should be converted into measurable variables and tested across participants. Priority analyses include quantifying lane-boundary and lane-center sampling sequences, anticipatory curve glances, search behavior around occluding vehicles, the breadth of global versus roadway-centered search, and changes in search following salient events.

Age and gender differences in fixation patterns should be tested, and heads-up-display fixations should be separated from nearby roadway-center fixations to determine whether HUD information supplements or competes with vehicle-control visual sampling patterns. Additional physiological measures such as pupil dilation and eye-based workload metrics may be more sensitive than heart rate alone, data that is available within what was collected in this study.

The appended technical paper provides the full statistical methods, model results, figures, limitations, and supporting literature for these conclusions.

Outcomes

The strongest potential outcome of this research is a change in how agencies approach vulnerable road user visibility and speed management. The study found that both roadway context and operating speed were strongly associated with whether pedestrians, cyclists, and motorcyclists were detected, with increasing speed producing a substantial decline in the odds of detection. These findings indicate that conspicuity treatments alone cannot compensate for operating environments in which higher speeds are common.

For DOT's within New England and other transportation agencies, the research supports a shift toward treating operating speed as a primary VRU-detection and safety variable, particularly in urban, campus, commercial, and other contexts where drivers must process high levels of visual information. Potential outcomes include greater use of context-sensitive design and speed-management practices, stronger consideration of operating speed during VRU safety reviews, and refinement of design guidance so that conspicuity treatments are evaluated in relation to the speed and visual complexity of the roadway environment.

The findings may also support development of screening tools or design criteria that identify locations where prevailing speeds are inconsistent with reliable VRU detection. In those settings, roadway design, geometric changes, or other speed-management measures may be more effective than relying primarily on signs, markings, lighting, or high-visibility crossing treatments to attract driver attention.

Impacts

If these outcomes are incorporated into roadway design and safety practice, the principal potential impact is improved pedestrian and bicyclist safety through earlier and more reliable driver detection. Reducing operating speeds in locations with frequent VRU activity would not only reduce crash severity when collisions occur, but may also increase the likelihood that drivers notice and respond to VRUs before a conflict develops.

This approach could improve the effectiveness of transportation safety investments by helping agencies distinguish between locations where conspicuity treatments are likely to be sufficient and locations where the operating environment itself limits driver detection. Rather than repeatedly adding signs, markings, beacons, or other visibility treatments to high-speed contexts, agencies could target the underlying speed and roadway conditions that contribute to missed detection.

For Connecticut communities, this could lead to fewer severe pedestrian and bicycle crashes, safer access to schools, campuses, downtowns, transit stops, and commercial areas, and greater confidence in walking and bicycling as practical transportation modes. At a broader level, the research supports Safe System policies that address human perceptual limitations through roadway design rather than relying primarily on perfect driver attention or individual road-user behavior.