PI-0362 - Assessing the implementation of AASHTO T 360-16 (OBSI method) on the 4-SCl-85 corridor to determine the effectiveness of quieter pavements strategies for noise mitigation

Requested by
Bruce Rymer MEngr, PE, TE, Senior Transportation Engineer, Division of Environmental Analysis

Prepared by
Alireza Shams, PhD, Transportation Engineer, DRISI

March 4, 2025

Table of Contents

Executive Summary

Background

Traffic noise, as an environmental pollutant, has significantly impacted the quality of life for individuals living near roadways over extended periods. Numerous studies indicate that when traffic noise exceeds safe levels, it can lead to hearing impairment, sleep disturbances, and elevated blood pressure (*1*). Consequently, one of the top concerns usually voiced by roadside communities at public-project-outreach meetings, is reducing traffic noise levels.

Traditional noise abatement strategies, such as constructing barriers, are effective under specific conditions and remain the primary approach endorsed by the Federal Highway Administration (FHWA). However, barriers have limitations, including the need to block the line-of-sight and reduced effectiveness in areas with uneven terrain or frequent gaps due to access points to neighborhoods. Furthermore, noise barriers represent a significant financial investment. In 2013 alone, the California Department of Transportation (Caltrans) spent over $44 million on noise barriers (*2*). Nationwide, between 2014 and 2016, the FHWA reported that construction costs for noise barriers exceeded $671 million over three years, averaging approximately $2 million per mile of noise wall (*3*). The Caltrans sound wall inventory is currently about 800 miles and represents total assets cost of $1.6 billion. Numerous projects are underway across the state, for example, Caltrans District 7, I-5 project includes construction of more than 27 miles of HOV lanes, railroad-grade separations and sound walls are planned (*4*).

Quieter pavement has shown promise in reducing noise at the tire-pavement interface, particularly for vehicles traveling over 30 mph (*2*). Unlike barriers, quieter pavements reduce noise at its source, making quieter pavements a potentially cost-effective and versatile solution. For example, quieter pavement can be implemented without the spatial or structural constraints of noise barriers, which often require significant land use and visual obstructions. Quieter pavements can provide immediate benefits in terms of reduced noise exposure for both urban and rural communities. Additionally, pavement is one of the most significant assets managed by State Departments of Transportation (DOTs), and prioritizing pavement investments can enhance the overall efficiency of taxpayer fund utilization.

Research supports the effectiveness of quieter pavements in noise reduction. Caltrans has led significant efforts in this area over the last 20 years, including the Quieter Pavement Research Plan, which evaluates surface treatments, materials, and construction techniques that minimize noise while maintaining safety and durability. A study conducted by Caltrans analyzed tire/pavement noise characteristics on various concrete pavements and bridge decks across California, providing insights into acoustic performance, friction, and long-term durability (*5*). The National Center for Asphalt Technology (NCAT) has also investigated quieter asphalt mixes, such as open-graded friction courses (OGFC), which have consistently demonstrated lower noise levels compared to dense-graded asphalt or concrete pavements (*6*). The International Grooving & Grinding Association (IGGA), has developed a very quiet Next-Generation-Concrete-Surface (NGCS), as a durable low noise alternative for rigid pavements (*7*).

While quieter pavements offer noise reducing design alternative they are not without challenges. The noise-reducing properties of these pavements can degrade over time due to normal wear and tear, requiring periodic replacement to preserve their low-noise performance. Additionally, the effectiveness of quieter pavements is influenced by traffic speed, pavement type, and environmental factors. Despite these challenges, quieter pavements remain a compelling option, particularly in areas where barriers are impractical or prohibitively expensive. Additionally, the FHWA has a well-established pavement rehabilitation program which periodically funds replacement of old pavement.

Sound walls are designed to reduce traffic noise by 5^+ dBA and only block noise on one side of the road for about 150-200 feet behind the wall. Quieter pavement can reduce noise 5-10 dBA on both sides of the road and reduce noise at much greater distances than any wall could (*8*). In conclusion, quieter pavements provide an innovative design alternative to traditional noise barriers, reducing traffic noise pollution at the source. While barriers continue to play an important role in noise abatement strategies, the adoption of quieter pavement technologies could reduce overall costs and improve the quality of life for communities affected by traffic noise.

Summary of Findings

Quieter pavement has emerged as a promising design alternative for reducing traffic noise, particularly in areas where transportation infrastructure noise is a concern or impacts the quality of life. While it is not yet recognized as an FHWA-approved noise abatement method, it has garnered significant interest over the past two decades from federal, state, and local agencies (*2*). The focus on tire-pavement noise stems from its dominance as the primary noise source for vehicles traveling above 30 mph (*9*). In response, research and pilot studies have demonstrated the capability of quieter pavements, such as OGFC and rubberized asphalt concrete (RAC), and rigid pavement NGCS to significantly reduce tire-pavement noise.

The field has been further advanced by the development of standardized tire/pavement noise measurement method: On-Board Sound Intensity (OBSI). General Motors first developed the acoustic measurement process and a team of Caltrans and FHWA engineers modified it to become The AASHTO T-360-16 (2020) (*10*), Standard method of test for measurement of tire/pavement noise using the OBSI method (*11*). This technique enables researchers to directly measure tire-pavement noise at its source, providing a quick, accurate, portable, and repeatable approach to evaluating pavement acoustics. OBSI has been widely adopted for its precision, allowing for detailed comparisons of different pavement designs and their noise-reducing capabilities (*12*).

Quieter pavement offers several advantages over traditional noise barriers, such as sound walls. Unlike barriers, it does not require the physical blocking of a line of sight or encounter limitations due to uneven terrain or frequent access points (*2*). Additionally, quieter pavements are cost-effective, with lower initial investments compared to barriers, which can cost an average of $2 million per mile (*3*). Quieter pavements also provide noise reduction benefits to both drivers and nearby residents, addressing a wider range of stakeholders. Meanwhile, Caltrans is actively exploring the use of sound walls to help contain vehicle particulate matter (PM) and improve air quality (AQ) in roadside communities. Masonry walls could function as noise barriers or help with PM containment. Walls could serve to address both noise and AQ concerns together or separately. Noise reduction from quieter pavements and noise reduction from sound walls are additive and could be used together or separately as needed by the design team and project requirements require. There is more flexibility in design options and overlapping functionality in addressing environmental impacts, environmental justice, and equity issues.

However, the performance of quieter pavement can degrade over time due to wear, environmental factors, and material aging. This necessitates regular monitoring and additional maintenance to sustain noise reduction capabilities. The degradation of surface texture, for example, can reduce the pavement's ability to minimize noise. Therefore, quieter pavement is most effective when integrated into long-term pavement maintenance strategies, ensuring its acoustic benefits are preserved throughout its lifecycle (*2*).

Despite these challenges, quieter pavement represents a significant design option for addressing traffic noise at the source. Continued advancements in pavement materials, surface designs, and maintenance practices are likely to enhance the long-term viability of this approach, making it a critical complement to traditional noise abatement strategies. As research progresses, quieter pavements could gain broader recognition as a cost-effective and practical solution for improving quality of life in noise-impacted areas.

Gaps in Findings

Quieter pavements have been widely recognized for their ability to reduce noise pollution by targeting the primary source of highway noise—tire-pavement interaction. While significant advancements have been made in quieter pavement materials, designs, and measurement methodologies, certain limitations hinder their widespread application and long-term efficiency.

- Air Quality Benefits of Roadside Barriers: Quieter pavements are noise reducing design alternative which might or might not be a replacement for sound walls. Decision processes would need to be developed to determine which environmental issue, AQ or Noise, might be primary concern to the project development team (PDT). While quieter pavements offer noise reduction at the source, they do not provide the air quality benefits associated with traditional noise barriers. Studies indicate that roadside barriers can reduce near-source pollutant concentrations by 20-40% within 180 meters (≈ 600 ft) of the roadway (*13*), a benefit that quieter pavements alone cannot replicate.

- Acoustic Longevity and Maintenance: As pavement ages, the noise-reduction performance of quieter pavements tends to degrade over time due to wear, clogging, and environmental factors. However, the exact mechanisms and rates of this degradation under different conditions is a gap in predicting acoustic lifespan accurately (*2*).

- Durability Trade-offs: Many quieter pavement designs, such as OGFC, reduce noise effectively but often face significant challenges related to durability. These pavements are susceptible to rutting, and moisture infiltration, limiting their feasibility for long-term and high-traffic applications (*2*). An alternative for this is the IIGA NGCS for rigid pavement provides a more durable and longer lasting quieter pavement option. Caltrans is developing an even quieter high-traffic load pavement which combines NGCS with continuously reinforced concrete pavements (CRCP) which eliminated joints and joint impulse noise. A recent demonstration project combining NGCS and CRCP was completed on SB-101 (*14*).

- Heavy Vehicle Noise: Heavy Vehicle Noise: Research on the impact of heavy vehicles on quieter pavements is limited. While heavy trucks contribute significantly to traffic noise due to their larger tires and axle loads. However, pavement noise levels also depend on tire tread design, which Caltrans does not regulate. Even the quietest pavement may produce high noise levels when paired with loud tread tires.

Additionally, there are potential limitations in using OBSI data to adjust tire/pavement noise levels in the FHWA Traffic Noise Model (TNM) for accounting pavement effects (*12*). These include:

- The FHWA TNM software is 25 years old and its acoustic assumptions about tire/pavement noise needs to be updated.

- OBSI data covers 400–5000 Hz range, which accounts for over 90% of the human hearing range and where most A-weighting occurs. However, pavement effects outside this range are not included, potentially missing minor sound contributions.

Next Steps

The recent federal Notice of Proposed Rule Making (NPRM) for 23 CFR 772 (*15*), which guides Caltrans Noise Policy and Protocol, hinted at allowing the use of quieter pavements for noise abatement on federally funded projects. In addition, addressing existing gaps requires efforts focused on innovative materials, policy integration, and improved predictive tools. Strengthening these areas can enhance the effectiveness of quieter pavements and support their broader adoption in transportation infrastructure. The following recommendations aim to guide future research and applications.

- Explore the combined use of quieter pavements and sound walls to maximize noise reduction and air quality benefits, especially in areas with sensitive populations or air quality concerns.

- Advanced Materials Research: Invest in the development of innovative materials, such as hybrid binders and enhanced absorbent pavements, to improve both noise reduction and durability (*2*).

- Enhanced Modeling and Inventory: Update noise analysis tools like the FHWA TNM to incorporate quieter pavement types and their acoustic degradation rates (*2*).

- Pilot Projects and Field Validation: Conduct large-scale pilot projects to evaluate the real-world performance of quieter pavements under diverse environmental and traffic conditions. These projects can provide data on durability, acoustic longevity, and cost-effectiveness.

- Heavy Vehicle Focus: Prioritize research on reducing heavy vehicle noise through optimized tire-pavement interaction, including pavement designs and low-noise tire technologies for trucks (*2*).

- Global Best Practices Leverage insights from successful implementations in Europe, such as double-layer porous asphalt pavements, while adapting them to U.S. environmental and regulatory conditions.

The further develop the OBSI method, key next steps include (*12*):

- Building a comprehensive OBSI adjustment database within TNM, using the Standard Reference Test Tire (SRTT) and ensuring pavements in the database are at least 5 years old to reflect aging effects.

- Determining how pavements should be grouped, how many data points are needed per group, and how users could select or define pavements within the model.

- Gathering and organizing data for the database

Detailed Findings

Background

Traffic noise pollution is a growing concern, especially in urban areas where dense populations reside near major roadways with high volumes of commuters. In general, noise intensity is measured in decibels (dB), with the A-weighted scale (dB(A)) closely approximating human hearing sensitivity. On this scale, faint sounds start at 0 dB(A), normal conversation measures around 50 dB(A), and highway traffic noise averages approximately 75 dB(A). Discomfort typically begins at noise levels between 70 and 80 dB(A). To mitigate the impact of traffic noise, the FHWA has set 67 dB(A) as the threshold for considering noise reduction efforts (*16*).

Traffic noise is composed of three main sources (*2*):

- Propulsion Noise: Generated by the engine, exhaust, intake, and powertrain components. Dominates at very low speeds.

- Tire-Pavement Noise: Produced as the tire interacts with the pavement, becoming the primary noise source at typical highway speeds (above 30 mph).

- Aerodynamic Noise: Created by air turbulence as vehicles move through the air, significant at very high speeds (e.g., above 60 mph)

At highway speeds, tire-pavement noise contributes up to 78% of the overall noise for light vehicles (*9*). Overall traffic noise is affected by the following:

- Traffic Volume: A doubling of traffic volume increases noise by approximately 3 dB.

- Vehicle Speed: Increasing speed by 10 mph results in a 2 to 3 dB increase in sound level.

- Vehicle Type: Heavy trucks generate noise levels about 10 dB louder than passenger cars due to their larger tires and powertrain systems. One truck generates the same noise as about ten cars.

- Vehicle Operating Characteristics: Braking, acceleration, climbing, and cornering can increase noise levels to varying degrees.

Therefore, by reducing noise on each vehicle at the principle noise source, quieter pavements offer highway engineers a new tool to lower highway infrastructure noise levels.

Several Candidates methods for measuring tire-pavement noise were reviewed and examined and the near field sound intensity (SI) method was chosen due to directivity, its ability to reject extraneous noise, minimize reflections from the vehicle body, offering advantages over traditional sound pressure (SP) measurements (*2*). In 2010 The OBSI adjustment method for incorporating pavement effects is appealing due to its simplicity and cost-effectiveness (*12*). Key advantages include: ease of collecting tire/pavement noise data, availability of large datasets for various pavements, proper accounting for sound propagation effects, and straightforward integration into the FHWA TNM (*12*).

Transportation Pooled Fund 5-135 (*17*) worked on reducing hardware costs of OBSI system, producing equipment guidelines, data collection forms, and spreadsheets for practitioners. Collaborating with Illingworth & Rodkin, validated its system through testing at the Honda Proving Center and NCAT test tracks. They collected tire/pavement noise data across multiple states, prioritizing pavements aged 5+ years.

Figure 1 Dual probe vertical OBSI setup (*2*)

Review of State DOT Practices

- Arizona Department of Transportation (ADOT)

ADOT initiated the Quiet Pavement Pilot Program (QPPP) in April 2003, in collaboration with the FHWA and USDOT Volpe, to explore the potential of asphalt rubber friction courses (ARFC) in mitigating traffic noise. The program involved overlaying existing Portland Cement Concrete Pavements (PCCP) on urban freeways in the Phoenix area with ARFC. Initial findings indicated a noise reduction ranging from 5.5 to 9 decibels, depending on measurement methods and specific locations (*18*). Over a four-year period, subsequent measurements assessed the durability of these noise reductions. Results showed an average increase of about 2 decibels in noise levels, suggesting that while ARFC overlays effectively reduce noise initially, their acoustic benefits diminish over time (*19*).

Some experts suggested that a more effective and sustainable approach would have been to modify pavement surface texturing methods. Longitudinal tinning of PCCP, as implemented in California since the 1970s, has demonstrated significant and lasting noise reduction benefits of 8-10 dBA. Improved collaboration between engineers and acousticians in pavement design could lead to more effective noise mitigation strategies that are both durable and cost-efficient.

- Virginia Department of Transportation (VDOT)

VDOT in partnership with the Virginia Transportation Research Council (VTRC), has been actively exploring quieter pavement technologies to mitigate traffic noise. In 2011, VDOT initiated the Virginia Quiet Pavement Implementation Program, conducting five demonstration projects on four-lane, divided, high-speed roads with stable underlying structures (*20*). To evaluate the noise-reduction benefits of these alternative materials and processes, the Virginia Tech Transportation Institute (VTTI) conducted OBSI measurements. Research indicates that certain asphalt mixes, such as Stone Matrix Asphalt (SMA) or

OGFC, can reduce highway noise by 3 to 5 dB(A). This reduction is comparable to doubling the distance between the noise source and the receiver (*20*).

- Washington State Department of Transportation (WSDOT)

WSDOT has explored the use of quieter pavement technologies, such as OGFCs and ARFCs, to mitigate traffic noise. However, studies have indicated that the noise reduction benefits of these pavements in Washington's climate are short-lived. For instance, an experimental ARFC section experienced a near-total loss of noise reduction within just over two years (*21*). Additionally, research has shown a rapid deterioration of sound level benefits for quieter pavements in the state, based on OBSI measurements. These findings suggest that while quieter pavements may offer initial noise reduction, their effectiveness diminishes quickly under Washington's environmental conditions (*21*). Consequently, WSDOT primarily relies on noise barriers, such as free-standing concrete walls ranging from 6 to 20 feet in height, to address traffic noise concerns (*22*).

- New Jersey Department of Transportation (NJDOT)

New Jersey has actively explored and implemented quieter pavement technologies to mitigate traffic noise. The New Jersey Asphalt Pavement Association (NJAPA) highlights that asphalt pavements, particularly those utilizing open-graded surfaces, fine-graded surfaces, and two-layer open-graded pavements, can reduce highway noise by 3 to 10 decibels (*23*). In 2007, NJDOT resurfaced a section of Route 95 in Mercer County using eco-friendly asphalt rubber. This material not only incorporated recycled tires but also functioned as a quieter pavement, reducing traffic noise for nearby residents. Further research conducted by the Center for Advanced Infrastructure and Transportation (CAIT) at Rutgers University has focused on measuring pavement noise levels across New Jersey. Utilizing the Close-Proximity (CPX) method. Microphones placed near the tire-pavement interface measure noise levels while isolating external noises. The database created showed that PCCP generated the highest noise, while OGFC surfaces produced the lowest noise (*24*).

- California Department of Transportation (Caltrans)

Caltrans has been actively researching and implementing quieter pavement technologies to mitigate traffic noise. A key initiative is the Quieter Pavement Research Plan, which aims to identify surface treatments, materials, design specifications, and construction methods that result in quieter, safe, durable, and cost-effective roadways (*25*). Caltrans has developed a pavement acoustic measurement process based on OBSI method which has become the AASHTO Standard Method of Test T 360-16 (*25*). In the early 2000s, Caltrans conducted research on concrete pavements and bridge decks to assess tire/pavement noise (*5*). Caltrans worked with UCDPRC and evaluated OGFC mixes for their potential to reduce tire/pavement noise. Using Heavy Vehicle Simulator (HVS) tests and lab evaluations, three new OGFC mixes were compared to a control. Results indicate that:

- The #4P mixes showed lower noise levels and superior durability but varied rutting and moisture damage performance based on binder type.
- The Georgia 1/2-inch mix demonstrated better skid resistance and rutting performance but had production challenges and higher costs.

While the new mixes showed promising noise-reduction capabilities, the reduction of 0.8–1.6 dBA was minimal and barely perceptible to humans. The study recommended adjustments to aggregate gradations for broader production feasibility, pilot testing with rubberized binders, and revisions to minimum temperature specifications for OGFC paving to ensure better constructability and performance (*26*). Through these efforts, Caltrans continues to advance quieter pavement technologies, aiming to enhance the quality of life for residents near highways by reducing traffic noise.

Consultation With Experts

California Department of Transportation (Caltrans)

Contacts: Bruce Rymer, MEngr. PE TE, Senior Engineer, Noise Vibration and Hydroacoustic, Caltrans HQ - Division of Environmental Analysis, Office of Hazardous Waste, Air, Noise, and Paleontology, (916) 956-3272, bruce.rymer@dot.ca.gov

Related Research and Resources

- **NCHRP 635 Acoustic Beamforming: Mapping Sources of Truck Noise** (*27*)

https://nap.nationalacademies.org/catalog/14311/acoustic-beamforming-mapping-sources-of-truck-noise

This report investigates the use of acoustic beamforming technology to identify and analyze noise sources from heavy trucks. By using microphone arrays, the study maps noise emissions from different truck components, such as tires, engines, and exhaust systems, at various speeds. The findings highlight that tire-pavement interaction is the dominant noise source at highway speeds, while engine and exhaust noise are more significant at lower speeds. The research provides valuable insights for noise mitigation strategies, including quieter pavement designs and improved truck components.

- **NCHRP 842 Mapping Heavy Vehicle Noise Source Heights for Highway Noise Analysis** (*28*)

https://nap.nationalacademies.org/catalog/24704/mapping-heavy-vehicle-noise-source-heights-for-highway-noise-analysis

This report examines the vertical distribution of noise emissions from heavy trucks to enhance highway noise prediction models. Utilizing acoustic beamforming techniques, the study measured noise sources during truck pass-by across various sites. The findings show that tire-pavement interaction is the dominant noise source, while engine and powertrain noise are secondary contributors. Elevated sources, such as exhaust stacks, were rarely significant.

- **NCHRP 1107 Effective Low Noise Rumble Strips** (*29*)

https://nap.nationalacademies.org/catalog/27861/effective-low-noise-rumble-strips

This report explores the development of rumble strip designs that effectively alert drivers to lane departures through in-vehicle noise and vibration, while minimizing external noise pollution. The report presents updated designs aimed at enhancing driver safety without adversely affecting surrounding communities.

- **NCHRP REPORT 630 - Measuring Tire-Pavement Noise at the Source** (*30*)

https://nap.nationalacademies.org/catalog/14212/measuring-tire-pavement-noise-at-the-source

This report provides a standardized method for evaluating tire-pavement noise directly at the source using OBSI techniques. The report outlines procedures for accurately measuring noise generated by tire-pavement interaction, focusing on test setup, instrumentation, and data analysis. It aims to improve understanding of noise generation mechanisms and support the development of quieter pavement surfaces. This methodology serves as a tool for researchers and transportation agencies to assess pavement noise performance and guide noise mitigation strategies effectively.

- **NCHRP REPORT 738 – Evaluation Pavement Strategies and Barriers for Noise Mitigation** (*31*)

https://nap.nationalacademies.org/catalog/22541/evaluating-pavement-strategies-and-barriers-for-noise-mitigation

This report assesses the effectiveness and cost-efficiency of quieter pavement surfaces (e.g., rubberized asphalt) and noise barriers in reducing highway traffic noise. The report highlights how tire-pavement interaction and barrier designs impact noise levels, using performance metrics like OBSI. It concludes that combining quieter pavements with well-designed barriers offers optimal noise reduction, though quieter pavements may require more frequent maintenance. The findings provide transportation agencies with practical frameworks for selecting and implementing noise mitigation strategies effectively.

- **Quieter Pavement Acoustic Measurement and Performance** (*2*)

https://dot.ca.gov/-/media/dot-media/programs/environmental-analysis/documents/env/quieter-pavement-a11y.pdf

This report from Caltrans summarizes efforts to quantify and compare pavement acoustics, providing an index of relative noise levels across different pavement surfaces. It serves as a valuable reference for understanding the acoustic performance of various pavement types.

- **Quiet Pavements: Lessons Learned from Europe** (*32*)

https://www.fhwa.dot.gov/publications/focus/05apr/04.cfm

This document summarizes key findings from European experiences with quiet pavements, highlighting effective techniques and potential challenges. It provides valuable lessons for implementing similar strategies in the U.S.

- **The little book of quieter pavement** (*33*)

https://rosap.ntl.bts.gov/view/dot/41905

This guide, published by FHWA, introduces the fundamentals of sound and noise, explores the relationship between pavement types and noise generation, and discusses design and maintenance practices to achieve quieter pavements.

References

1. Ling, S., F. Yu, D. Sun, G. Sun, and L. Xu. A Comprehensive Review of Tire-Pavement Noise: Generation Mechanism, Measurement Methods, and Quiet Asphalt Pavement. *Journal of Cleaner Production*, Vol. 287, 2021, p. 125056.
2. Lodico, D., and P. Donavan. *Quieter Pavement Acoustic Measurement and Performance*. California Department of Transportation (Caltrans), 2018.
3. Riley, J. DOT Jurisdiction Sound Barrier Aesthetics. *Aesthetics and performance in highway sound walls*. https://www.ailsoundwalls.com/dot-jurisdiction-sound-barrier-solutions/. Accessed Jan. 22, 2025.
4. Beyer, B., and M. Espenshade. *California Department of Transportation, District 7, Project Audit*. 2024.
5. Bernhard, R., R. L. Wayson, J. Haddock, N. Neithalath, A. El-Aassar, J. Olek, T. Pellinen, and W. J. Weiss. *An Introduction to Tire/Pavement Noise of Asphalt Pavement*. Institute of Safe, Quiet and Durable Highways, Purdue University, 2005.
6. Tsai, B.-W., J. T. Harvey, and C. L. Monismith. *Evaluation of Open-Graded Friction Course (OGFC) Mix Design: Summary Version*. University of California Pavement Research Center (UCPRC), California Department of Transportation (Caltans), 2012.
7. IGGA. The next Generation Concrete Surfaces (NGCS). International Grooving & Grinding Association (IGGA), Oct, 2023.
8. Frequently Asked Questions About Noise Barriers | Ohio Department of Transportation. https://www.transportation.ohio.gov/programs/noise/resources/faqs-new?utm_source. Accessed Feb. 14, 2025.
9. Donavan, P. R., and R. Schumacher. Exterior Noise of Vehicles—Traffic Noise Prediction and Control. In *Handbook of Noise and Vibration Control* (M. J. Crocker, ed.), Wiley, pp. 1427–1437.
10. AASHTO T 360-16 (2020). https://store.accuristech.com/standards/aashto-t-360-16-2020?product_id=1916380&srsltid=AfmBOoqACJWPHP9O6H9N1LHAWbmSLMhfGBGwTw3tfv0-g6Dhwp1LuDAp. Accessed Mar. 3, 2025.
11. AASHTO. *Standard Method of Test for Measurement of Tire/Pavement Noise Using the On-Board Sound Intensity (OBSI) Method*. American Association of State Highway and Transportation Officials (AASHTO), 2016.
12. FHWA. Investigating Use of Pavement-Specific Tire/Pavement Source Levels Adjustments. *Pavement Effects Implementation Study*. https://www.fhwa.dot.gov/Environment/noise/resources/pavement_effects_implementation_study/pei03.cfm. Accessed Jan. 26, 2025.
13. Gonzales-Rocha, J., R. R. Thiruvenkatachari, Y. Ding, and A. Venkatram. *Quantify the Effect of Roadside Barrier on Near Road Air Pollutant Dispersion and Concentration*. UC Riverside, Caltrans, 2023.
14. SWCPA. Caltrans Leads Field Review of NGCS Pilot Projects. *Southwest Concrete Pavement Association (SWCPA)*. https://swcpa.org/caltrans-leads-field-review-of-ngcs-pilot-projects/. Accessed Feb. 27, 2025.
15. FHWA. Procedures for Abatement of Highway Traffic Noise and Construction Noise. *Federal Register*. https://www.federalregister.gov/documents/2024/10/18/2024-23751/procedures-for-abatement-of-highway-traffic-noise-and-construction-noise. Accessed Feb. 27, 2025.
16. NJAPA. Why Asphalt? Quiet Pavement. *New Jersey Asphalt Pavement Association*. https://www.njapa.com/why-asphalt/quiet-pavement/. Accessed Jan. 22, 2025.
17. Tire/Pavement Noise Research Consortium; Transportation Pooled Fund TPF-5(135). 2019.

18. Donavan, P., and C. Janello. *Arizona Quiet Pavement Pilot Program: Comprehensive Report*. Arizona Department of Transportation (ADOT), Federal Highway Administration (FHWA), 2018.
19. Donovan, P., J. Reyff, and A. Pommerenck. *Quiet Pavement Pilot Program: Progress Report 3*. Arizona Department of Transportation (ADOT) Research Center, 2012.
20. VTTI. Virginia Quiet Pavement Implementation Program. *Virginia Tech Transportation Institute (VTTI)*. https://www.vtti.vt.edu/research/csri/quiet-pavement.html. Accessed Jan. 27, 2025.
21. Anderson, K., J. S. Uhlmeyer, T. Sexton, M. Russell, and J. Weston. *Evaluation of Long-Term Pavement Performance and Noise Characteristics of Open-Graded Friction Courses Project 3–Final Report*. Publication WA-RD 749.2. Washington state Department of Transportation (WSDOT).
22. WSDOT. Noise Walls & Barriers. *Washington state Department f Transportation (WSDOT)*. https://wsdot.wa.gov/construction-planning/protecting-environment/noise-walls-barriers. Accessed Jan. 27, 2025.
23. NJDOT. NJDOT Resurfaces Route 95 in Mercer County with Eco-Friendly, Quiet Pavement. *New Jersey Department of Transportation (NJDOT)*. https://nj-dot.nj.gov/transportation/about/press/2007/100307.shtm?utm_source. Accessed Jan. 27, 2025.
24. Bennert, T., D. Hanson, and A. Maher. *Demonstration Project–The Measurement of Pavement Noise on New Jersey Pavements Using the NCAT Noise Trailer*. Publication FHWA-NJ-2003-021. New Jersey Department of Transportation (NJDOT), Federal Highway Administratoin (FHWA), 2004.
25. Caltrans. Quieter Pavements. *California Department of Transportation (Caltrans)*. https://dot.ca.gov/programs/maintenance/pavement/concrete-pavement-and-pavement-foundations/quieter-pavement?utm_source. Accessed Jan. 27, 2025.
26. Wu, R., I. Guada, E. Coleri, A. Rezaei, M. Kayhanian, and J. T. Harvey. Implementation of New Quieter Pavement Research: Accelerated Pavement Testing and Laboratory Evaluation of Different Open-Graded Hot-Mix Asphalt Materials. 2013.
27. Donavan, P. R., Y. A. Gurovich, K. J. Plotkin, D. H. Robinson, and W. K. Blake. *Acoustic Beamforming: Mapping Sources of Truck Noise*. National Academies Press, Washington, D.C., 2009.
28. Janello, P. R. D. A. C. J. *Mapping Heavy Vehicle Noise Source Heights for Highway Noise Analysis*. Transportation Research Board, Washington, D.C., 2017.
29. Donavan, P. R., C. J. Janello, J. Rochat, and S. McKenna. *Effective Low-Noise Rumble Strips*. National Academies Press, Washington, D.C., 2024.
30. Donavan, P. R., and D. M. Lodico. *Measuring Tire-Pavement Noise at the Source*. National Academies Press, Washington, D.C., 2009.
31. Donavan, P. R., L. M. Pierce, D. M. Lodico, J. L. Rochat, and H. S. Knauer. *Evaluating Pavement Strategies and Barriers for Noise Mitigation*. Transportation Research Board, Washington, D.C., 2013.
32. FHWA. Quiet Pavements: Lessons Learned from Europe. https://www.fhwa.dot.gov/publications/focus/05apr/04.cfm. Accessed Feb. 14, 2025.
33. Rasmussen, R. O., R. J. Bernhard, U. Sandberg, E. Mun, and United States. Federal Highway Administration. Office of Pavement Technology. *The Little Book of Quieter Pavements*. Publication FHWA-IF-08-004. 2007.