Evaluation of Partial Depth Pavement Repairs on Routes Heavily Traveled by Amish Horse and Buggies-Phase 2

Prepared by:
Munir D. Nazzal
Sang Soo Kim
Ala Abbas
Mandi Lopez

Hamzeh Saqer
Mohammad Al-Khasweneh

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This report summarizes the results of a research project that was conducted to identify and evaluate the cost-effectiveness of alternative repair mixtures and methods and their combination that can be used to improve the performance and service life of partial depth repairs performed on Amish buggy routes in Ohio, and identify all possible changes that could be made to the Amish horseshoes and buggies to mitigate their damage to pavement structures. This project was divided into two phases. The results of Phase 1 indicated that partial depth repairs performed on routes with heavy Amish buggy traffic were four times more expensive than those of routes without Amish buggy traffic.

Based on the outcome of Phase 1 of this project, Phase 2 involved designing several asphalt mixtures with improved rutting resistance. The field evaluation of the test sections constructed in this study indicated that that the designed mixtures had better performance than those typically used for repairing of Amish buggy routes. In addition, Phase 2 also identified several alternative horseshoes to reduce damage to Amish buggy routes. The results of cost analyses indicated that using the alternative horseshoes with new calk design can result in reducing the annual repair costs of Amish buggy routes by at least 40%. In addition, the results suggested that using alternative horseshoes reduce the annual horse costs encountered by Amish when considering the effects of those shoes on the horse service life.

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Prepared by:

Munir D. Nazzal, Ph.D., P.E.
Department of Civil and Architectural Engineering and Construction Management,
University of Cincinnati,
Cincinnati, OH 45221

Sang Soo Kim
Department of Civil Engineering
Ohio University
Athens, OH 45701

Ala Abbas
Department of Civil Engineering
University of Akron, Akron, OH

Mandi J. Lopez, DVM, MS, PhD
School of Veterinary Medicine
Louisiana State University
Baton Rouge, LA, 70803

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Executive Summary

This report summarizes the results of a research project that was conducted to: 1-document Ohio Department of Transportation (ODOT) current practices for partial depth repairs performed on roadways with and without Amish buggy traffic, 2- identify and evaluate the cost-effectiveness of alternative repair mixtures and methods and their combination that can be used to improve the performance and service life of partial depth repairs performed on Amish buggy routes in Ohio, and 3- identify all possible changes that could be made to the Amish horseshoes and buggies to mitigate their damage to pavement structures. This project was divided into two phases. The results of Phase 1 indicated that the partial repairs for non-Amish routes can have up to 10 years of service life. However, partial depth repairs lasted about two years on routes with heavy Amish buggy traffic. The life cycle cost analyses (LCCA) results showed that partial depth repairs performed on routes with heavy Amish buggy traffic were four times more expensive than those of routes without Amish buggy traffic. Several alternatives were identified in Phase 1 to improve the rutting resistance of asphalt mixtures used in partial depth repairs on Amish buggy routes. Phase 1 results also suggested that in order for the Amish community to consider an alternative horseshoe, it should be economical, has similar traction to the horseshoes currently used, and is not rejected by their horses.

Based on the outcome of Phase 1 of this project, Phase 2 involved designing several asphalt mixtures with improved rutting resistance. The asphalt mixtures that showed the best lab performance were evaluated in the field by constructing several test sections on Amish buggy routes and monitoring their performance. In addition, Phase 2 also identified several alternative horseshoes to reduce damage to roads. These included: A horseshoe with a new calk design consisting, a horseshoe coated with the selected tungsten carbide coating design, and a composite horseshoe. Laboratory tests were performed to quantifying the reduction in local roads damage due to alternative horseshoes. In addition, experiments were conducted at the College of Veterinary Medicine at Louisiana State University to evaluate the effects of the new horseshoe alternatives on horse hoof and legs. Finally, comprehensive cost analyses were conducted to estimate the horse costs as well as the Amish buggy repair costs when the different horse shoes alternatives considered in this study are used.

The results of this field evaluation of the test sections constructed in this study, indicated that airport mixtures designed with polymer modified binders, PG 76-22M and PG 88-22M and with an aggregate structure modified based on Bailey's method had better performance than those constructed with the asphalt mixture typically used for repairing of these routes (i.e. ODOT Type 1 mix). In addition, the lab tests that were conducted to quantify the damage of horseshoes to asphalt mixtures, indicated that the use of alternative horseshoes can significantly reduce the road damage. The experiments performed to evaluate the effect of alternative horseshoes on horse hoof indicated there the alternative horseshoes reduced the stresses on the horse hoof by at least 45%, while not affecting traction. The results of life cycle cost analyses indicated that using the alternative horseshoes with new calk design can result in reducing the annual repair costs of Amish buggy routes by at least 40%. In addition, the results suggested that using alternative horseshoes

reduce the annual horse costs encountered by Amish when considering the effects of those shoes on the horse service life.

1. Project Background

A smooth pavement surface with good skid resistance is necessary for comfortable and safe travel of the public. To preserve these characteristics, the Ohio Department of Transportation (ODOT) performs routine repairs on roadways in Ohio. Roadways in Ohio with heavy buggy traffic see more frequent partial depth repairs as it encounters more damage. This is typically seen in areas with Amish communities that use buggies pulled by horses as their means for travel. For Holmes County, which has the largest Amish community in Ohio, the problem is enlarged as it attracts about four million tourists every year.

To address this problem, ODOT initiated the project entitled "Evaluation of Partial Depth Pavement Repairs on Routes Heavily Traveled by Amish Horse and Buggies-Phase 1" (referred to as Phase 1 hereinafter) to document current practices for partial depth repairs performed on roadways with and without Amish buggy traffic, identify and evaluate the cost-effectiveness of alternative repair mixtures and methods, and identify all possible changes that could be made to the Amish horse and buggies to mitigate their damage to pavement structures. The results of Phase 1 indicated that the partial repairs for non-Amish routes can have up to 10 years of service life. However, partial depth repairs lasted about two years on routes with heavy Amish buggy traffic. The main distress in repairs on Amish buggy routes was rutting in the surface layer(s) caused by the high stress intensity due to the Amish buggy traffic. The life cycle cost analyses (LCCA) results showed that partial depth repairs performed on routes with heavy Amish buggy traffic were four times more expensive than those of routes without Amish buggy traffic.

Several alternatives were identified in Phase 1 to improve the rutting resistance of asphalt mixtures used in partial depth repairs on Amish buggy routes, which included using alternative: mix design procedure, asphalt binder type, aggregate structure, and aggregate type. In addition, it was also proposed to use the vibratory steel roller for compaction of asphalt mixtures used in partial depth repair and monitor density of compacted mix. The LCCA analysis indicated that the identified alternative mixtures/method could reduce the life cycle costs of partial depth repairs on routes with heavy Amish buggy by more than 60%.

Phase 1 results suggested that in order for the Amish community to consider an alternative horseshoe, it should be economical, has similar traction to the horseshoes currently used, and is not rejected by their horses.

Despite the potential benefits of using the identified alternative repair material/methods, there is currently no data on their performance and life cycle costs when used to repair routes with heavy buggy traffic.

Phase 2 evaluated the performance and cost effectiveness of all alternative mixtures/ method that were designed to improve service life of partial depth repairs performed on state routes and local roads with Amish buggy traffic. In addition, it evaluated the effectiveness of using different alternative horseshoes designs to reduce the Amish buggy damage. The main outcome of this project was to develop a long-term and cost-effective solution for construction and maintenance of state routes and local roads with heavy horse and buggy traffic. Thus, this project helped in extending the service life of pavements in Ohio and reducing their costs.

2. Research Context

The goal of this project was to improve the service life of partial depth repairs performed on state routes and local roads with Amish buggy traffic. The specific objectives were:

1- document ODOT current practices for partial depth repairs performed on roadways with and without Amish buggy traffic,
2- identify alternative methods and mixtures and their combination that can be used to improve the performance and service life of partial depth repairs performed on Amish buggy routes in Ohio,
3- evaluate the cost-effectiveness of identified alternative material and repair methods,
4- identify all possible changes that could be made to the horses or buggies to mitigate their damage to pavement structures.
5- develop longer lasting repairs for state routes and local roadways in Ohio particularly those with high buggy traffic

This study was divided into two phases. Phase 1 of this study included conducting the following tasks:

Task 1. Evaluate ODOT Current Practices for partial depth repair
Task 2. Conduct Literature Review
Task 3. Develop a Matrix of Alternatives and Evaluate their Cost Effectiveness
Task 4. Provide an Analysis of Repair Cycles for Routes With or Without Buggy Traffic
Task 5. Provide Recommendations Concerning Changes for Horses or Buggies
Task 6. Prepare and Submit Interim Report

Phase 2 of this of this study included conducting the following tasks:
Task 1. Conduct Laboratory Study
Task 2. Conduct Statistical Analyses to Rank Mixtures
Task 3. Implementing Recommendations into Field Trials
Task 4. Field Evaluation of Field Test Sections
Task 5. Evaluate the Effectiveness for Changes for Horses or Buggies
Task 6. Evaluate the Cost Benefits of New Repair Mixes/Method
Task 7. Conduct Analysis of Repair Cycles for State Routes and LPA Roads with or without Buggy Traffic
Tasks 8. Quantify the Reduction in Local Roads Damage Due to Alternative Horseshoes
Tasks 9. Evaluate the Effects of New Horseshoes Alternative on Horse Hoof
Task 10. Develop Specifications for Partial Depth Repair Mixtures/ Method
Task 11. Provide Recommendations Concerning Changes for Horses or Buggies
Task 12. Prepare and Submit Interim Report

A summary of the comprehensive literature review performed in this study is presented in Interim report in Appendix E. Few studies were conducted during the past decades to evaluate the different techniques and materials that can enhance the performance of repairs performed on roads with Amish buggy traffic. Stoffels et al. (1995) evaluated three methods for repairing Amish buggy routes: continuous paving repair, spot patching repair, and horsetrack chip seal. The results of the study showed that while the continuous paving repair method had the longest performance

life of 2 to 4 years, the chip seal had the shortest performance life of 1 to 2 years. In addition, spot patching repair was the most commonly used method and typically lasted 2 to 3 years. The chip seal method was not recommended due to the excessive loss of aggregate under heavy buggy traffic. The results of life cycle cost analysis conducted as part of that study indicated that the continuous paving repair method was the most cost-effective method when used on roads with heavy buggy traffic. Hare (1990) evaluated four different repair mixtures on roadways with heavy buggy traffic. The results of his study showed that the ID-2 special blend have best performance but it was the most expensive. Recently, Indiana DOT used steel furnace slag in an asphalt mixture overlay to repair two miles of Indiana State Route 5 that has heavy Amish buggy traffic. The roadway was first patched to eliminate rutting caused by the buggy traffic, then milled, and finally resurfaced with an overlay that contained steel furnace slag. The steel furnace slag was used to protect against wear from horseshoes (Heydorn, 2013).

Some studies have also explored using alternative horseshoes materials and design to mitigate the damage in roads with heavy buggy traffic. Stoffels et al. (1995) suggested that plastic shoes with metal interior cores would provide a solid connection for the nails while maintaining the flexibility needed for the horse hoof circulation. In addition, Stoffels et al. (1995) also evaluated the application of a steel plate to the horseshoe, then screwing a plastic sole onto the steel plate. With this alternative, only the plastic sole would have to be replaced after wearing rather than the entire horseshoe. This study also evaluated various synthetic horseshoes. Based on the results of this evaluation, the Slypner Athletic shoes were the most cost effective. This shoe is a composite shoe made up of a thin steel baseplate and a plastic sole that interlocks to the steel plate without the need of screws or glue. The plastic is light weight and provides high traction. Stoffels et al. (1995) concluded that alternative available horseshoes including Slypner Athletic shoes can reduce the pavement damage but won't eliminate it.

3. Research Approach

Phase 1 of this study included documenting current practices for partial depth repairs performed on roadways with and without Amish buggy traffic, identifying and evaluate the cost-effectiveness of alternative repair mixtures and methods, and identifying all possible changes that could be made to the Amish horse and buggies to mitigate their damage to pavement structures. The results of Phase 1 indicated that the service life of partial repairs for non-Amish routes ranges between 5 to 7 years. However, partial depth repairs lasted about two years on routes with heavy Amish buggy traffic. The main distress in repairs on Amish buggy routes was found to be rutting in the surface layer(s), which was caused by the high stress intensity due to the Amish buggy traffic. The life cycle cost analyses (LCCA) results conducted in Phase 1, showed that partial depth repairs performed on routes with heavy Amish buggy traffic were about three times more expensive than those of routes without Amish buggy traffic. Several alternatives were identified in Phase 1 to improve the rutting resistance of asphalt mixtures used in partial depth repairs on Amish buggy routes, which included using alternative mix design procedure, asphalt binder type, aggregate structure, and aggregate type. In addition, it was also proposed to use vibratory steel rollers for compaction of asphalt mixtures used in partial depth repair and monitor the density of compacted mix. Literature review conducted in Phase 1 indicated that using alternative horseshoes was expensive and won't significantly reduce the damage to the pavement since the calks or cleats welded to the horseshoes are the main cause of damage to pavement structures. Based on

information collected in Phase 1, alternative horseshoe designs were identified. The following subsections summarize the research approach that was followed in Phase 2 of this study.

3.1 Design and Evaluation of Mixes for Use on Amish routes

A laboratory testing program was conducted to design different alternative mixes to improve the rutting resistance of mixes used to roads with heavy Amish buggy traffic; these mixes included:

1. Mixtures designed using with polymer modified PG 76-22M binder and steel slag aggregates.
2. Airport mixture designed with polymer modified PG 76-22M and limestone aggregates.
3. Airport mixture designed with polymer modified PG 76-22M and limestone aggregates, but with an aggregate structure modified based on Bailey's method.
4. Airport mixture designed with polymer modified PG 88-22M and limestone aggregates, but with an aggregate structure modified based on Bailey's method.
5. Airport mixture designed with Ground Tire Rubber (GTR) modified binder and limestone aggregates, but with an aggregate structure modified based on Bailey's method.

All the aggregates used in this study were obtained from an ODOT-approved supplier. The control mix was obtained during the repair of Amish buggy route in ODOT Homes County. To design the other mixes, aggregate gradation of a dense graded mixture previously used for a local airport in Ohio was first obtained. A mixture was designed using the Superpave mix design method. Bailey's method was then used to adjust obtained gradation. Bailey's method provides a systematic approach for aggregate gradation selection. This method takes into account aggregate interlock and packing properties for stronger aggregate structure, and thus, high rutting resistance, while maintaining the volumetric properties of the asphalt mixtures for durability (Vavrik et al., 2002).

Three mixes with different binders with the same aggregate structure that was selected based on Bailey's method were evaluated. The binders that were considered were: a polymer modified binder meeting PG 76-22M, a polymer modified binder meeting PG 88-22M, and Ground Tire Rubber (GTR) modified binder meeting PG 70-22M. Using these three mixes allowed to investigate the effects of binder grade and modification using Bailey's method on rutting performance of HMA. A laboratory testing program was conducted to evaluate the rutting of the designed mixtures and compare them to those of the control repair mixture (Type 1 mixture).

3.2 Construction of Test Section On State Route 241

The best performing mixes designed in the laboratory part of this study were selected for further evaluation in the field. The field evaluation involved constructing several test sections in August 2017 as part of a partial depth repair project on State Route (SR) 241. The test sections included the airport mixtures that had an aggregate structure designed based on Bailey's method and polymer modified binder. Three different polymer modified binders were used meeting PG 70-22M, PG 76-22M, and PG 88-22 M. In addition, a mixture typically used in partial-depth repairs in ODOT Holmes county was used as the control mix. The research team monitored the placement and compaction of the test sections. This included measuring the mat temperature and recording the in-situ density at core locations. Field density was measured using a PQI 380 asphalt density

gauge. Photos were collected and videos of the test sections were recorded during and after construction.

3.3   Construction of Test Section On Holmes County 114

Test sections were constructed as part of a resurfacing project on Holmes County Road 114 to evaluate the use of mixtures with GTR modified asphalt binder on local roads with heavy Amish buggy traffic. While a GTR mix designed using the same aggregate structure and type as those used in AP2 76-22 mix was placed in one lane of CR 114, another GTR mix designed using typical aggregate materials and structure used by Holmes County was placed on the other lane. The two sections were constructed 10/05/2018 and 10/08/2018, respectively. Samples of the GTR modified asphalt were obtained at the asphalt plant. In addition, at least eight buckets of each mix were obtained at the asphalt plant. Photos were collected and videos of the test sections were recorded during and after construction.

3.4   Laborary Testing of Field Mixes

Loose asphalt mixture samples were obtained at the plant for each mixture used in the test sections. Specimens of the loose mixtures were compacted in the laboratory to achieve target air voids of 7±0.5%. Laboratory tests were conducted on the core and lab-compacted specimens to evaluate the rutting performance and durability (moisture damage) of all mixtures. To this end, flow Number test was conducted to examine the rutting resistance of field mixes. In addition, AASHTO T283 (Modified Lottman Test) was used to evaluate the moisture susceptibility of those mixes.

3.5   Field Evaluation of Constructed Test Sections

A field and laboratory testing methodology was developed to evaluate the performance of the constructed test sections. The developed field methodology included evaluating the performance of the test sections by the research team during the duration of this project. All field evaluations involved examining the severity and extent of the distresses developed in these sections.

3.6   Alternative Horseshoes Materials and Designs

The research team met with Amish farriers and the Ohio Amish Steering Committee representatives several times to identify the alternative horseshoes that can be used to reduce the damage on roads. The Amish farriers identified by the Amish Steering Committee have indicated that some farriers are using high profile with narrow tips calks. They suggested that the design is used to provide adequate traction that is needed in some chipsealed roads, which become very slippery during the winter. The Amish farriers indicated that they have used low profile calks that are spread on larger area of the shoes, which they believe it tends to reduce the stresses on the horse and roads. Based on that, the use of horseshoes with low profile calks was identified as the first alternative to reduce damage on roads.

As the main function of the calks is to provide adequate traction, the research team worked on identifying different coating methods and materials that can provide the needed traction while not causing damage to the roads. The first coating material and method identified was Carbinite. Carbinite is a metallurgically bonded textured coating that can be applied to a wide variety of industrial applications in order to increase friction, reduce wear, and improve performance. It consists tungsten/carbide alloy and is applied to metals using a process called Electro Spark Deposition (ESD), which yields a true metallurgical bond. Different horseshoes were obtained by

one the Amish farriers identified by the Amish Steering Committee. The shoes were coated with two different grades (grade #1 and #4). The coated shoes were used on the Amish farrier horses. The farriers indicated that while the #4 grade provided adequate traction for the horses, it wears off in less than 60 miles. Therefore, this coating method was not further evaluated.

Another coating method that was explored was developed by Tunco Manufacturing. This method applies the tungsten carbide through furnace heating. Different horseshoes were obtained by the Amish farrier identified by the Amish steering committee. The shoes were coated with two different grades (grade #16 and #36). The coated shoes were used on the Amish farrier horses. Initial evaluation showed that horseshoes with #16 grade had good traction but moderate wearing. In addition, horseshoes with #36 grade had moderate traction but better wearing resistance. Therefore, a coating grade of #24 was used. In addition, the Amish farrier also suggested that leaving the edge lines uncoated to give the horse some flexibility (Figure 1). Two Amish farriers evaluated this design and found it to provide the adequate traction during the summer and fall season. In addition, the coating was good after more than 120 miles of travel. Therefore, this alternative was selected for further evaluation.

Figure 1. The Selected tungsten carbide coating design for horseshoes

A composite horseshoe that has a steel core and a very stiff synthetic plastic shell that can be shaped to fit the hoof by using the anvil to shape the steel and a grinder or nipper/rasp to shape the plastic. The steel inlay in the composite horseshoe protects the coffin bone and surrounding vascular supply as a toe callus on a barefoot horse. The synthetic plastic material is durable and wears equivalent to steel horseshoes. The horseshoes can be nailed or glued on, and can be reset. Those shoes were used by one of the Amish farriers on several horses. The Amish farrier indicated that it provides good traction and have excellent wearing resistance. Based on that, this alternative was selected for further evaluation.

3.7 Quantifying the Reduction in Local Roads Damage Due To Alternative Horseshoes

The research team quantified the reduction in horseshoes damage to local roads due to using the alternative shoes. To achieve that, experiments were conducted on different horseshoes alternatives shown in Figure 2, which included:

1. Three horseshoes with high profile Drilltec (tungsten carbide) calk design that the Amish community commonly used.

2. A horseshoe with a new calk design consisting of low profile Drilltec (tungsten carbide) calks that was identified by the designated Amish farriers as an alternative to reduce damage on roads.
3. A horseshoe coated with the selected tungsten carbide coating design.
4. Composite horseshoe

Figure 2. Horseshoes identified in this study

The conducted experiments involved attaching a horseshoe to a 150mm diameter Marshall hammer that was modified for this purpose. A compacted sample of an asphalt mix typically used on state routes and local roads were obtained. At least 50 blows of the hammer with attached horseshoes were applied to compacted asphalt mixture sample to evaluate the damage of the different horseshoes. This was used to quantify the reduction of damage to asphalt mixes with the alternative horseshoes.

3.8 Evaluate the Effects of New Horseshoes Alternative on Horse Hoof
A study was conducted at the in the College of Veterinary Medicine at the Louisiana State University to evaluate the effects of the new horseshoe alternatives on horse hoof and legs. Four different shoes were evaluated
1. A horseshoe with high profile Drilltec (tungsten carbide) calks design that the Amish community commonly used.
2. A horseshoe with a new calk design consisting of low profile Drilltec (tungsten carbide) calks that was identified by the designated Amish farriers as an alternative to reduce damage on roads.
3. A horseshoe coated with the selected tungsten carbide coating design.
4. Composite horseshoe

The study had a six-way cross-over, prospective study design. The order of shoe application was determined by a randomized block design. Hoof preparation and shoe fitting and application were

all performed. A licensed farrier performed all hoof preparation and shoe application. Prior to the application of the first set of shoes, gait data was collected with no shoes three days after hoof preparation. Horses were maintained in stall confinement for the duration of the study. As noted above, shoes were applied in random order. Shoes were sized and shaped for each hoof of all horses (Figure 3). Two nails were used on each side of shoe for stabilization and to avoid unnecessary hoof damage. Force platform data collection was performed no less than 24 hours after shoe application. After the force platform data collection, shoes were replaced with the next set. No shoes were worn for more than 30 hours.

The kinetic gait data collection process is standard in the laboratory and has been described previously (Mirza et al. 2016; Taguchi et al. 2018). A 900 × 900 mm force platform embedded in the center of a 40 m concrete runway (Advanced Mechanical Technology, Inc., Watertown, MA) was used to collect ground reaction force data (Figure 4). The force platform surface is the same color and the texture as the runway. Horses were conditioned to the force platform and experienced handlers trotted them for all trials. A trial was considered successful if a forelimb contacted the force platform followed by contact of the ipsilateral hind limb at a velocity of 2.00-3.80 m/s and an acceleration of -0.9 to 0.9 m/s^2. Data logging was trigged by a force of 50 N. Trials were rejected if the hoof was not straight on the force platform, was not completely on the force platform or was within 5 cm of the force platform edge. A series of five retroflected photocell sensors (Mek 92-PAD, Doslyn Clark Controls, Inc.) were used to determine the velocity and acceleration for each trail. A minimum of five successful trials were recorded for each side. All trials were recorded at a rate of 1,000 Hz and processed with commercially available software (Acquire V7.3, Sharon Software).

Current Calk Design   New Calk Design

Tungesten Carbide Coted Shoes   Composite Shoes

Figure 3. Pictures of different horseshoes tested in on fore (left) and hind (right) hoof

3.9 Determining the Pavement Service Life When Using Different Horseshoes

A numerical model was developed for a typical pavement structure used on an Amish route. The vertical stress obtained from experiment at LSU were used in this model to compute the vertical strain in the surface/repair layer. The obtained vertical strains were used to compute the number of Amish buggies to cause rutting failure using the model developed by Witczack and El-Basyouny

(2005) shown in Equation 1. Based on that, the service life computed by determining the number of Amish buggies passes needed for to develop a rutting of 0.5 inch and assuming that an Amish buggy traffic of 20 buggies per hour.

$$\delta_p = \varepsilon_v[h_{ac} * k_1 10^{-3.4488} T^{1.5606} N^{0.473844}] \tag{1}$$

where,

δ_p: is the accumulated rutting at N repetitions of load

h_{ac}: asphalt layer thickness

N: is the number of load cycles

ε_v: vertical strain obtained from response model

T: is mixture temperature, °F.

Figure 4. Pictures of horses and handler taken during gait experiment

3.10 Cost Analysis of Partial Depth Repair

All available information on partial depth repairs for selected Amish buggy routes as well as several routes that do not have any Amish buggy traffic but had similar traffic volumes were obtained from Holmes county and Wayne County. Life cycle cost analysis (LCCA) was performed to evaluate the cost of repairs on routes with and without Amish buggy traffic. The LCCA involved computing the Net Present Value (NPV) using Equation 2. The NPV expresses all repair costs throughout the analysis period in the form of a single cost in terms of the present year monetary value. Equivalent Uniform Annual Costs (EUAC) of the all repairs of the Amish and non-Amish buggy routes were then determined based on NPV values using Equation 3. It is noted that an analyses period of 12 years and a discount rate of 4% were used in this study.

$$NPV = \sum_{k=1}^{n} \left(PMC_k \frac{1}{(1+i)^k} \right) \tag{2}$$

$$. \quad EUAC = NPV \left[\frac{i(1+i)^n}{(1+i)^n - 1} \right] \tag{3}$$

Where

i: discount rate (4%)

k: year of expenditure

PMC_k: repair cost at year k

n=analysis period (12 years)

3.11 Cost Analysis of Horsehoes Alternatives

A comprehensive cost analyses were conducted to estimate the cost of the different horseshoes alternatives considered in this study. The cost analysis considered:

✓ The cost of shoes per shoeing period (6 weeks)
✓ The cost of horse
✓ The horse expected service life
✓ The cost of pavement repairs due to the damage caused by the shoes.

The average cost of for a horse used for Amish buggies is about $11,000. The average service life for horses used for Amish buggies is on average 10 years. According to the Amish farrier identified by Amish Steering committee, the use of shoes with new calk design will increase the service life by at least 50%. This might be related to the reduction in the stresses on the horse hoof and joints. Based on that the Equivalent Uniform Annual Cost was computed for the different cases using the following equation

$$EUAC = COST\left[\frac{i(1+i)^n}{(1+i)^n-1}\right]$$
(4)

where,
i: discount rate
n: service life

3.12 Cost of Road Repairs When using Different Horshoes

Based on the results of experiment do to quantify the damage of horseshoes to the roads as well as the stresses measure in experiments done at LSU, it was determined that using horseshoes with new calk design will increase the service life of Amish buggy routes by about 90% as compared to using horseshoes with current calk deign. In addition, the use of horseshoes coated with tungsten carbide or composite horseshoes will result in the increasing the service life of roads with heavy Amish buggy traffic to be similar to those without any Amish buggy traffic. Based on the estimated service life, the cost of repairing state and local roads with high Amish buggy traffic was computed when using different horseshoes.

3.13 Meeting To Discuss Study Results with Amish Community

The research team organized a meeting on December 19th, 2019 to discuss the study results with the Amish community. The meeting was attended by representatives from the Amish community, townships, counties and ODOT. In this meeting, the attendees were provided with an overview of this study. In addition, the steps needed to implement the results of this study were discussed. During this meeting, a task force was formed to ensure the implementation of the study results.

4. Research Findings and Conclusions

Appendices A, B and C present a detailed summary of the results of tests and analyses conducted in this study. The main findings of this phase are:

- The testing of laboratory-produced samples of the airport mixtures designed with polymer modified binders, PG 76-22M and PG 88-22M or ground tire rubber modified (GTR) binder, and with an aggregate structure modified based on Bailey's method had much better rutting resistance than the ones currently used for repairing Amish buggy routes.
- The field evaluation of test section constructed on Amish buggy routes using the airport mixtures designed with polymer modified binders, PG 76-22M and PG 88-22M and with an aggregate structure modified based on Bailey's method had better performance than those constructed with the asphalt mixture typically used for repairing of these routes (i.e. ODOT Type 1 mix).
- The laboratory tests that were conducted to quantify the damage of horseshoes to asphalt mixtures, indicated that the horseshoes with the new calk design can reduce the horseshoes abrasion wear by about 45%. In addition, the tungsten carbide coated shoes and composite shoes almost eliminated the road damage.
- The experiments that were conducted to evaluate the effect of alternative horseshoes on horse hoof indicated that there was no indication that any of the considered shoe designs caused detectable lameness in the horses used in this study for the short time that the shoes were applied.
- The use of horseshoes with the new calk design reduced the vertical stresses on the road by at least 45% as compared to those with the calk design typically used by the Amish community. In addition, the horseshoes coated with tungsten carbide and the composite shoes resulted in 89% and 98% reduction in these stresses, respectively.
- The results of experiments showed that horseshoes with the new calk design and coated with tungsten carbide as well as the composite shoes had, in general, similar traction to horseshoes with calk design typically used by the Amish community.
- The results of analyses conducted in this study indicated that horseshoes with new calk design might increase the service life of Amish buggy routes by about 90%. In addition, the use of horseshoes coated with the tungsten carbide or composite horseshoes will result in increasing the service life of roads with heavy Amish buggy traffic to be similar to those without any Amish buggy traffic
- The results of life cycle cost analysis suggested that using horseshoes with new calk design can result in reducing the annual horse costs by at least 20%, when considering the effects of those shoes on the horse service life. Furthermore, the use of horseshoes coated with tungsten carbide or composite shoes can result in reducing the annual horse cost by about 15%.
- The results of cost analysis indicated that the cost of partial-depth repairs performed on routes with heavy Amish buggy traffic are about three times more expensive than those on routes without any Amish buggy traffic.
- The results of the cost analysis indicated that using horseshoes with new calk design can reduce the annual repair costs of Amish buggy routes by at least 40%. In addition, the use of horseshoes coated with tungsten carbide or composite shoes will result in reducing the annual repair cost of Amish buggy routes to be similar to those without any Amish buggy traffic.

5. Recommendations for Implementation

Based on the results of this study, it is recommended to:

- Use the decision tree shown in Figure 5 when repairing roads with Amish buggy traffic.

- Continue to monitor the test sections on CR 114, to determine the performance and cost-effectiveness of GTR modified mixtures when used on local roads with heavy Amish buggy traffic.
- The results of experiments in this study showed that the three alternative horseshoes considered in this study can be economical for the Amish and reduce the life cycle cost of Amish buggy routes. The horseshoes with the new calk design are the most economical and easiest to be implemented at the current time. However, the Amish farriers dress the horseshoes for worse case scenarios (typically township chip sealed roads). Therefore, a task force led by Amish community representatives and includes representatives from the townships, counties and ODOT has been established to address this issue and develop an implementation plan to ensure that the Amish community start using the alternative horseshoes identified in this study.
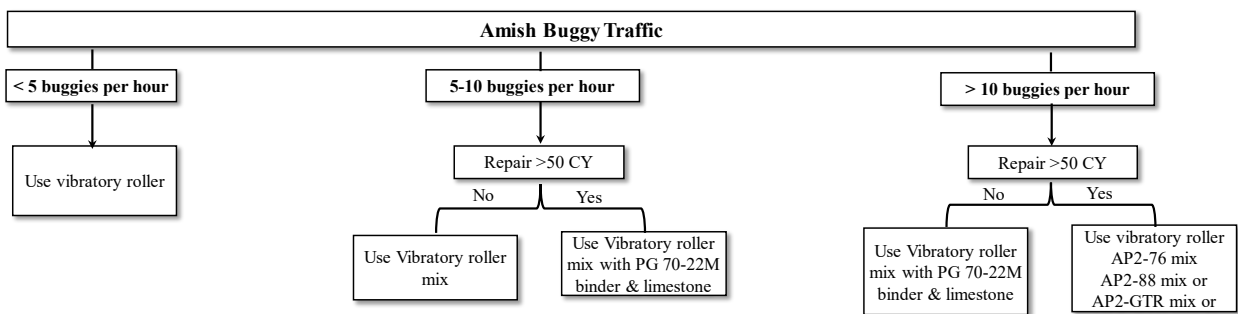

Figure 5. Recommended Decision Tree for Partial Depth Repairs on Amish Buggy Routes

6. References

- Hare, B.D (1990). "Comparison of Repair Methods for Rutting by Horse and Buggy" Final Report, project 84-107, Pennsylvania Department of Transportation
- Heydorn, A. (2013), "Paving for Horse and Buggy, Pavement, Maintenance & Reconstruction." Volume 28, issue 7.
- Mirza, M.H., et al., Gait Changes Vary among Horses with Naturally Occurring Osteoarthritis Following Intra-articular Administration of Autologous Platelet-Rich Plasma. Front Vet Sci, 2016. **3**: p. 29.
- Stoffels, S. M., Bitonti, T. A., Gleason, G. L., & Bahia, H. (1995). Mitigation Of Horseshoe Damage To Pavements (No. FHWA/PA 95-0204).
- Taguchi, T., et al., Agmatine for Pain Management in Dogs With Coxofemoral Joint Osteoarthritis: A Pilot Study. Front Vet Sci, 2018. 5: p. 311.
- El-Basyouny, M. M., Witczak, M., & El-Badawy, S. (2005). Verification for the calibrated permanent deformation models for the 2002 design guide (with discussion). Journal of the Association of Asphalt Paving Technologists, 74.

Appendix A Design and Evaluation of Mixtures for Amish Buggy Routes

A.1 Design of Mixes for Partial Depth Repairs on Amish routes

A laboratory testing program was conducted to design different alternative mixes to improve the rutting resistance of mixes used to roads with heavy Amish buggy traffic; these mixes included:

6. Mixtures designed using with polymer modified PG 76-22M binder and steel slag aggregates.
7. Airport mixture designed with polymer modified PG 76-22M and limestone aggregates.
8. Airport mixture designed with polymer modified PG 76-22M and limestone aggregates, but with an aggregate structure modified based on Bailey's method.
9. Airport mixture designed with polymer modified PG 88-22M and limestone aggregates, but with an aggregate structure modified based on Bailey's method.
10. Airport mixture designed with Ground Tire Rubber (GTR) modified binder and limestone aggregates, but with an aggregate structure modified based on Bailey's method.

All the aggregates used in this study were obtained from an ODOT-approved supplier. The control mix was obtained during the repair of Amish buggy in ODOT Homes County. To design the other mixes, aggregate gradation of a dense graded mixture previously used for a local airport in Ohio was first obtained. A mixture was designed using the Superpave mix design method. Bailey's method was then used to adjust the obtained aggregate gradation. Bailey's method provides a systematic approach for aggregate gradation selection. This method takes into account aggregate interlock and packing properties for stronger aggregate structure, and thus, high rutting resistance, while maintaining the volumetric properties of the asphalt mixtures for durability (Vavrik et al., 2002). In this method, aggregate packing is used as one of the design inputs, and coarse and fine aggregates were redefined. Coarse aggregate was defined as the particle size that creates voids when blended in a unit volume, and fine aggregate as the small particles that fill these voids. US sieve No.4 has been traditionally used to distinguish between coarse and fine aggregate. However, in the Bailey method, coarse aggregate was defined as the range of aggregate particles that create voids when placed in a unit volume, and fine aggregate as the particle sizes that can fill these voids. Accordingly, a primary control sieve (PCS) was introduced, which separates coarse from fine aggregate depending on the nominal maximum particle size (NMPS) in the blend. The PCS is determined using the following equation:

$$PCS = 0.22 * NMPS \qquad (A.1)$$

This method also requires the determination of loose and rodded unit weights of each stockpile used in the mix. Then, a chosen unit weight should be selected as a percentage of the loose unit weight based on the type of the mix. Coarse-graded mixtures should have a chosen unit weight between 95-105% of the loose unit weight of coarse aggregate. The volume of voids between coarse aggregate is then determined and filled with certain amount of fine material in order to achieve the desired void in mineral aggregate (VMA).

Three mixes with different binders with the same aggregate structure that was selected based on Bailey's method. The binders that were considered were: a polymer modified binder meeting PG 76-22M, a polymer modified binder meeting PG 88-22M, and Ground Tire Rubber (GTR)

modified binder meeting PG 70-22M. Using these three mixes allowed to investigate to the effects of binder grade and modification using Bailey's method on rutting performance of HMA. A mix that was used by ODOT Holmes county to perform repairs on Amish buggy routes was obtained. This mix meets specifications for ODOT 101G specifications and was used a control mix. Aggregate gradations for all mixtures designed in the lab are provided in Table A.1. Table A.2 provides summary of properties of asphalt binders considered in this study.

Table A.1. Aggregate gradation for mixes designed in the lab

Sieve size (mm)	Percent Passing %			
	AP1-76	AP2-76, AP2-88	Control	GTR-AP2 Mix
3/4" (19)	100	100	100	100
1/2" (12.5)	98	98	100	96
3/8"(9.5)	81	81	98	81
#4 (4.75)	48	54	61	55
#8 (2.36)	33	40	36	43
#16 (1.18)	21	25	22	28
#30 (0.6)	13	16	13	19
#50 (0.3)	9	9	8	11
#100 (0.15)	7	6	5	7
#200 (0.075)	6	4	3	5

Table A.2. Asphalt binders properties

Property	Superpave Spec.	Polymer-modified			GTR-modified
		PG 70-22M	PG 76-22M	PG 88-22M	PG 70-22M
Original Binder					
Flash point, $^{\circ}$C	$\geq$230	340	340	340	316
Rotational Viscosity @135°C, Pa-S	$\leq$3.00	1.05	1.30	1.5	2.04
DSR, 10 rad/sec, $G^*/\sin\delta$, kPa	$\geq$1.00	1.95 @70°C	1.47 @76°C	1.90 @88°C	1.61 @70°C
RTFO-aged binder					
DSR, 10 rad/sec, $G^*/\sin\delta$, kPa	$\geq$2.20	5.78 @70°C	4.06 @76°C	3.40 @88°C	3.89 @70°C
Mass Loss, %	$\leq$0.750	0.212	0.207	0.165	0.297
PAV-aged binder					
DSR, 10 rad/sec, $G^*\sin\delta$, kPa	$\leq$5000	2460 @28°C	1560 @31°C	176 @37°C	1870 @28°C
BBR Creep Stiffness, S_{max}, MPa, at -12°C	$\leq$300	146	124	59	161
BBR Creep Slope, m-value, at -12°C	$\geq$0.300	0.317	0.320	0.398	0.327

After the aggregate gradation was selected, the optimum asphalt content was determined for each mix used in the study. The Superpave mix design procedure was adopted to determine the optimum asphalt content. The design number of gyrations for all mixes was obtained from ODOT specification item 442 for heavy traffic at 65. For each mix, at least four gyratory specimens and three loose mix were prepared to determine the volumetric properties of the mixtures. A summary of the volumetric properties for all mixtures is shown in Tables A.3.

Table A.3 Volumetric properties for lab-produced mixes

Property	Control	AP1-76	AP2-76	AP2-88
AC (%)	5.8	4.5	5.3	5.3
Air voids (%)	4	4	4	4
G_{mm}	2.485	2.538	2.530	2.530
VMA (%)	14.2	11.5	13.5	13.5

A.2   Evaluation of Rutting Resitance of Designed Mixes Using Flow Number Test

The laboratory testing program focused on evaluating the rutting resistance of different mixtures designed and mixtures used by ODOT for partial depth repair (101G control mix) as well as for construction of surface course on a high volume roads (Interstate (IR) 270 surface mix) using the Flow Number test. The flow number test is a repeated axial load test. Many researchers have used this test to evaluate the rutting performance of difference asphalt mixes. The flow number test was performed based on the AASHTO TP79-13 standard method. For this test, specimens with a diameter of 100 mm and a height of 150 mm were used for each mix. At least three specimens were prepared, with a target air void content of 7.0±0.5 percent. After compaction, specimens were trimmed from both ends a using wet sawing machine and checked for their flatness and perpendicularity. Test specimens were placed in an environmental chamber that controls the temperature during the test. All specimens were conditioned at 130ºF (54ºC) for three hours prior to running the test. Double latex friction reducers were placed in between the specimen surface and the loading platens on top and bottom of the specimen.

The test consists of applying 10,000 load cycles as an axial load on an unconfined specimen. Each cycle consists of 0.1 loading/unloading time and 0.9 seconds of rest time to generate creep. During the test, the applied load and the resulting axial deformation were recorded every 2 milliseconds. Also, the applied stress level every cycle was set to 600 kPa. Materials testing system (MTS) was used to perform the test. The test configuration is shown in Figure A.1. The test was terminated when the total axial deformation of the specimen reached 1.2 inches.

A.3   Results of Flow Number Test

The permanent deformation response of asphalt mixtures under cyclic load can be divided into three main stages, primary flow, secondary flow, and tertiary flow. According to AASHTO TP79-13, the flow number is defined as the number of loading cycles required to reach the tertiary flow. Francken's model, a mathematical fitting model that was recommended by Biligiri et al. (2007), was used to fit the flow number test data. This model is a combination of power and exponential models as given in Equation (A.2). The flow number was then determined as the cycle

number at which the slope of slope (or second derivative) of the permanent deformation curve changes from negative to positive as illustrated in Figure A.2.

$$\varepsilon_p = A\,N^B + C\,(e^{DN} - 1)$$

(A.2)

Where ε_p is the permanent axial strain, N is number of load cycles, and A, B, C, and are model fitting coefficients.
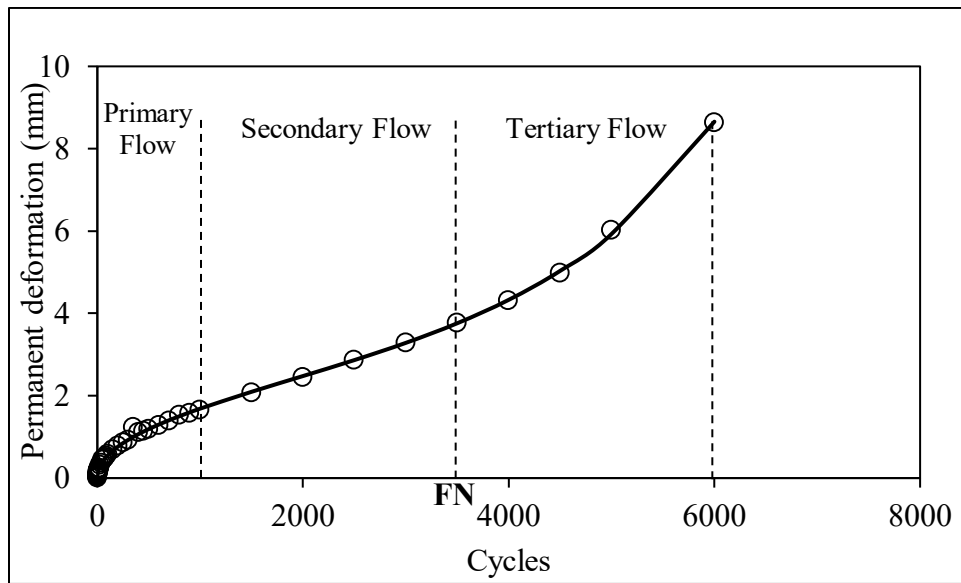

Figure A.1. Flow number test configuration

Figure A.2 Permanent deformation curve from the flow number test

The flow number was determined as the cycle number corresponding to the start of the tertiary flow stage. It was determined by fitting the permanent deformation curve to Francken's model, as previously described. The results of this test are shown in Figure A.3. The flow number indicates

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the rutting resistance of each mix. The higher the flow number, the higher resistance the mix can provide. Based on these results, mixes AP2-76, AP2-88, and AP2-GTR had the best performance in terms of rutting resistance. However, AP2-76 have shown the highest variability of the flow number value among these mixes. The flow number for AP2-76 is significantly higher than that for AP1-76, indicating that the modification of aggregate gradation was effective in improving the rutting resistance. Between AP2-76 and AP2-88 that had the same aggregate structure, there is no significant difference in the flow number, indicating similar binder contribution towards permanent deformation resistance. The control mix has the smallest flow number, indicating poor resistance to rutting as compared to the other mixes. The average flow number for the control mix is 80, which means it reached the tertiary flow stage more than 20 times faster than AP2 mixes.
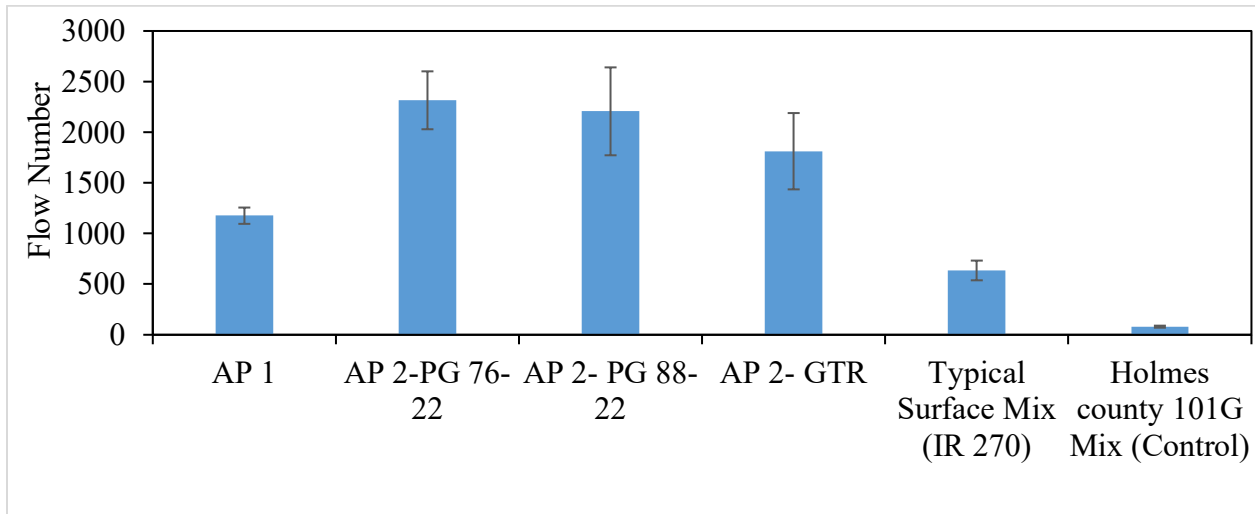

Figure A.3 Flow number of different mixes

A.4   Construction of Test Section On State Route 241

The best performing mixes designed in the laboratory part of this study were selected for further evaluation in the field. The field evaluation involved constructing several test sections in August 2017 as part of a partial depth repair project on State Route (SR) 241. The test sections included the airport mixtures that had an aggregate structure designed based on Bailey's method and polymer modified binder. Three different polymer modified binders were used meeting PG 70-22M, PG 76-22M, and PG 88-22 M. In addition, a mixture typically used in partial-depth repairs in ODOT Holmes County was used as the control mix. The control mix had a polymer modified binder PG 70-22M, and aggregate gradation meeting that of ODOT item 441. Figures A.2 shows the layout and location of the test section constructed on SR 241. The research team monitored the placement and compaction of the test sections. This included measuring the mat temperature and recording the density at core locations. Field density was measured using a PQI 380 asphalt density gauge. Photos were collected and videos of the test sections were recorded during and after construction. Figure A.3 presents some of the photos taken.

Figure A.3 Pictures taken during construction of test sections on SR 241

A.5   Construction of Test Section On Holmes County Road 114

Test sections were constructed as part of a resurfacing project on Holmes County Road (CR) 114 to evaluate the use of mixtures with GTR modified asphalt binder on local roads with heavy Amish buggy traffic. AP-2 GTR mix designed using the same aggregate structure and type as those used in AP2 76-22 mix but with GTR modified binder was placed in one lane of CR 114, another GTR mix (GtR Mix) designed using typical aggregate materials and structure used by Holmes County was placed on the other lane. The two sections were constructed 10/05/2018 and 10/08/2018, respectively. Samples of the GTR modified asphalt were obtained at the asphalt plant. In addition, at least eight buckets of each mix were obtained at the asphalt plant. Photos were collected and videos of the test sections were recorded during and after construction. Figure A.4 presents some of the photos taken.

A.6   Labarory Testing of Field Mixes

Loose asphalt mixture samples were obtained at the asphalt plant for each mixture used in the test sections. Specimens of the loose mixtures were compacted in the laboratory to achieve target air voids of 7±0.5%. Laboratory tests were conducted on the core and lab-compacted specimens to evaluate the rutting performance and durability (moisture damage) of all mixtures. To this end, Flow Number Test was conducted to examine the rutting resistance of field mixes. In

addition, AASHTO T283 (Modified Lottman Test) was used to evaluate the moisture susceptibility of those mixes.

Figure A.4 Pictures taken during construction of test sections on CR 114

A.7 Results of Flow Number Testing of Field Mixes

The flow number values for mixtures obtained during construction of test section on SR 241 and CR 114 are shown in Figure A.5. The test was performed at 54ºC. Specimens were conditioned at testing temperature for three hours in the environmental chamber prior to the start of the test. The flow numbers for field-produced mixtures were higher than the lab-produced mixtures. This difference may be attributed to the short-term aging that field-produced mixtures encountered. The difference in aggregate gradation and asphalt content between the lab-produced and plant-produced mixes might also affected the flow number. It can be observed that AP2-88 field mix has the highest flow number. This indicate that it has the highest resistance to rutting. Among the other mixes, AP2-GTR1 was the best performing mix and its flow number was significantly higher. As expected, GTR-Mix had the lowest flow number and, and thus the lowest resistance to rutting. This is attributed to the excessive amounts of natural sand that reduces internal friction which is necessary for shear strength development. However, there is no significant difference between the flow numbers of AP2-70 and GTR-Mix.

According to AASHTO TP79, an HMA mix is required to have a flow number higher than 740 for a traffic level of 30 million EASALs or higher. Therefore, only mixes AP2-88, AP2-GTR, and AP2-76 exceeded this requirement for heavy traffic.
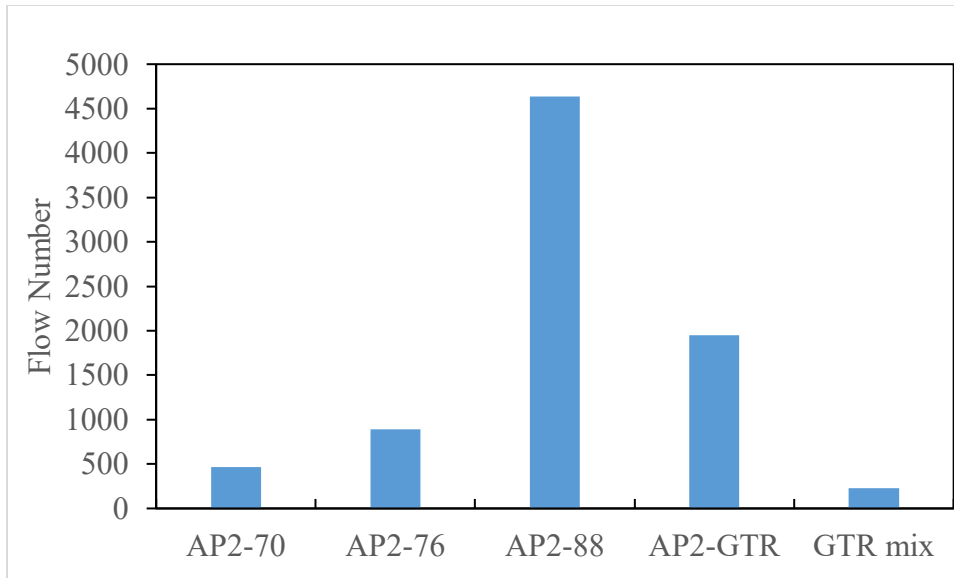
Figure A.5 Flow number test results for mixes included in Phase 2

Table A.4 Results of ANOVA Analysis on Flow Number

Effect	Num DF	Den DF	F Value	p-value
binder	4	13	3530.06	<.0001

Table A.5 Results of Post ANOVA LSM Analysis on Flow Number i

Mix ID	FN	Letter Group
AP2-88	4633	A
AP2-GTR	1949	B
AP2-76	888	C
AP2-70	466	D
GTR-Mix	229	D

A.8 Modified Lottman Test

This test is intended to evaluate the durability against moisture induced damage of asphalt mixtures. It was performed according to AASHTO T283-07 standard test procedure. A set of six cylindrical specimens were fabricated for each mix with a target air voids content of 7.0±0.5%. For each mix, three specimens were tested dry and the other three were tested wet after applying freeze and thaw conditioning. However, both sets were tested at room temperature 77°F (25°C). The standard test method implies saturating the wet specimens to 70-80% degree of saturation. This was achieved by submerging the specimens in a vacuum container filled with water at room temperature and applying a vacuum pressure. Each specimen was then wrapped in a plastic bag with 10 ml of water. The specimens were then placed in an environmental chamber at 0°F (-18°C) for 16 hours. After that, the specimens were immediately removed and placed in a hot water bath

at 160ºF (60ºC) for 24 hours. The water bath temperature was then adjusted to 77ºF (25ºC) for two hours before running the test.

The test applies an increasing load along the diameter of the specimen at a constant rate of 2 in./min (50 mm/min). During the test, the vertical and lateral deformations were recorded using an LVDT system. The indirect tensile strength for both dry and wet specimens was determined using Equation A.3. The tensile strength ratio (TSR) was then determined for each mix as the ratio of the average tensile strength of the wet-conditioned set over the average tensile strength for the dry set (Equation A.4). It indicates mixture susceptibility to moisture-induced damage. The higher the TSR value, the better resistance it has to moisture damage.

$$\text{Indirect tensile strength}, \text{ITS} = \frac{2\,P}{2\,\pi DT} \qquad (A.3)$$

Where;
P: maximum load, lb.
D: specimen diameter, in.
T: specimen thickness, in.

$$\text{Tensile strength ratio}, \text{TSR}\,(\%) = \frac{S_w}{S_d} \qquad (A.4)$$

Where S_w is the average indirect tensile strength of the conditioned (wet) set, and S_d is the average tensile strength of the dry set.

The average ITS for dry and wet conditioned samples are presented in Figures A.6. Based on the ITS test results, AP2-76 and AP2-88 provided the highest ITS values. They are both ranked the best in terms of ITS values. Also, mixes Ap2-GTR and AP2-70 provided similar ITS values and their results were not significantly different. GTR mix provided the smallest strength among all mixtures included in field part of this study. TSR values are shown from Figure A.7. It is noted that all mixes exceeded the TSR limit set by ODOT at 80%, which indicates adequate resistance to freezing and thawing and thus, good durability. It is worth noting that AP2-88 provided the highest TSR value, which means that freezing and thawing of the specimens did not reduce the ITS significantly.
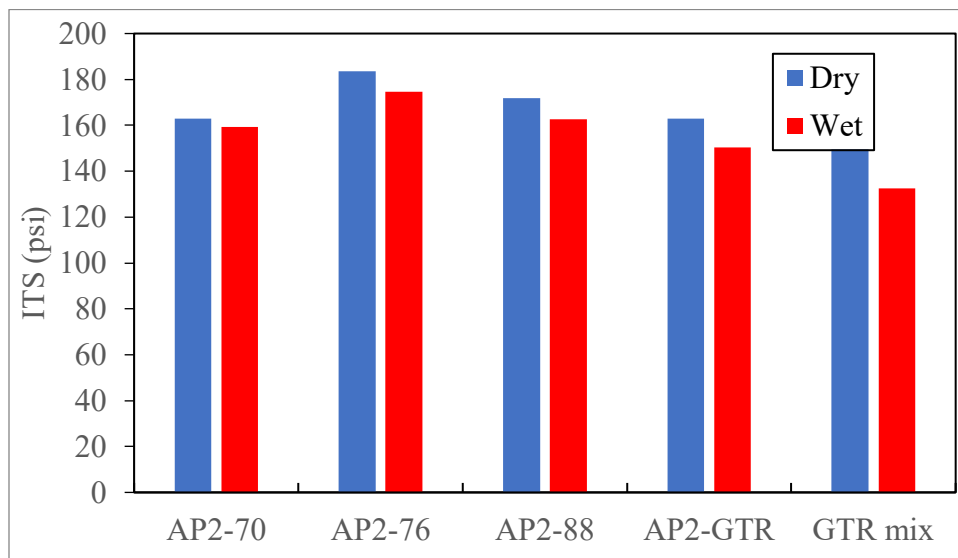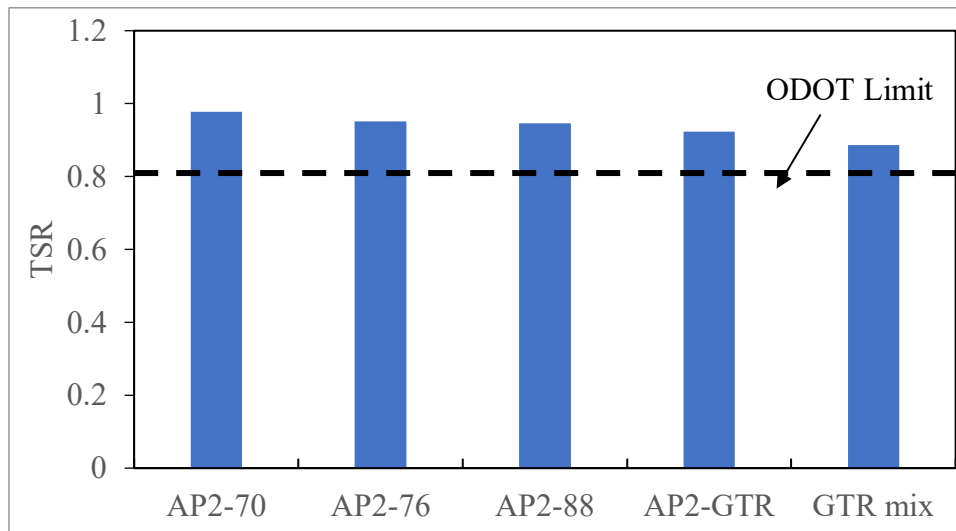

Figure A.6 Average ITS values for field mixes

Figure A.7 TSR values for field mixes

A.9 Field Evaluation of Constructed Test Sections

A field and laboratory testing methodology was developed to evaluate the performance of the constructed test sections. The developed field methodology included evaluating the performance of the test sections by the research team during the duration of this project. All field evaluations involved examining the severity and extent of the distresses developed in these sections.

The section below presents the results of the last evaluation done after twenty months of the construction of test sections.

Test Section with Control mix

As can be noticed in Figure A.8, this test section had significant deterioration in terms of rutting. In addition, severe surface aggregate detachment and raveling. Also, several transverse thermal cracks propagated from the old adjacent pavement into this section. It is clear that the joint with the adjacent old pavement has significantly deteriorated. Potholes developed in some parts along the joint and within the section and were patched.

Test Section with AP2-70 Mix

There was some deterioration in this section as shown in Figure A.9. The edge of the test section was noticeably split from the old pavement at some locations. Also, there were about three transverse cracks per 100 ft. No significant rutting problem was noticed, but there was some abrasion of surface aggregates at certain locations, which was due to horseshoes.

Test Sections with AP2-76 Mix

As shown in Figure A.10, these sections had no significant damage. The joint along the interface with at the old pavement is relatively in good condition in one section but had some deterioration on the old pavement side in the other section. In general, there was minimal rutting in these sections. In addition, there was low severity deterioration of surface aggregate. However, some aggregate particles were crushed but were not detached. A few transverse cracks propagated from adjacent old pavement.

Figure A.8 Pictures of sections with control mix after 20 months of construction

Figure A.9 Pictures of section with AP2-70 mix after 20 months of construction

Test Sections with AP2-88 Mix
These test sections did not have any rutting or noticeable deterioration. However, there was some deterioration in adjacent old pavement along the joint between the Amish buggy test sections and adjacent old pavement. This may be attributed to the significant damage in the adjacent pavement as shown in Figure A.11. In addition, not sealing the joints after constriction of test section might have contributed to that. Some few transverse cracks propagated from the old adjacent pavement to the test section.

Figure A.10 Pictures of sections with AP2-76 mix after 20 months of construction

Figure A.11 Pictures of sections with AP2-88 mix after 20 months of construction

GTR Sections
In general, both GTR sections did not show any rutting or signs of deterioration after 7 months of construction. As shown in Figure A.12 and A.13, both sections had some abrasion wear due to

horseshoe hits. However, this did not result in crushing of the aggregates or detachment of surface aggregates.

Figure A.12 Pictures of AP2-GTR test sections after 7 months of construction

Figure A.13 Pictures of GTR-Mix test sections after 7 months of construction

Appendix B Design and Evaluation of Horseshoes

B.1 Alternative Horse Shoes Materials and Designs

The research team met with Amish farriers and the Ohio Amish Steering committee representatives several times to identify the alternative horseshoes that can be used to reduce the damage on roads. The Amish farriers have indicated that some Amish farriers are using high profile with narrow tipped calks. They suggested that the design is used to provide adequate traction that is needed in some chipsealed roads, which become very slippery during the winter. The Amish farriers indicated that they have used low profile calks that are spread on larger area of the shoes, which they believe it tends to reduce the stresses on the horse and roads. Based on that, the use of horseshoes with low profile calks was identified as the first alternative to reduce damage on roads.

As the main function of the calks is to provide adequate traction, the research team worked on identifying different coating methods and materials that can provide the needed traction while not causing damage to the roads. The first coating material and method identified was Carbinite. Carbinite is a metallurgically bonded textured coating that can be applied to a wide variety of industrial applications in order to increase friction, reduce wear, and improve performance. It consists tungsten/carbide alloy and is applied to metals using a process called Electro Spark Deposition (ESD), which yields a true metallurgical bond. This high bond strength far surpasses any spray-on coating currently available. Carbinite has been used as an alternative to spray, thermal, or diamond coatings in many applications including oil and gas tools such as static gripping jaws. There are different carbinite grades as shown in Figure B.1. Different horseshoes were obtained by one of the Amish farriers identified by the Amish steering committee. The shoes were coated with two different grades (grade #1 and #4). The coated shoes were used on the Amish farrier horses. The farriers indicated that while the #4 grade provided adequate traction for the horses, it wears off in less than 60 miles. Therefore, this coating method was not further evaluated.

Figure B.1 Carbinite grades

Another coating method that was explored was developed by Tunco Manufacturing. This method applies the tungsten carbide through furnace heating. As shown in Figure B.2, there are different coating grading that depends on the particles size and distribution. Standard Horseshoes were obtained by the Amish farrier identified by the Amish steering committee. The shoes were coated with two different grades (grade #16 and #36). The coated shoes were used on the Amish farrier's horses. Initial evaluation showed that horseshoes with #16 grade had good traction but moderate wearing. In addition, horseshoes with #36 grade had moderate traction but better wearing resistance. Therefore, a coating grade of #24 was selected for further evaluation. In addition, the Amish farrier also suggested that leaving the edge lines uncoated (Figure B.3) to give the horse some flexibility. Two Amish farriers evaluated this design and found it to provide the adequate traction during the summer and fall seasons. In addition, the coating was good after more than 120 miles of travel. Therefore, this alternative was selected for further evaluation.
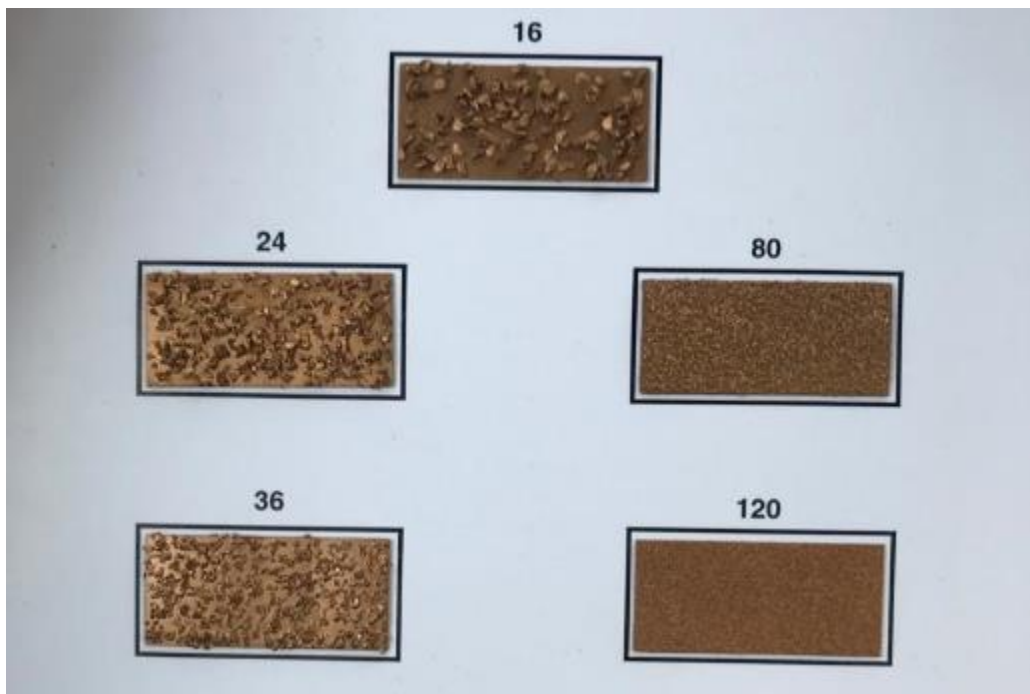

Figure B.2 Different grades of tungsten carbide coating

Figure B.3 The selected tungsten carbide coating design for horseshoes

A composite horseshoe that has a steel core and a very stiff synthetic plastic shell that can be shaped to fit the hoof by using the anvil to shape the steel and a grinder or nipper/rasp to shape the plastic. The steel inlay in the composite horseshoe protects the coffin bone and surrounding vascular supply as a toe callus on a barefoot horse. The synthetic plastic material is durable and wears equivalent to steel horseshoes. The horseshoes can be nailed or glued on, and can be reset. Those shoes were used by one of the Amish farriers on several of his horses. The Amish farrier indicated that it provides good traction and have excellent wearing resistance. Based on that, this alternative was selected for further evaluation.

B.2 Quantifying the Reduction in Local Roads Damage Due To Alternative Horseshoes

The research team quantified the reduction in horseshoes damage to local roads due to using the alternative shoes. To achieve that, experiments were conducted on different horseshoes alternatives shown in Figure B.4, which included:

1. Three horseshoes with high profile Drilltec (tungsten carbide) calk design that the Amish community commonly used.
2. A horseshoe with a new calk design consisting of low profile Drilltec (tungsten carbide) calks that was identified by the designated Amish farriers as an alternative to reduce damage on roads.
3. A horseshoe coated with the selected tungsten carbide coating design.
4. Composite horseshoe

Current Calk Design

New Calk Design

Tungsten Carbide Coated Shoes

Composite Shoes

Figure B.4 Horseshoes considered in this study

The conducted experiments involved attaching a horseshoe to a 6 inch Marshall hammer that was modified for this purpose. A sample of an asphalt mix typically used on state routes and local roads were obtained. At least 50 blows of the hammer with attached horseshoes were applied to compacted asphalt mixture sample to evaluate the damage of the different horseshoes. This was used to quantify the reduction of damage to asphalt mixes with the alternative horseshoes.

Figure B.5 shows the maximum penetration obtained in the experiments. It is clear that new calk design had much less penetration than the current calk design. In addition, both the tungsten carbide coated shoes and the composite shoes did not show any abrasion wear and therefore there was no penetration.

Figure B.6 shows the number of blows needed to reach a penetration of 4 mm in the experiments conducted. It is clear that new calk design had resulted in much high number of blows as compared to the current calk design. Figure B.6 shows that the new calk design can reduce the horseshoes abrasion wear by about 45%. In addition, both the tungsten carbide coated shoes and the composite shoes almost eliminated the road damage by the horseshoes.

B.3   Evaluating the Effects of New Horseshoes Alternative on Horse Hoof

A study was conducted at the College of Veterinary Medicine at the Louisiana State University to evaluate the effects of the new horseshoes alternatives on horse hoof and legs. Four different shoes were evaluated:

1. A horseshoe with high profile Drilltec (tungsten carbide) calk design that the Amish community commonly used.
2. A horseshoe with a new calk design consisting of low profile Drilltec (tungsten carbide) calks that was identified by the designated Amish farriers as an alternative to reduce damage on roads.
3. A horseshoe coated with the selected tungsten carbide coating design.
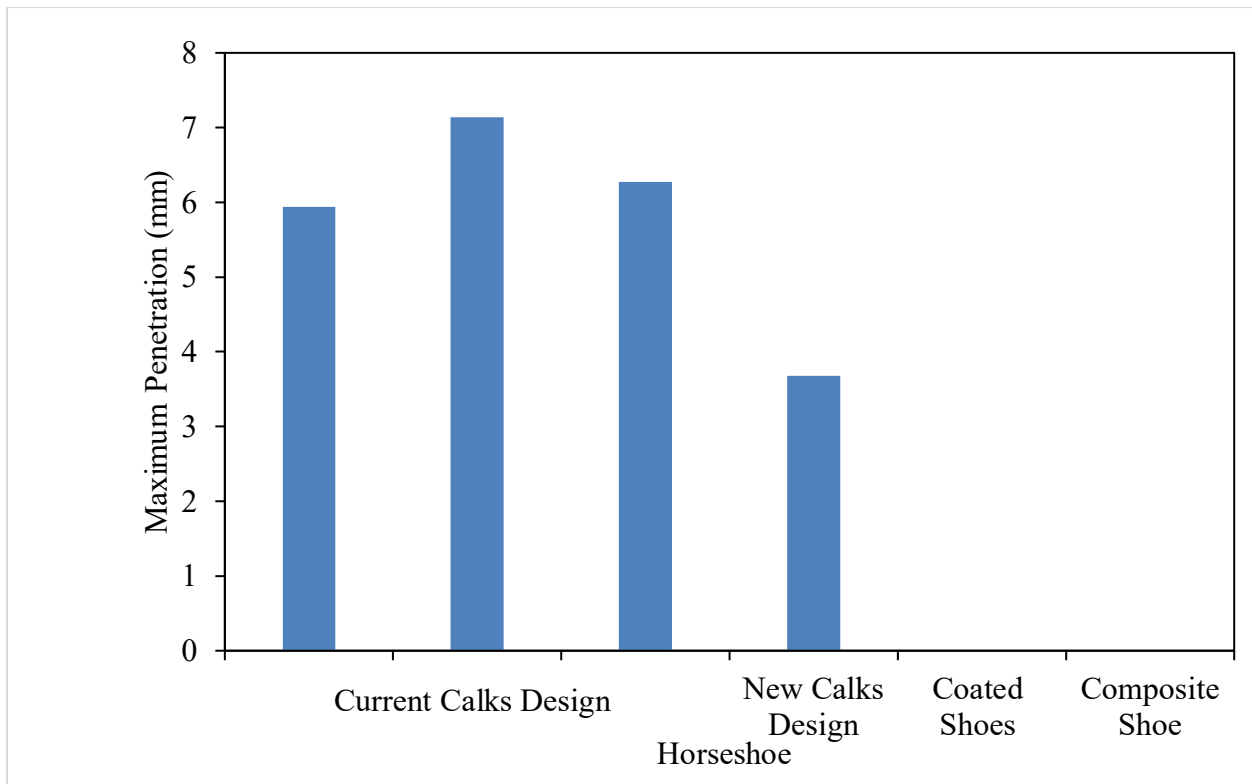4. Composite horseshoe

Figure B.5 Maximum penetration obtained for different horseshoes
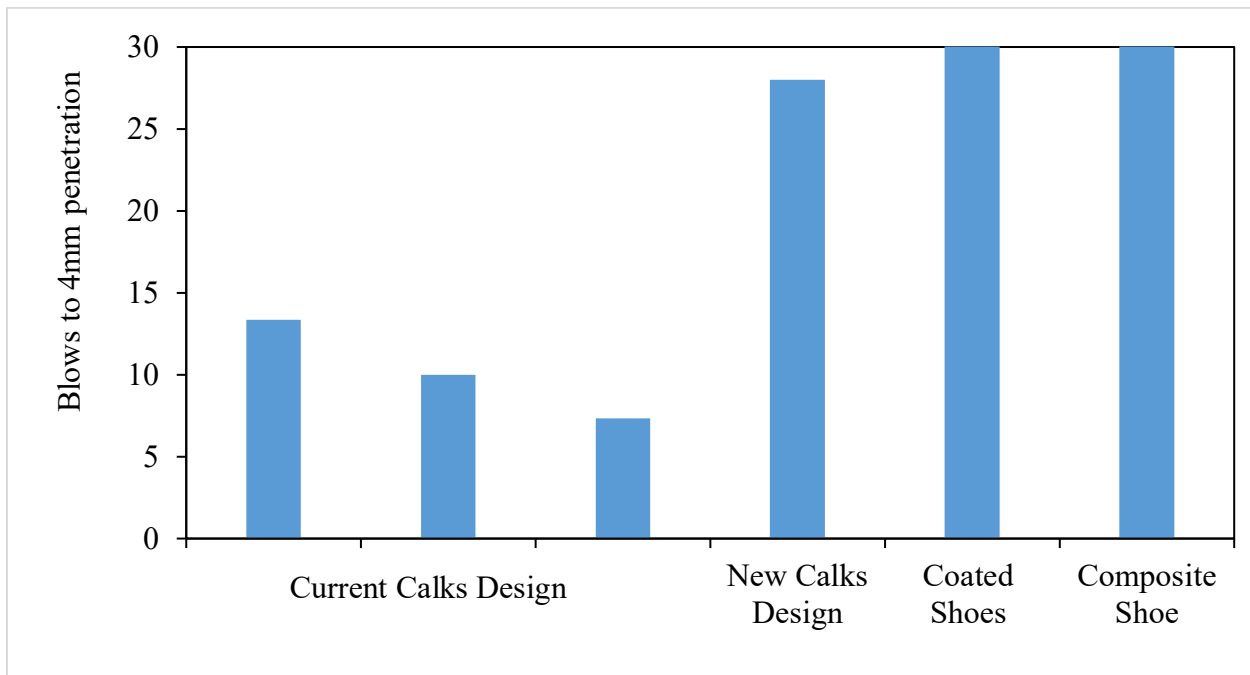
Figure B.6 Maximum penetration obtained for different horseshoes

 The study had a six-way cross-over, prospective study design. The order of shoe application was determined by a randomized block design. A licensed farrier performed all hoof preparation and shoe application. Prior to the application of the first set of shoes, gait data was collected with no shoes three days after hoof preparation. Horses were maintained in stall confinement for the duration of the study. As noted above, shoes were applied in random order. Shoes were sized and shaped for each hoof of all horses (Figure B.7). Two nails were used on each side of shoe for stabilization and to avoid unnecessary hoof damage. Force platform data collection was performed no less than 24 hours after shoe application. After the force platform data collection, shoes were replaced with the next set. No shoes were worn for more than 30 hours.

The kinetic gait data collection process is standard in the laboratory and has been described previously (Mirza et al. 2016; Taguchi et al. 2018). A 900 × 900 mm force platform embedded in the center of a 40 m concrete runway (Advanced Mechanical Technology, Inc., Watertown, MA) was used to collect ground reaction force data (Figure B.8). The force platform surface is the same color and the texture as the runway. Horses were conditioned to the force platform and experienced handlers trotted them for all trials. A trial was considered successful if a forelimb contacted the force platform followed by contact of the ipsilateral hind limb at a velocity of 2.00-3.80 m/s and an acceleration of -0.9 to 0.9 m/s2. Data logging was trigged by a force of 50 N. Trials were rejected if the hoof was not straight on the force platform, was not completely on the force platform or was within 5 cm of the force platform edge. A series of five retroflected photocell sensors (Mek 92-PAD, Doslyn Clark Controls, Inc.) were used to determine the velocity and acceleration for each trail. A minimum of five successful trials were recorded for each side. All trials were recorded at a rate of 1,000 Hz and processed with commercially available software (Acquire V7.3, Sharon Software).

Current Calk Design New Calk Design

Tungesten Carbide Coted Shoes Composite Shoes

Figure B.7 Pictures of different horseshoes tested in on fore (left) and hind (right) hoof

Figure B.8 Pictures of horses and handler taken during gait experiment

B.4 Results of Experiments to Evaluate of Horshoes on Horse Hoof

Figures B.9 and B.10 present the average normalized peak vertical force (PVF_Z) vertical impulse (IMP_Z) obtained for the horseshoe alternatives, which was based on experiment data that was collected from five, light breed, non-lame horses. It is noted that, in general, the vertical force and impulse were similar for different horseshoes considered. Although the vertical force is similar, the contact stress is different as it depends on the contact area. Picture of the different shoes considered were taken. Image analyses of the obtained picture was performed to estimate the contact area. Based on the measured contact area, the vertical contact stress was then computed based on the measured vertical force and contact area. Figure B.11 presents the computed contact stress for the different shoes considered. It is noted that the use of shoes with new calk design reduced the stresses by at least 45%. In addition, the shoes coated with tungsten carbide had by about 89%. Finally, the composite shoes had reduced the stresses on the contact stresses by 98%. This indicates the alternative shoes can significantly reduce vertical stresses on the horses and those applied to road.

Figure B.12 shows the peak braking force (PBF) obtained for the different alternatives. This parameter is used to examine the traction for different horseshoes alternatives. For forehooves, the PBF magnitude of horseshoe with the current calks design was slightly higher than other horseshoes alternatives. However, for hind hooves, the PBF of alternative shoes were higher than those with calks design the Amish use. The composite shoes had the highest PBF followed by the shoes coated with tungsten carbide.

Figure B.13 presents the stance time obtained in experiments. Stance time for the horseshoes with the current calks design were much lower than the alterative horses considered in this study. This might indicate that the horses were more comfortable with the alternative shoes than those with the current calks design.
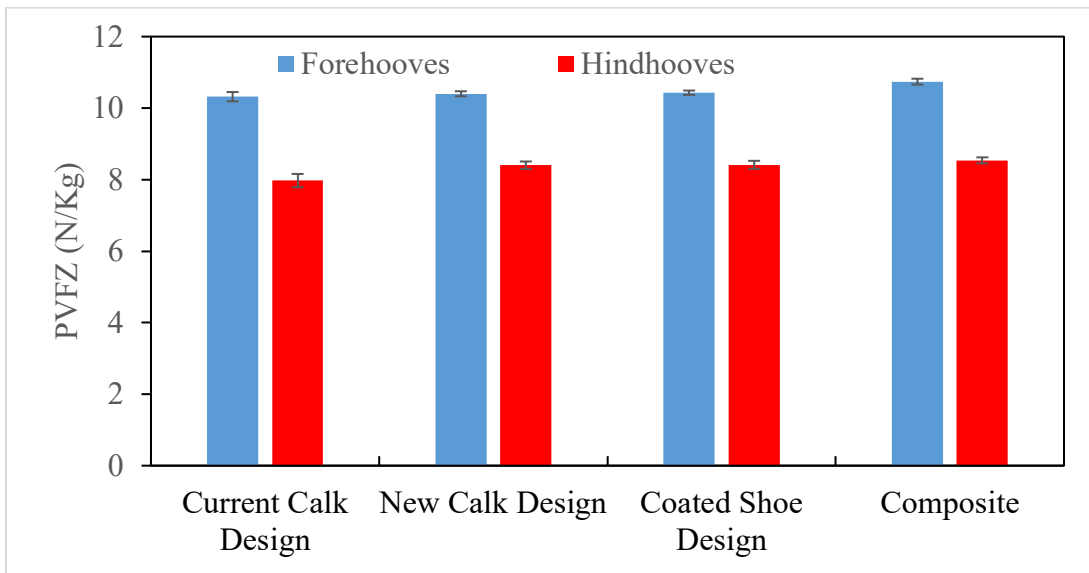
Figure B.9 Peak vertical force (PVF$_Z$) obtained for the horseshoe alternatives
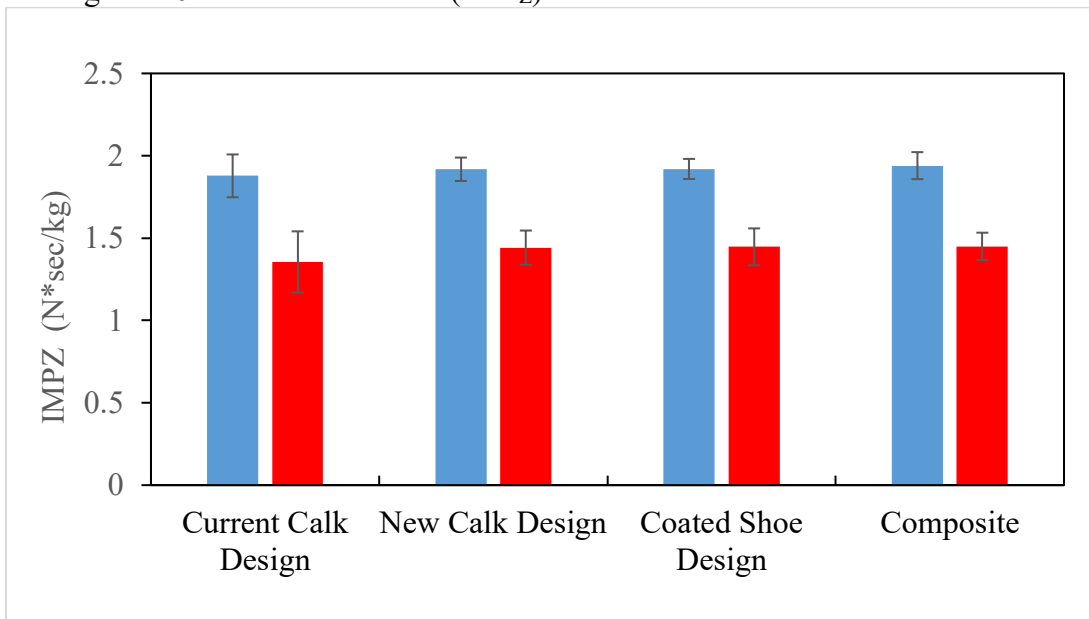
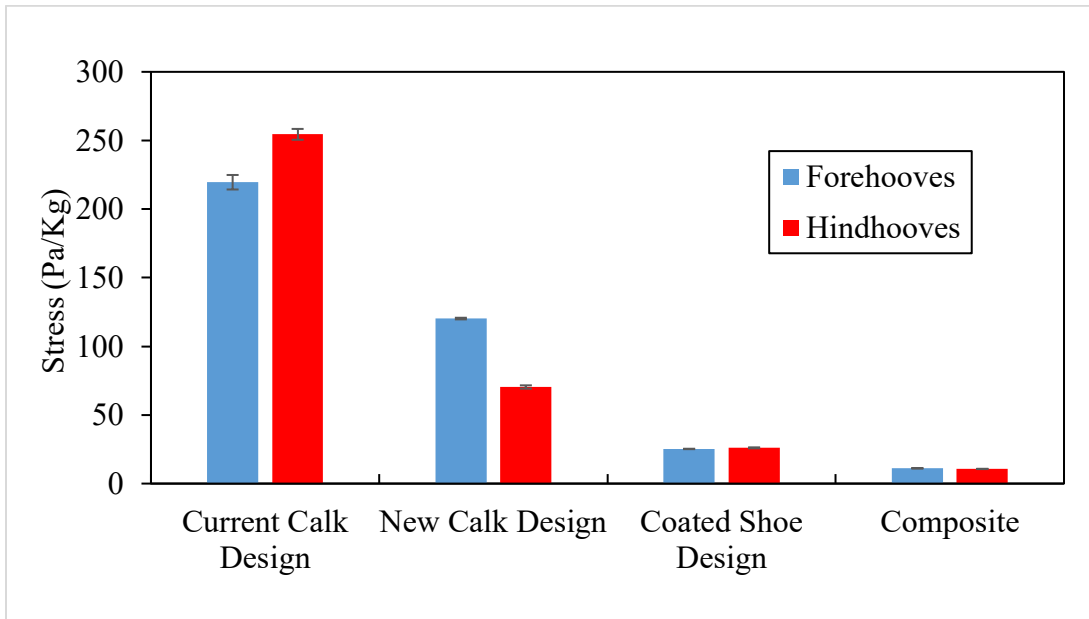Figure B.10 Vertical impulse (IMP$_Z$) obtained for the horseshoe alternatives

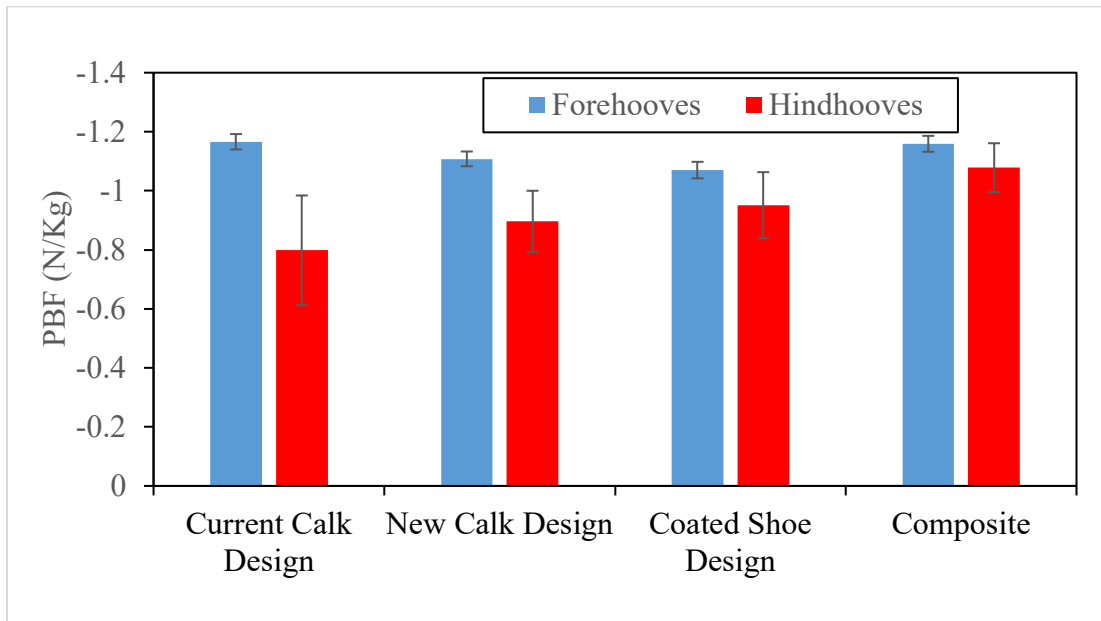Figure B.11 Vertical stress obtained for the horseshoe alternatives

Figure B.12 Peak braking force (PBF) obtained for different horseshoe alternatives

B.5 Determining the Pavement Service Life When Using Different Horseshoes

A numerical model was developed for a typical pavement structure used on an Amish route. The vertical stress obtained from experiment at LSU were used in this model to compute the vertical strain in the surface/repair layer. The obtained vertical strains were used to compute the number of Amish buggies to cause rutting failure using the model developed by Witczack and El-Basyouny (2005) shown in Equation B.1. Based on that, the service life computed by determining the number of Amish buggies passes needed for to develop a rutting of 0.5 inch and assuming that an Amish buggy traffic of 20 buggies per hour.

$$\delta_p = \varepsilon_v[h_{ac} * k_1 10^{-3.4488} T^{1.5606} N^{0.473844}] \tag{B.1}$$

where,

δ_p: is the accumulated rutting at N repetitions of load

h_{ac}: asphalt layer thickness

N: is the number of load cycles

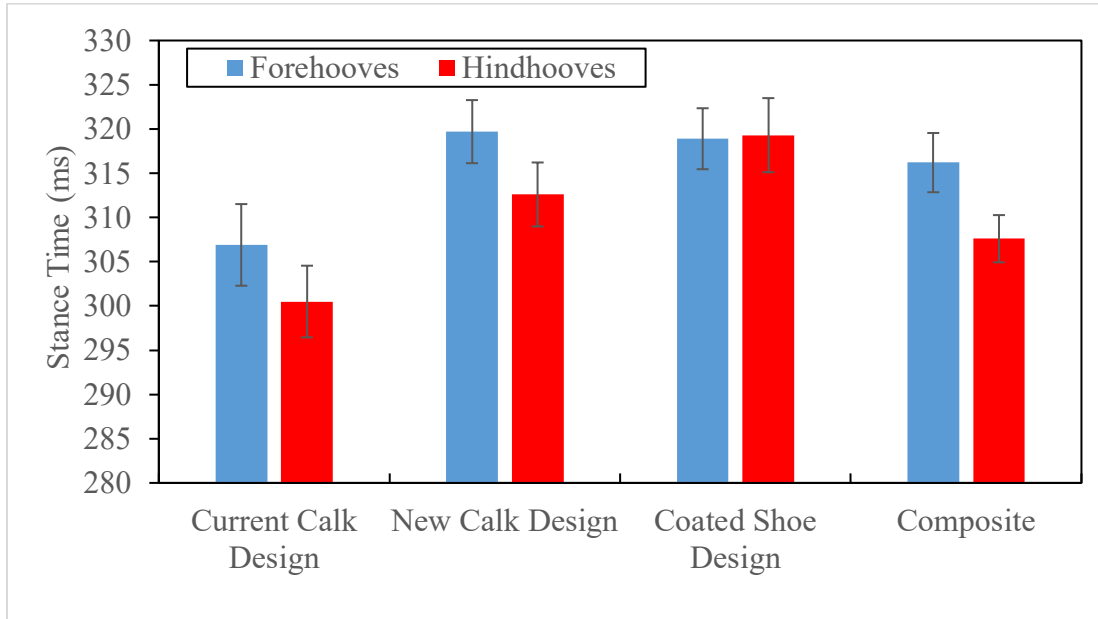ε_v: vertical strain obtained from response model

T: is the mixture temperature, °F.

Figure B.13 Stance time obtained for different horseshoes alternatives

Figure B.14 presents the computed service life of roads with heavy Amish buggy traffic when using different horseshoe alternatives. It is noticed that using horseshoes with current calk design will result in less than 3 years of road service life. In addition, the use of horseshoes with the new calk design, horseshoes with coated with tungsten carbide, or composite horseshoes will increase the service life to at least 39 years, which suggests that the roads will not fail of rutting developed from these horse traffic. It is worth noting that the previous laboratory experiment showed that horseshoes with coated with tungsten carbide and composite horseshoes did not cause any abrasion wear to mixtures; however, the new calk design reduced the abrasion wear but did not eliminate it. Therefore, horseshoes with new calk design will increase the service life by about 90%. In addition, the use of horseshoes coated with tungsten carbide or composite horseshoes will result in the increasing the service life of roads to similar with heavy Amish buggy traffic to be similar to those without any Amish buggy traffic.
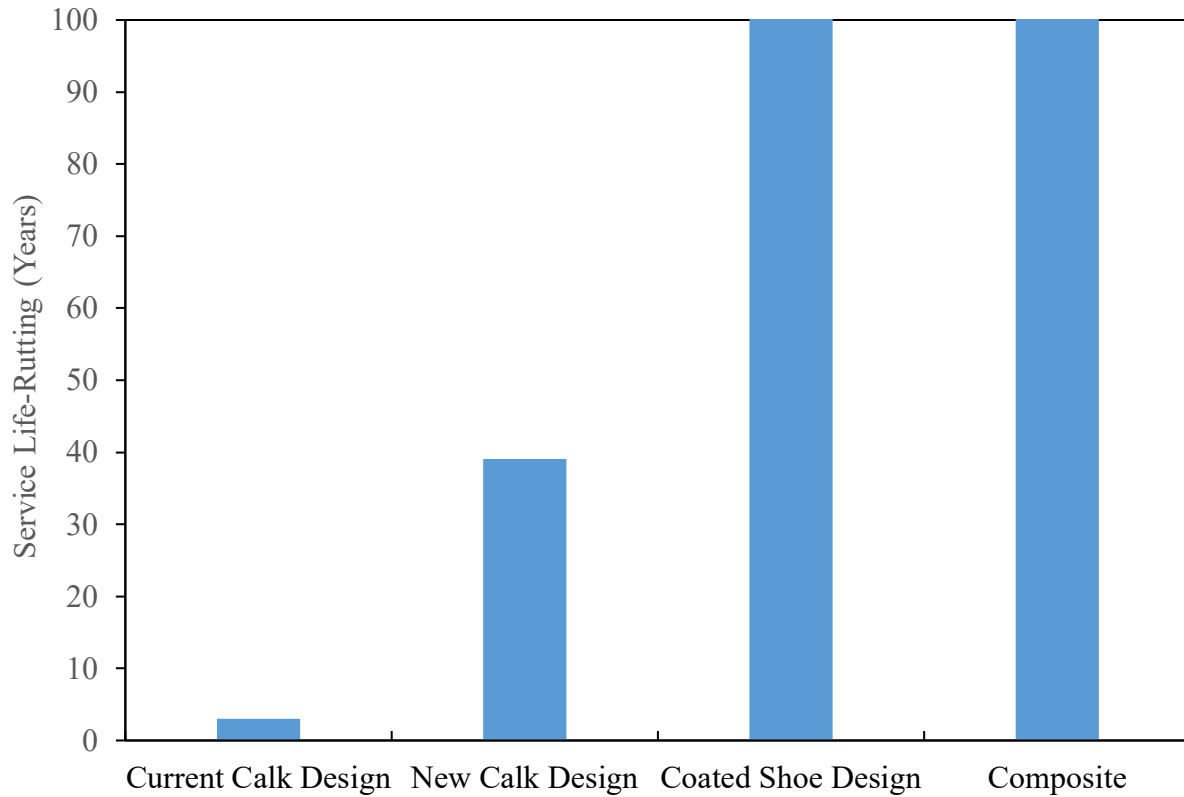
Figure B.14 Computed service life of roads when using different horseshoes alternatives

B.6 References

- Mirza, M.H., et al., Gait Changes Vary among Horses with Naturally Occurring Osteoarthritis Following Intra-articular Administration of Autologous Platelet-Rich Plasma. Front Vet Sci, 2016. **3**: p. 29.
- Stoffels, S. M., Bitonti, T. A., Gleason, G. L., & Bahia, H. (1995). Mitigation Of Horseshoe Damage To Pavements (No. FHWA/PA 95-0204).
- Taguchi, T., et al., Agmatine for Pain Management in Dogs With Coxofemoral Joint Osteoarthritis: A Pilot Study. Front Vet Sci, 2018. 5: p. 311.
- El-Basyouny, M. M., Witczak, M., & El-Badawy, S. (2005). Verification for the calibrated permanent deformation models for the 2002 design guide (with discussion). Journal of the Association of Asphalt Paving Technologists, 74.

Appendix C Cost Analyses

C.1 Cost Analysis of Partial Depth Repair

All available information on partial depth repairs for selected Amish buggy routes as well as several routes that do not have any Amish buggy traffic but had similar traffic volumes were obtained from Holmes County and Wayne County. Table C.1 shows the Amish and non-Amish routes that were selected. Life cycle cost analysis (LCCA) was performed to evaluate the cost of repairs on routes with and without Amish buggy traffic. The LCCA involved computing the Net Present Value (NPV) using Equation C.1. The NPV expresses all repair costs throughout the analysis period in the form of a single cost in terms of the present year monetary value. Equivalent Uniform Annual Costs (EUAC) of the all repairs of the Amish and non-Amish buggy routes were then determined based on NPV values using Equation C.2. It is noted that an analyses period of 12 years and a discount rate of 4% were used in this study. Figure C.1 and C.2 compares EUAC for Amish buggy routes and routes without Amish buggy traffic in Holmes County and Wayne County, respectively. The cost of partial depth repairs performed on routes with heavy Amish buggy traffic are about three times more expensive than those on routes without any Amish buggy traffic.

Table C.2 Cost repairs performed for non-Amish buggy routes

Project Road	County	Route
CR 77	Holmes	Amish
CR 400	Holmes	Non-Amish
CR 80	Wayne	Amish
CR 06	Wayne	Non-Amish
CR 48	Wayne	Non-Amish

$$EUAC = NPV\left[\frac{i(1+i)^n}{(1+i)^n - 1}\right] \tag{C.1}$$

$$NPV = \sum_{k=1}^{n}\left(PMC_k \frac{1}{(1+i)^k}\right) \tag{C.2}$$

Where
i: discount rate (4%)
k: year of expenditure
PMC_k: repair cost at year k
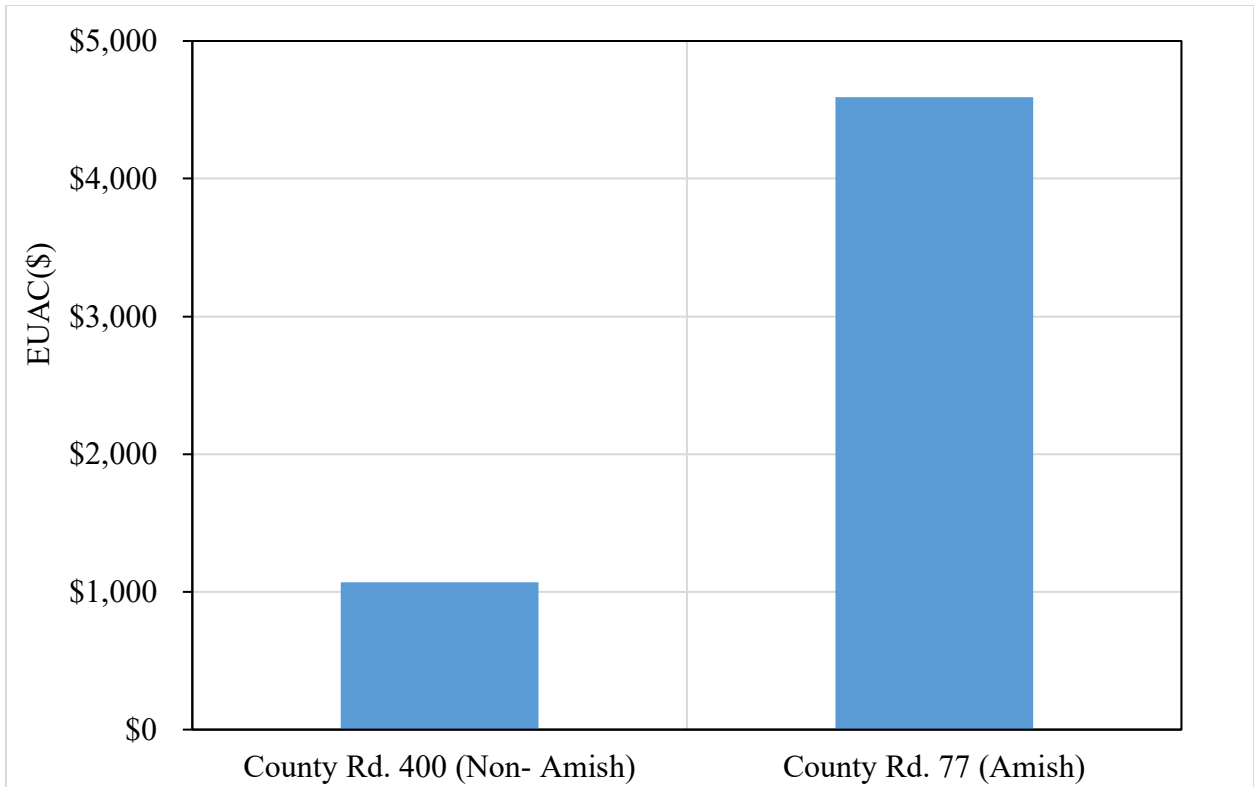n=analysis period (12 years)

Figure C.1 EUAC for Amish buggy routes and routes without Amish buggy traffic in Holmes County
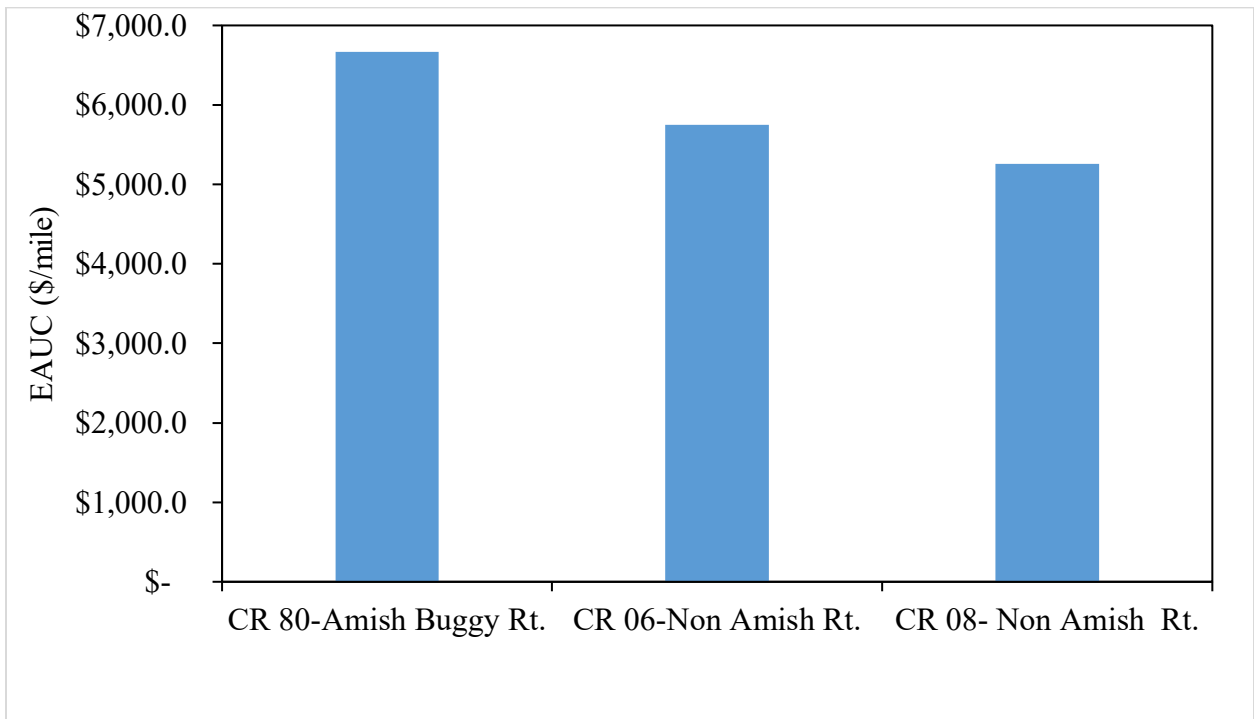

Figure C.2 EUAC for Amish buggy routes and routes without Amish buggy traffic in Wayne County

C.2 Cost Analyses of Horseshoes Alternatives

A comprehensive cost analyses were conducted to estimate the cost of the different horseshoe alternatives considered in this study. The cost analysis considered:

- ✓ The cost of shoes per shoeing period (6 weeks)
- ✓ The cost of horse
- ✓ The expected service life of horse
- ✓ The cost of pavement repairs due to the damage caused by the shoes.

Table C.1 presents the cost of shoes per shoeing period (6 weeks) and the total cost per year. It is noted that the while the horseshoes with the new calk design has similar cost to those with current calk design, horseshoes coated with tungsten carbide and the composite shoes have higher cost.

Table C.1 Costs of different horshoes per shoeing period

Shoe	6 weeks	One year
Current calk design	$30.00	$260.0
New calk design	$30.00	$260.0
Coated with tungsten carbide	$56.00*	$485.3
Composite	$60.00*	$520.0

* Cost if used/fabricated in large quantities

The average cost of a horse used for Amish buggies is $11,000. The average service life for horses used for Amish buggies is on average 10 years. According to the Amish farrier identified by Amish Steering committee, the use of shoes with new calk design will increase the service life by at least 50%. This might be related to the reduction in the stresses on the horse hoof and joints.

Based on that, the Equivalent Uniform Annual Cost was computed for the different cases using the following equation

$$EUAC = COST\left[\frac{i(1+i)^n}{(1+i)^n-1}\right]$$
(C.3)

where,
i: discount rate
n: service life

Horseshoe	Average Estimated Amish Buggy Horse Service Life (Years)
Current calk design	10
New calk design	15
Coated with tungsten carbide	17
Composite	19

Figure C.3 presents the computed equivalent uniform annual horse cost when using different horseshoes considered in this study. It is noted that using horseshoes with new calk design can result in reducing the annual horse costs by at least 20%. Furthermore, the use of horseshoes coated with tungsten carbide or composite shoes will result in reducing the annual horse cost by about 15%.
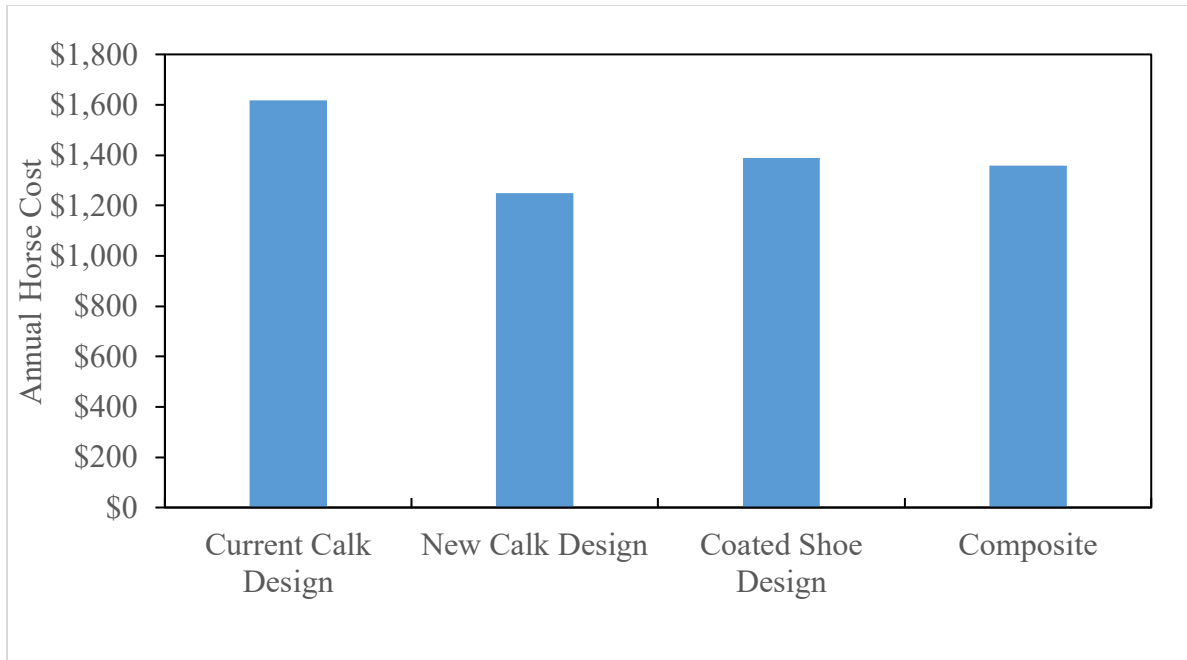
Figure C.3 Annual cost of horses when using different shoes

C.3 Cost of Road Repairs When using Different Horshoes

Based on the results of experiment do to quantify the damage of horseshoes to the roads as well as the stresses measure in experiments done at LSU, it was determined that using horseshoes with new calk design will increase the service life of Amish buggy routes by about 90% as compared to using horseshoes with current calk deign. In addition, the use horseshoes coated with tungsten carbide or composite horseshoes will result in the increasing the service life of roads with heavy Amish buggy traffic to be similar to those without any Amish buggy traffic. Based on that the estimated service life, the cost of repairing state and local roads with high Amish buggy traffic was computed when using different horseshoes. Figure C.4 presents the Equivalent Uniform Annual Cost (EUAC) for routes with heavy Amish buggy traffic when different horseshoes are used. It is clear that using horseshoes with new calk design, horseshoes coated with tungsten carbide, or composite shoes will significantly reduce the life cycle costs of costs Amish buggy routes. The cost ratio of Amish buggy routes with used the alternative horses relative to when current horseshoes design currently used was calculated using Equations C.2. Figure C.5 presents the computed values. It is noted that using horseshoes with new calk design can result in reducing the annual repair costs of Amish buggy routes by at least 40%. In addition, the use of horseshoes coated with tungsten carbide or composite shoes will result in reducing the annual repair cost of Amish buggy routes to be similar to those without any Amish buggy traffic.

$$\text{Cost Ratio} = \frac{\text{EUAC}_{\text{new horseshoe}}}{\text{EUAC}_{\text{current horeshoe}}} \tag{C.2}$$
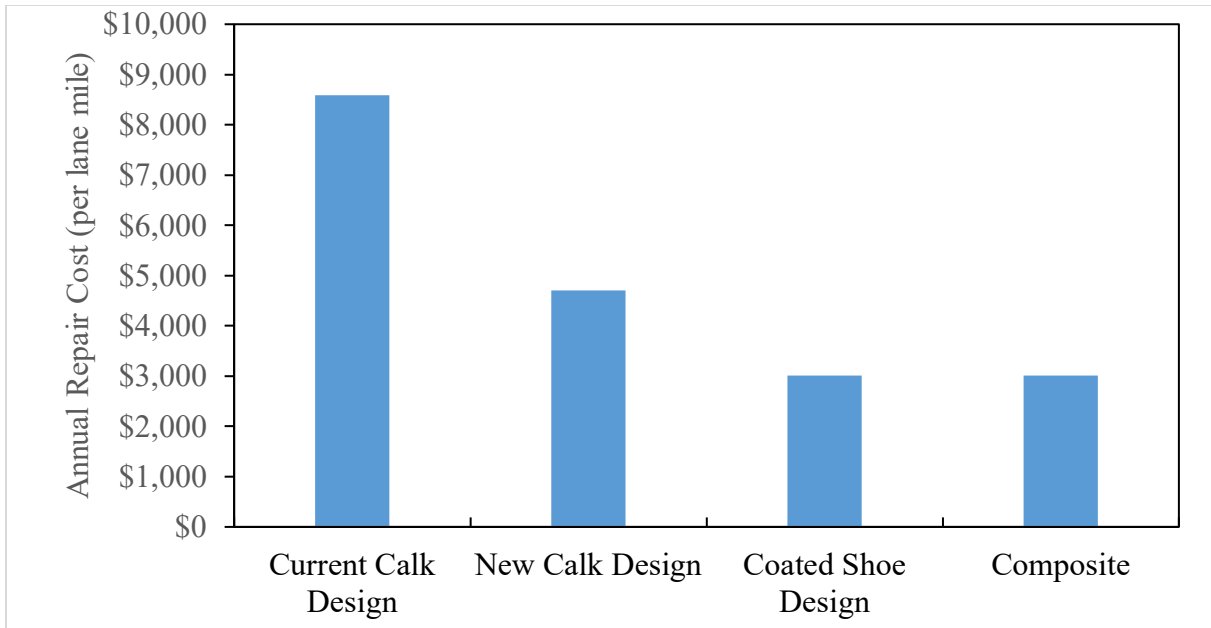
Figure C.4 EUAC for Amish buggy routes when using different horseshoes
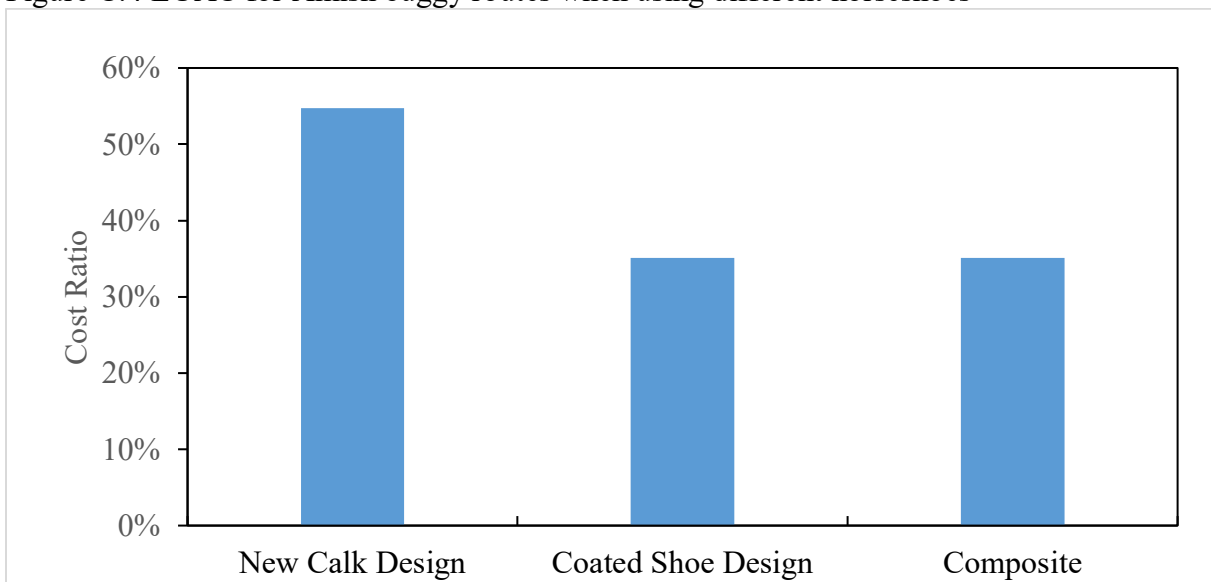

Figure C.5 Cost Ratio for Amish buggy routes when using different horseshoes