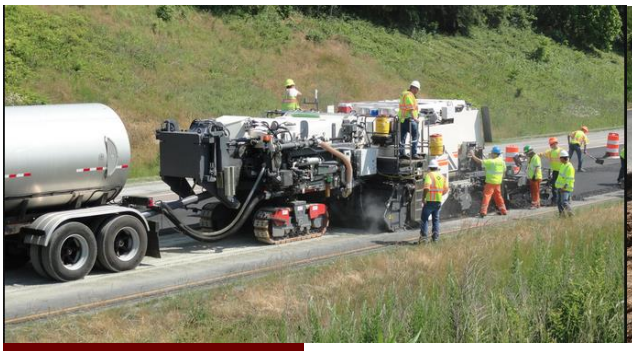

VIRGINIA TECH

NATIONAL SUSTAINABLE PAVEMENT CONSORTIUM

Transportation Pooled fund TPF-5(268)

FINAL REPORT

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TRANSPORTATION INSTITUTE
VIRGINIA TECH

Center for Sustainable
Transportation Infrastructure

VTRC
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Contents

Background

The construction and maintenance of a reliable and sustainable transportation infrastructure (that is economically viable, minimizes the impact on the environment, and operates fairly) is a priority for all transportation agencies. One of the most important areas of the transportation infrastructure where sustainability must be achieved is highway construction, maintenance, and operation because of its importance and the level of investment. Therefore, a broadly stated sustainability framework for research, which includes a full understanding of sustainable pavement assets, has the possibility of delivering real benefits.

The Federal Highway Administration (FHWA) has defined that sustainable transportation means providing exceptional mobility and access in a manner that meets development needs without compromising the quality of life of future generations. A sustainable transportation system is safe, healthy, affordable and renewable, operates fairly, and limits emissions and the use of new and nonrenewable resources. Although there is no widely accepted definition of a "sustainable pavement," it could be inferred that sustainable pavement systems have optimized surface properties, are long lasting and efficiently preserved, minimize life cycle costs, maximize reuse and recycle, are operated fairly and efficiently using sound asset management principles, are constructed, maintained and operated using materials processes and policies that minimize the environmental impact (life-cycle assessment), are multifunctional (e.g., can be used for supporting other secondary functions, such as generating energy or controlling water runoff), and can be adapted to accommodate evolving environmental (e.g., climate change) and traffic demands. Adoption of more sustainable practices allow agencies to save money, reduce their impact on the environment, and provide safer, and provide more efficient mobility and access.

The appreciation of the importance of highway sustainability, and of the enormity of the challenges that it brings, continues to develop rapidly. An international workshop held in January 2010 sponsored by the FHWA and National Science Foundation (NSF) brought together the leading researchers in this field to establish a roadmap for research. The workshop concluded that "***for pavements, business as usual is NOT sustainable****; however, focused near-term research can/will provide practical, scientifically-based tools/solutions to effectively guide decision makers and strategic research in identified areas will provide the scientific answers necessary to support the green economy of the future*." The agenda presented a series of short, medium, and long term strategies for increasing the sustainability of our pavement materials, systems, and programs. This *Sustainable Pavements Consortium* developed some of the research proposed in the roadmap, with focus on products that will have direct application for the participating agencies and complemented and supported the implementation by the consortium members of the activities being pursued by the FHWA Sustainable Pavements Program.

Objective

The objective of the pooled-fund project was to establish a research consortium focused on enhancing pavement sustainability.

Research Efforts and Outcomes

To achieve the objective, the pooled-fund project established a multi-year program in cooperation with the consortium participants, which included research and outreach and educational activities.

Research Activities

The research efforts were organized in various research areas as discussed following.

R1. How to measure the benefits of emerging materials and processes

This research area developed a tool (in cooperation with the University of Coimbra) to assess the economic and environmental impacts of pavement and apply this tool in series of case studies that show the benefits of in situ pavement recycling. The main findings have been presented in the following peer-reviewed publications:

- ✓ Giustozzi, F., Crispino, M., Flintsch, G.W., (2012) "Multi-Attribute Life Cycle Assessment of Preventive Maintenance Treatments on Road Pavements for Achieving Environmental Sustainability," *The International Journal of Life Cycle Assessment*, May 2012, vol. 17(4), pp. 409-419.
  Link: https://doi.org/10.1007/s11367-011-0375-6.
  Preprint: NSPC Paper 2.
- ✓ Santos, J., Bryce, J., Flintsch, G.W., Ferreira, A. and Diefenderfer, B. (2014) "A life cycle assessment of in-place recycling and conventional pavement construction and maintenance practices," *Structure and Infrastructure Engineering: Maintenance, Management, Life-Cycle Design and Performance*, vol.11(9), pp. 1199-1217.
  Link: https://doi.org/10.1080/15732479.2014.945095.
  Preprint: NSPC Paper 7.
- ✓ Santos, J., Bryce, J., Flintsch G.W., Ferreira, A. (2015) "A Comprehensive Life Cycle Costs Analysis of In-Place Recycling and Conventional Pavement Construction and Maintenance Practices," *Proceedings of the 9th International Conference on Managing Pavement Assets*, Alexandria, VA, May 2015.
  Link: https://vtechworks.lib.vt.edu/bitstream/handle/10919/56432/ICMPA9-000255.PDF?sequence=2&isAllowed=y (open access).
- ✓ Santos, J., Flintsch, G. and Ferreira, A. (2017) "Environmental and economic assessment of pavement construction and management practices for enhancing pavement sustainability," *Resources, Conservation & Recycling*, vol. 116, pp. 15-31.
  Link: https://doi.org/10.1016/j.resconrec.2016.08.025.
  Preprint: NSPC Paper 20.
- ✓ Santos, J., Bryce, J., Flintsch, G. and Ferreira, A. (2017) "A Comprehensive Life Cycle Costs Analysis of In-Place Recycling and Conventional Pavement Construction and Maintenance Practices." *International Journal of Pavement Engineering*, vol. 18, pp. 727-743. Link: https://doi.org/10.1080/10298436.2015.1122190.
  Preprint: NSPC Paper 21.

R2. Incorporating use-phase into LCA for pavements

This research area focused on how to apply life-cycle thinking to make better pavement decisions and included the following main efforts and associated peer-reviewed publications:

Development of the Project-level LCA-LCCA tool (in collaboration with University of Coimbra and University of Twente)

- ✓ Santos, J., Ferreira, A., Flintsch, G. (2014) "Development and application of a life-cycle assessment model for pavement management," *Proceedings of the Transport Research Arena*, CD Ed., TRA2014_Fpaper_18702.pdf, 1-10, Paris, France.
  Pre-print: NSPC Paper 4.
- ✓ Santos, J., Ferreira, A., Flintsch, G.W. (2015) "A Life Cycle Assessment Model for Pavement Management: Methodology and Computational Framework. *International Journal of Pavement Engineering*, vol. 16 (3), pp. 268-286.
  Link: http://doi.org/10.1080/10298436.2014.942861.
  Pre-print: NSPC Paper 6.
- ✓ Santos, J.M., Thyagarajan, S., Keijzer, E., Flores, R.F., Flintsch G.W. (2017) "Comparison of Life-Cycle Assessment Tools for Road Pavement Infrastructure," *Transportation Research Record: Journal of the Transportation Research Board*, vol. 2646, pp. 28-38.
  Link: https://doi.org/10.3141/2646-04.
  Pre-print: NSPC Paper 17.

Probabilistic Network-level LCA

- ✓ Flintsch, G., Bryce, J. (2014) "Chapter 13 - Sustainable Pavement Management," in *Climate Change, Energy, Sustainability and Pavements*, eds. Gopalakrishnan, K., Steyn, W.J., and Harvey, J., pp. 373-392. Springer: Berlin Heidelberg.
  Pre-print: NSPC Paper 1.
- ✓ Bryce, J., Santos, J., Flintsch, G.W., Katicha, S. McGhee, K.K., Ferreira, A. (2014) "Analysis of Rolling Resistance Models to Analyze Vehicle Fuel Consumption as a Function of Pavement Properties." *Proceedings of the 12th International Conference on Asphalt Pavements*, Kim, R. (ed.), June 2014, pp. 263-273. Taylor and Francis Group: London.
  Pre-print: NSPC Paper 3.
- ✓ Bryce, J., Katicha, S., Flintsch, G.W., Sivaneswaran, N., Santos, J. (2014) "Probabilistic Lifecycle Assessment as a Network-Level Evaluation Tool for the Use and Maintenance Phases of Pavements." *Transportation Research Record: Journal of the Transportation Research Board*, vol. 2455 (1), pp. 44-53.
  Link: https://doi.org/10.3141%2F2455-06.
  Pre-print: NSPC Paper 5.

Multi-criteria Analysis

- ✓ Dehghani, M., Giustozzi, F., Flintsch, G.W., Crispino, M. (2013) "Cross-asset Resource Allocation Framework for Achieving Performance Sustainability," *Transportation Research Record: Journal of the Transportation Research Board*, vol. 2361, pp 16-24,
  Link: https://doi.org/10.3141%2F2361-03.
  Pre-print: NSPC Paper 8.

- ✓ Bryce, J., Flintsch, G.W., Hall, R.P. (2014) "A Multi Criteria Decision Analysis Technique for Including Environmental Impacts in Sustainable Infrastructure Management Business Practices." *Transportation Research Part D: Transport & Environment*, No. 32, pp. 435-445.
  Link: https://doi.org/10.1016/j.trd.2014.08.019.
  Pre-print: NSPC Paper 9.
- ✓ Santos J., Ferreira, A., Flintsch, G., Cerezo, V. (2016) "A multi-objective optimization approach for sustainable pavement management." *Fifth International Symposium on Life-Cycle Civil Engineering*, Oct 16-19 2016, Delft, The Netherlands.
  Pre-print: NSPC Paper 12.
- ✓ Santos, J., Ferreira, A., Flintsch, G.W., Cerezo, V. (2017) "Consideration of Life Cycle Greenhouse Gas Emissions in Optimal Pavement Maintenance Programming: a Comparison between Single-Objective and Multi-Objective Optimization Approaches," *Proceedings of the World Conference on Pavement and Asset Management*, Baveno, Italy, June 12-16, 2017.
  Pre-print: NSPC Paper 18.
- ✓ Santos, J.M., Ferreira, A., Flintsch, G.W. (2017) "A multi-objective optimization-based pavement management decision-support system for enhancing pavement sustainability," *Journal of Cleaner Production*, vol. 164, pp 1380-1393.
  Link: https://doi.org/10.1016/j.jclepro.2017.07.027.
  Pre-print: NSPC Paper 19,
- ✓ Santos, J., Ferreira, A., Flintsch, G.W., Cerezo, V., (2018) "A Multi-Objective Optimisation Approach for Sustainable Pavement Management," *Structure and Infrastructure Engineering: Maintenance, Management, Life-Cycle Design and Performance*, vol. 14(7).
  Link: https://doi.org/10.1080/15732479.2018.1436571.
  Pre-print: NSPC Paper 22.

Incorporating Stakeholder's input

- ✓ Bryce, J., Parry, T., Lo Presti, D. Flintsch, G.W. (2016) "Approaches to Weighting within Transportation Infrastructure," Paper No. 16-3987, *Proceedings of the 95th Annual Meeting of the Transportation Research Board*, Jan 10-14, 2016, Washington, DC.
  Pre-print: NSPC Paper 11.

R3. Impact of Climate change on Pavement Engineering

This research area investigated the potential impact of climate change on pavement design and management practices.

- ✓ Qiao, Y., Flintsch, G.W., Dawson, A., Parry, T. (2013) "Examining the Effects of Climate Change on Pavement Deterioration and Service Life," *Journal of the Transportation Research Board*, vol. 2349, pp. 100-107.
  Link: https://doi.org/10.3141%2F2349-12.
  Pre-print: NSPC Paper 10.
- ✓ Qiao, Y., Dawson, A., Parry, T., Flintsch, G.W. (2015) "Evaluating the Effects of Climate Change on Road Maintenance Intervention Strategies and Life-Cycle Costs," *Transportation Research Part D: Transport and Environment*, 2015, vol. 41, pp 492–503.
  Link: https://doi.org/10.1016/j.trd.2015.09.019.
  Pre-print: NSPC Paper 13.
- ✓ Qiao, Y., Dawson, A.R., Parry, T., Flintsch, G.W., (2016) "Immediate effects of some corrective maintenance interventions on flexible pavements," *International Journal of*

Pavement Engineering, vol. 19(6), pp 502-508.
Link: https://doi.org/10.1080/10298436.2016.1176164.
Pre-print: NSPC Paper 15.

- ✓ Qiao, Y., Dawson, A., Parry, T., Flintsch, G.W., (2019) "Life Cycle Cost of Flexible Pavements and Climate Variability: Case Studies from Virginia." *Structure and Infrastructure Engineering, Maintenance, Management, Life-Cycle Design and Performance*, vol. 15(12), pp 1665-1679.
  Link: https://doi.org/10.1080/15732479.2019.1642364.
  Pre-print: NSPC Paper 23.
- ✓ Qiao, Y., Santos, J., Stoner, A., Flintsch, G.W. (2019) "Climate Change Impacts on Asphalt Road Pavement Construction and Maintenance: An Economic Life Cycle Assessment of Adaptation Measures in the State of Virginia, U.S.," *Journal of Industrial Ecology.*
  Link: https://doi.org/10.1111/jiec.12936 (open access).
- ✓ Qiao, Y., Dawson, A., Parry, T., Flintsch, G.W., Wang, W. (2020) "Flexible Pavements and Climate Change: A Comprehensive Review and Implications," *MDPI Sustainability*, vol. 12(3), pp. 1057.
  Link: https://doi.org/10.3390/su12031057 (open access).

R4. Synthesize long-term performance data from states with active in-place recycling programs

- ✓ Amarh, E., Fernandez-Gomez, W., Flintsch G.W., Diefenderfer, B., Bowers, B. (2017) "Non-Destructive In Situ Characterization of Elastic Moduli of Full-Depth Reclamation Base Mixtures," *Transportation Research Record: Journal of the Transportation Research Board*, vol. 2641 pp 1-11.
  Link: https://doi.org/10.3141%2F2641-01.
  Pre-print: NSPC Paper 16.
- ✓ Amarh, E., Flintsch G.W., Diefenderfer, B., Bowers, B., Santos, J. (2020) *Synthesis of Long - Term Performance Data from States with Active In-Place Recycling Programs*
  Link: Synthesis Report.

Outreach and Educational Activities

In addition to the collaborative research efforts discussed in the previous section, the Consortium participated in several outreach, educational, technology transfer, and international exchange activities.

O1. Outreach on Pavement Recycling

- ✓ Supported the organization of the ***Virginia Pavement Recycling Conference,*** Richmond, VA, November 26 – 27, 2012.
  Link: https://www.vtti.vt.edu/impact/vprc-2012.html
- ✓ Developed, in cooperation with ARRA, a Workshop on pavement recycling and delivered it in Madison, WI (2015) and Harrisburg, PA (2018).

O2. Outreach on Pavement LCA

- ✓ Supported the organization (organizing committee) and presented at the *International Symposium on Pavement LCA 2014* in Davis, California, October 14-16, 2014.
  Link: http://www.ucprc.ucdavis.edu/p-lca2014/.
- ✓ Supported the organization (scientific committee) and presented at the *Symposium Pavement Life-Cycle Symposium 2017*, Champaign, IL, April 12-13, 2017.
  Link: https://lcasymposium.ict.illinois.edu/post-conference-page/.
- ✓ Supported the organization (co-chair) and presented at the *International Symposium on Pavement, Roadway, and Bridge Life Cycle Assessment 2020*, Sacramento, CA, June 3-6, 2020.
  Link: http://www.ucprc.ucdavis.edu/LCA2020/.
- ✓ Participated in the instruction of a Summer School 2015, Sustainability Assessment of Transportation Infrastructure for the SUP&R ITN, Palermo, Italy, September 16-13, 2015.
  Link: http://www.superitn.eu/wp/?news=supr-itn-palermo-summer-school-2015.

O3. Academic Courses

- ✓ Supported the development of a new graduate class at Virginia Tech: *CEE 5784 - Sustainable Transportation Infrastructure*.

O4. Software Development

- ✓ The consortium developed two versions of a ***Pavement LCA software***. The initial version that was used in the initial phases of the project was programed in an Excel spreadsheet and it was not appropriate for general distribution. To enhance the usability of the tool, the research team re-programed the tool as an open source package that is being beta-tested and is available through the VTTI website.
  Link: https://www.vtti.vt.edu/research/csti/index.php.

O5. International Collaborations

- ✓ Participated in a FHWA Twining with the European project ***LCE4Roads*****.** Participated in several coordination meetings and help organize joint technical sessions at the *95th Annual Meeting of the Transportation Research Board*, January 10-14, 2016, in Washington, DC and at the *European Road Infrastructure Congress*, Leeds, U.K., October 18-20, 2016
  Link: http://www.lce4roads.eu/.
- ✓ Collaborated with NTEC-led ***SUP&R*** International Training Network (ITN) Sustainable Pavement & Railway International Training Network as an associate member.
  Link: http://www.superitn.eu/.
- ✓ Supported the exchange of students, including four students that conducted part of their dissertation research time at Virginia Tech, Joao Santos (University of Coimbra), Gilberto Martinez (Politecnico di Milano), Yaning Qiao (University of Nottingham), and Esther Lizasoain (Universidad de Cantabria), and one Virginia Tech student, James Bryce, who conducted part of his dissertation research at the University of Nottingham.

O6. Other Presentations

- ✓ Members of the consortium presented the findings of the research at many national and international technical meetings.

Benefits

The establishment of a collaborative research program provided an accessible and efficient way for the partnering highway agencies to evaluate tools and products, conduct research, and coordinate testing, training, and deployment activities to enhance the sustainability of pavement assets. Examples of specific benefits included the access to extensive sources of data, information, and knowledge about sustainable pavement materials, practices, and systems and the opportunity to share experiences from colleagues from around the world.