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

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16. Abstract

This report summarizes Phase 1 research work that was completed 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 horses and buggies to mitigate their damage to pavement structures. To achieve the first objective, a survey was conducted to collect information from ODOT county garages on partial depth repairs. The results of this survey indicated that partial depth repairs on routes with and without Amish buggy traffic involves milling the distressed area of the pavement to depth of 2 ½ to 3 inches and filling with 448 Type 1 surface course asphalt mix. Limited number of county garages and districts indicated that they monitored compaction during partial depth repair. The survey results also indicated that, in general, the service life of repairs on non-Amish routes ranged between 5 to 7 years, but repairs on Amish routes lasted 2 years only. However, partial depth repairs lasted about two years on routes with heavy Amish buggy traffic. Factors affecting performance for routes with Amish buggy traffic included: Amish buggy volume, grade of road, compaction efforts, mix type, and joint deterioration from buggy wheels in longitudinal joints.

Analysis of repair cycles for routes with or without buggy traffic was also performed in Phase 1. The results of this analysis indicated that the rutting was mainly in the surface layer(s) and was not due to deficiency in the pavement structure. Furthermore, aggregates in surface mixes within the top 2.5 inches were cracked, which was 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 about three times more expensive than those of routes without Amish buggy traffic.

Several alternatives were proposed 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 proposed alternative mixtures/method could reduce the life cycle costs of partial depth repairs on routes with heavy Amish buggy by up to 46%.

Literature review conducted in Phase 1 indicated that using alteranative horseshoes was expensive and won‘t signficantly 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 this phase, using screw-in studs that are made from hard polymer material and have larger contact area or horse boots might help to reduce pavement damage caused by Amish buggies. The Amish community representatives were receptive to trying the screw-in studs and horse boots and using them in the future if they are proven to be cost effective and are not rejected by their horses.

Based on the outcome of Phase 1 of this project, it is recommended that Phase 2 of this study should evaluate all of the identified alternative mixtures/method for partial depth repairs on Amish buggy routes as well as the proposed changes to Amish buggies.

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Executive Summary

This report summarizes Phase 1 research work that was completed 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 horses and buggies to mitigate their damage to pavement structures. To achieve the first objective, a survey was conducted to collect information from ODOT county garages on partial depth repairs. The results of this survey indicated that partial depth repairs on routes with and without Amish buggy traffic involves milling the distressed area of the pavement to depth of 2 ½ to 3 inches and filling with 448 Type 1 surface course asphalt mix. Limited number of county garages and districts indicated that they monitored compaction during partial depth repair. The survey results also indicated that, in general, the service life of repairs on non-Amish routes ranged between 5 to 7 years, but repairs on Amish routes lasted 2 years only. However, partial depth repairs lasted about two years on routes with heavy Amish buggy traffic. Factors affecting performance for routes with Amish buggy traffic included: Amish buggy volume, grade of road, compaction efforts, mix type, and joint deterioration from buggy wheels in longitudinal joints.

Analysis of repair cycles for routes with or without buggy traffic was also performed in Phase 1. The results of this analysis indicated that the rutting was mainly in the surface layer(s) and was not due to deficiency in the pavement structure. Furthermore, some of the aggregates in surface mixes within the top 2.5 inches were cracked, which was 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 about three times more expensive than those conducted on routes without Amish buggy traffic.

Several alternatives were proposed 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 repairs on Amish buggy routes and to monitor density of compacted mix. The LCCA analysis indicated that the proposed alternative mixtures/method could reduce the life cycle costs of partial depth repairs on routes with heavy Amish buggy by up to 46%.

Literature review conducted in Phase 1 indicated that using alteranative horseshoes was expensive and won‘t signficantly reduce the damage to the pavement since the horseshoes calks, or cleat like welds, are the main cause of damage to pavement structures. Based on information collected in this phase, using screw-in studs that are made from hard polymer materials and have larger contact area or horse boots might help to reduce pavement damage caused by Amish buggies. The Amish community representatives were receptive to trying the screw-in studs and

horse boots and using them in the future if they are proven to be cost effective and are not rejected by their horses.

Based on the outcome of Phase 1 of this project, it is recommended that Phase 2 of this study should evaluate all of the identified alternative mixtures/method for partial depth repairs on Amish buggy routes as well as the proposed changes to Amish buggies.

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 typically 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.

The calks, or cleat like welds, that are placed on the horseshoes to provide adequate traction for the horses are believed to be the main cause of pavement damage. The material that composes these calks is much harder than the aggregates and the binder material in the pavement. In addition, since the weight of the horse, combined with the load being pulled, is applied to the small contact area of the calks, the horseshoe calks induce very high stresses onto the surface of the pavement. The main type of damage that horseshoes cause in pavements is rutting. Under large volumes of buggy traffic, the rutting can be more than two inches deep and 18 inches to 24 inches wide. The rutting is typically located in the middle of the lane but when there are high motor vehicular volumes the rutting appears in the outside wheel path. This is due to Amish buggy drivers allowing extra room for passing vehicles. Rutting allows the pavement to be exposed to water for extended periods, which causes the binder to become weaker resulting in some cases in the development of potholes. The grinding and skidding action of the horseshoes against the pavement also causes scarring. This damage is similar to that induced by studded tires.

During the past decades, states department of transportation (DOTs) have evaluated and used different asphalt mixtures that are designed to provide high rutting resistance under highly stressed areas, which can be used in repairing of Amish buggy routes. Some DOTs (e.g. Pennsylvania DOT and Indiana DOT) used harder aggregates such as steel furnace slag in their repair mixtures to improve the resistance to rutting and damage caused by the horseshoes. In addition, some DOTs has also used modified aggregate structure in asphalt mixes to improve their rutting resistance under very high traffic stress. Other DOTs evaluated using special asphalt binders in their mixtures to provide the highest rutting resistance. The initial cost of these mixtures is high but their life cycle costs might be lower than those currently used to perform partial depth repairs on Amish buggy routes.

In addition to using improved repair methods and materials, alternative approaches concerning the horseshoes have also been considered to reduce pavement damage in Amish routed areas. Pennsylvania DOT evaluated alternative horseshoe materials and designs to reduce the stress transferred to the pavement. These included: 1- plastic horseshoes with metal interior cores, 2- composite horseshoe consisting of an aluminum base plate and a polyurethane replaceable sole, 3- steel horseshoe encased in a black rubber material, and 4- application of a steel plate to the horseshoe, then screwing a plastic sole onto the steel plate. Despite the potential benefits of using those alternative horseshoes, there is currently no data on their performance on a paved roadway. In addition, before applying any alternative, it is essential to select the one that is most likely to be adopted by the Amish community.

This project will 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. In addition, the cost-effectiveness of the identified alternatives will be evaluated. The main outcome of this project will be to develop a long-term and cost-effective solution for construction and maintenance of routes with heavy horse and buggy traffic. Thus, this project will help in extending the service life of pavements in Ohio and reducing their costs.

2. Research Context

The main objectives of Phase 1 of this project were to:

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.

Phase 1 of this study included conducting the following tasks to achieve the outlined objectives:

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

A summary of the comprehensive literature review performed in this study is presented in Appendix B. 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

The following subsections summarize the research approach that was followed in this study.

3.1 ODOT Current Practice For Partial Depth Repairs

A survey was developed to document ODOT current practices for partial depth repairs in roadways with and without Amish buggy traffic. The survey was sent to all ODOT county garages and Districts on September 30th, 2016. The survey (see Figure A.1) included a total of 19 questions, the first nine questions focused on the information for partial depth repair on the ODOT roadways in general, while the rest of the questions targeted those on routes with Amish buggy traffic. Reponses from at least three counties in each district was received. The information collected in survey included: partial depth repair procedures equipment, material information (type of mixture used), cost & service life of repairs, maximum width and length of repairs, factors affecting performance of repairs, quality control monitoring, any alternative horseshoes material and design used, and routes with heavy Amish buggy traffic.

3.2 Literature Review

The results of the comprehensive literature review that was conducted in this study showed that few studies were performed in the past decades to evaluate methods and materials that can enhance the performance of repairs performed on roads with Amish buggy traffic. Details of those studies are provided in Appendix B. Continuous paving method was the most cost effective method for repairs on roads with heavy buggy traffic (Hare, 1990). In addition, several studies reported that compaction was an important factor affecting performance under Amish buggy loading (Stoffels et al., 1995; Miller, 2015). Some studies also reported good repair performance when using special mixes (Hare, 1990, Heydorn, 2013). The steel furnace slag was used to protect against wear from horseshoes (Heydorn, 2013). Stoffels et al. (1995) also explored using alternative horseshoes materials and designs to mitigate the damage in roads with heavy buggy traffic. Their study concluded that that the use of alternative horseshoes can reduce pavement damage but won't eliminate it.

3.3 Analysis of Repair Cycles for Routes with or without Buggy Traffic

Analysis of repair cycles for routes with or without buggy traffic was performed. This analysis included examining full depth core samples that were obtained from different locations of repaired roadways with heavy Amish buggy traffic to determine the cause of the rutting problem in these roadways. Stress Analysis was also conducted using KENLAYER software to determine the distribution of stresses that develop within the pavement structure due to Amish buggy traffic.

All available information on partial depth repairs for Amish buggy routes as well as several routes that do not have Amish buggy traffic but had similar traffic volumes were also obtained from ODOT Holmes County garage. Based on the information provided, the repair cycle for routes with and without Amish buggy traffic was determined. The obtained information was also used in Life cycle cost analysis (LCCA) that was performed to evaluate the cost of repair done on Amish buggy routes and routes without Amish buggy traffic. The LCCA involved computing the Net Present Value (NPV) using Equation 1. The NPV express 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 was then determined based NPV value using Equation 2. It is noted that an analyses period of 12 years and a discount rate of 4% were used in the LCCA analysis.

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

$$EUAC = NPV \left[\frac{(1+i)^n}{(1+i)^n - 1} \right] \tag{2}$$

where,
IC: intial cost
i: dicount rate
k: year of expendtiture
PMC_k:repair cost at year k
n=analysis period

3.4 Evaluation of Alternatives

Based on the analyses conducted in this study, different alternatives were identified to improve the rutting resistance of mixes used in these repairs, which included: alternative mix design procedure, alternative asphalt binder, alternative aggregate structure, and alternative aggregate material. In addition, modifications for current repair method was recommended. LCCA analyses of repairs using alternative repair method/materials were conducted to evaluate their cost effectiveness. For each of the identified repair alternatives, the net benefit (ΔEUAC), as well as cost ratio relative to the methods/materials currently used by ODOT for partial depth repair of Amish Routes, was calculated using Equations 3 and 4, respectively. The ranking for the identified repair alternatives based on the net benefit and cost ratio was used to evaluate their cost effectiveness.

$$\Delta\mathrm{EUAC} = \mathrm{EUAC}_{\text{current repair method/material}} - \mathrm{EUAC}_{\text{new repair method/material}} \tag{3}$$

$$\text{Cost Ratio} = \frac{\mathrm{EUAC}_{\text{new repair method/material}}}{\mathrm{EUAC}_{\text{current repair method/material}}} \tag{4}$$

3.5 Alternative Horse Shoes

Literature and information available on the web were reviewed to identify changes to horseshoes materials/designs that can reduce the applied stress intensity and can be used by the Amish. The ODOT Holmes county garage organized a meeting with the Amish community representatives to discuss those changes.

4. Research Findings and Conclusions

Appendices A, B and C present a detailed summary of the survey, literature review, and analyses conducted in Phase 1 of this study, respectively. The main findings of this phase are:

- ODOT current practice for partial depth repair involves milling the distressed area of the pavement to depth of 2 ½-3 inches and filling with 448 Type 1 surface course mix asphalt. The same method and material are used for routes with and without Amish buggy traffic.
- Few ODOT county garages are monitoring compaction during partial depth repair.
- Service life for routes without Amish buggy traffic ranged from 5 to 7 years depending on the traffic volume.
- Service life for repairs on routes with heavy Amish buggy traffic was about 2 years.
- Factors affecting performance for routes with Amish buggy traffic included: Amish buggy volume, grade of road, compaction efforts, mix type, and joint deterioration from buggy wheels in longitudinal joints.
- The main distress in repairs on Amish buggy routes was rutting of the surface layer(s). Some of the aggregates in surface mixes within the top 2.5 inches were cracked, which resulted from the high stress intensity due to the Amish buggy traffic.
- The life cycle costs of 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 proposed 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.
- Proper compaction of asphalt mixtures during partial depth repairs is essential to ensure satisfactory field performance. Therefore, vibratory steel roller compactor should be used for compaction of asphalt mixtures in partial depth repairs and density should be monitored during compaction.
- The results of LCCA analysis indicated that the alternative repair mixtures/method were much more cost effective as compared to the traditional mixture currently being used in partial depth repairs on Amish buggy routes, assuming they will perform better in the field.
- Using screw-in studs that are made from hard polymer and have larger contact area as well as horse boots might be two good solutions that can help reduce pavement damage caused by Amish buggies. The Amish community were receptive to trying the screw-in studs and horse boots and using them in the future if they are proven to be cost effective and are not rejected by their horses.

5. Recommendations for Implementation

Based on the results of the Phase 1 of this study, it is recommended to:

I. Use the decision tree shown in Figure 1. Phase 2 should be conducted to determine the mixture with optimal performance to be used in partial depth repairs on routes with heavy Amish buggy traffic. This can be achieved by:

1- Conducting laboratory testing to evaluate the rutting resistance and durability of the following mixtures:

a. Mixtures designed using Superpave mix design procedure but using 100 gyration with PG 76-22 binder and limestone aggregate.
b. Mixtures designed using Superpave mix design procedure but using 100 gyration with PG 76-22 binder and steel slag aggregates.
c. Mixtures designed using Superpave mix design procedure but using 100 gyration with PG 88-22 binder and limestone aggregate.
d. Mixtures designed using Superpave mix design procedure but using 100 gyration with PG 76-22 binder and aggregate structure modified based on Bailey's method.
e. Mixtures designed using Airport mixes' design procedure
f. Mixtures designed using Airport mixes' design procedure with PG 88-22 binder.

2- Evaluating the three mixtures with highest rutting resistance in the field. This can be achieved by using those mixtures in partial depth repair field trials and monitoring the performance of these repairs.

II. Evaluate in Phase 2 the use of screw-in studs with traditional steel horses and horse boots to reduce the Amish buggy damage to the pavement structure.

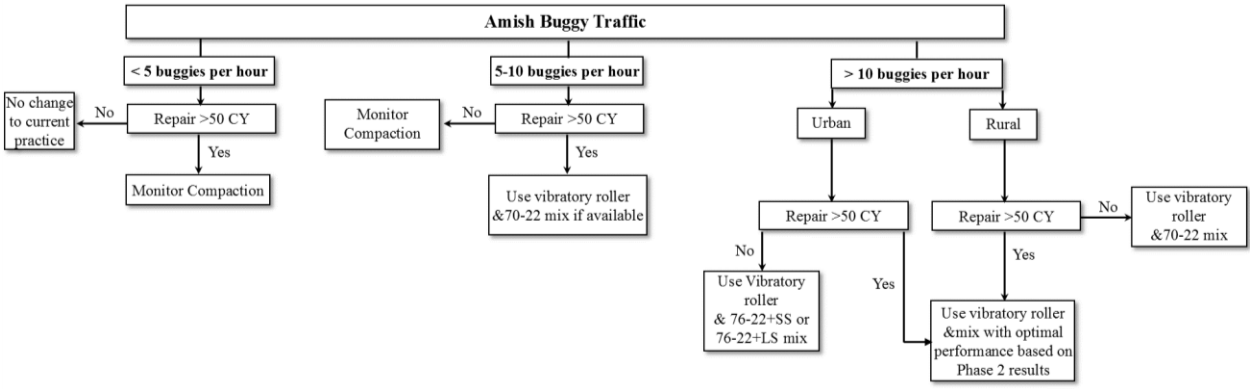

Figure 1. Proposed Decision Tree for Partial Depth Repairs on Amish Buggy Routes

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Appendix A Survey Results

Partial depth repair are a common procedure that are performed to preserve pavement in Ohio. In this study, a survey was conducted to document ODOT current practices for partial depth repairs in roadways with Amish buggy traffic and without. The survey was sent to all ODOT county garage managers on September 30th, 2016 and the recipients were given one week to respond. The survey included a total of 19 questions (see Figure A.1), the first nine questions focused on the information for repair on state routes in general, while the rest of the questions targeted those on routes with Amish buggy traffic. The information collected in the survey included: partial depth repair procedures equipment, material information (type of mixture used), cost & service life of repairs, maximum width and length of repairs, factors affecting performance of repairs, quality control monitoring, any alternative horseshoes material and design used, and routes with heavy Amish buggy traffic.

The survey information obtained from the county garages were analyzed and compiled for each ODOT District. Table A.1 presents the information obtained for partial depth repairs performed on state routes in general. County garages in different districts have similar practice for partial depth repair which involves milling the distressed area of the pavement to depth of 2 ½-3 inches and fill with 448 Type 1 surface course mix asphalt. A traditional milling machine is used for milling. While a paver is used by subcontractors for filling, a widening box is used for filling when repairs are done by the county garage. The majority of counties indicated that they do not monitor density of compacted mixes during partial depth repair. County garages indicated that the service life of partial depth repairs on state routes without any Amish buggy traffic depends on traffic: for routes with high traffic volume it was 3 to 4 years, for medium traffic routes it was 4 to 5 years and for routes with low traffic volumes it was typically 5 to 7 years, but can last up to 10 years. The main factors affecting performance identified by the survey responders included: traffic type and volume, repair efforts, pavement structure below repair, base course type, drainage conditions, and compaction.

Table A.2 presents a summary of the responses obtained for the survey question on partial depth repairs performed on Amish buggy routes. Table A.3 summarizes those obtained from counties that have routes with heavy Amish buggy traffic. In general, the same method, equipment and materials are used for Amish buggy routes as those without; except that additional grinding is done to smooth the road profile. However, the service life for partial depth repairs on Amish buggy routes is only two years, which is much shorter than routes without Amish buggy traffic, which was about 2 years. As indicated in Tables A.2 and A.3, Stone Matrix Asphalt (SMA) mixes have been used in resurfacing projects only, but seems to have similar or worse performance as compared to traditional Superpave mixes. Item 442 is typically used on some routes with heavy Amish buggy traffic. The survey responders identified several factors affecting partial depth repair performance, which included: Amish buggy volume, grade of road, compaction efforts, mix type, and joint deterioration from buggy wheels in longitudinal joints. The survey of ODOT counties garages indicated that there have not been any planned compromises with the Amish community on this issue. In addition, they have not considered changing the type and make of the horseshoes and buggy wheels.

Survey Questions

1. What are your current practices for partial depth repairs on asphalt pavements? Please list any special method/equipment used.
2. Are partial depth repairs on asphalt pavements done in house or subcontracted?
3. What types of asphalt mix have been used for partial depth repairs on asphalt pavements? Please provide ODOT specification for each mix type used as well as the binder and aggregate typically used in the mix.
4. What is the maximum width and length of partial depth repairs you have performed?
5. How long do partial depth repairs on asphalt pavements typically last? If this depends on traffic please provide approximate service life for low, medium, heavy traffic roads.
6. What are the main factors affecting performance and service life of partial depth repairs performed on asphalt pavements?
7. Do you monitor compaction in partial depth repairs on asphalt pavements?
8. What is the typical cost of partial depth repairs on asphalt pavements?
9. Do you have Amish buggy routes on which you perform partial depth repairs? If yes, please provide a list of all Amish buggy routes; please indicate whether Amish buggy traffic is low, medium or high for each route.

If your answer to Question 9 was NO please skip to the rest of the questions.

10. What are your current practices for partial depth repairs performed on Amish buggy routes? Please list any special method/equipment used for Amish buggy routes partial depth repairs.
11. What type of mix is generally used for partial depth repairs on Amish buggy route? Please provide ODOT specification for each mix type used as well as the aggregate and binder typically used in the mix.
12. How long do partial depth repairs performed on Amish buggy routes last? If this depends on buggy traffic please provide approximate service life for low, medium, heavy buggy traffic routes.
13. What are the main factors affecting performance and service life of partial depth repairs performed on Amish buggy routes?
14. Have you used stone matrix asphalt (SMA) mix for any of your Amish buggy routes? If yes, did SMA mixes have better performance and service life than other mixes used for Amish buggy routes?
15. Have there been any substantial problems with the partial depth repairs on Amish buggy routes?
16. Currently, what efforts have been made to reduce the pavement damage due to Amish buggy traffic?
17. Have you considered changing the type and make of the horseshoes and buggy wheels?
18. Have there been any planned compromises with the Amish community on this issue?
19. Do you have any performance and/or cost data for partial depth repairs performed on Amish buggy routes?

Figure A.1. Survey Questions

Table A.1. Summary of Survey Response to Questions on Partial Depth repairs

Dist.	Current Repair Methods/ Equipment	In House or Subcontracted?	Mixture	Max. Width &Length	Service Life	Factors Affecting Performance &Service Life	Compaction Monitored?	Cost of Repair	Amish Routes?
1	Mill 2.5-3" using Widening Box	Subcontracted, ODOT owns milling machine	448 Type 1 Surface Course	4' Wide	High traffic: 2-3 yr., Med.: 3-4 yr., Light: 4-5 yr.	traffic volume & load; Base type	No	$160/ton	No
2	Mill and Fill, wedging with grader	In House	448 Type 1 Surface Course	14' by 1,000'	high: 4 yr., medium: 5 yr., light: 7 yr.	Amount of farm equipment	Yes, randomly tested	$120/ton	No
3	Mill and Fill with grinder on skid steerer	Mostly in house, sometimes contracted	448 Type 1 Surface Course	4' by 1,600'	high:3-5 yr., med: 5 yr. light:7yr	compaction, subsurface drainage, proper joint sealing	No	$125-$150/ton	Yes
4	Mill and Fill with paver or widening box and skid steer	Both	448 Type 1 Surface Course	12' by 1,000'	3-4 yr.	Slot preparation, compaction	No	Varies	Yes
5	Mill and Fill with milling mach.	In House	448 Type 1 Surface Course	12' by 500'	5-10 yr.	traffic volume & load	Some counties do.	$78 to $200/ton	Yes
6	Mill and Fill using Milling Machine, Tack Truck, Paver and Roller	Both, District 6 uses about 6,000 tons of in house asphalt and the rest is contracted out	448 Type 1 Medium	12' by 250', maximum 120 tons by force account	5+ yr	Traffic, Subgrade quality, repair quality	No	$65/ton for materials only	Yes
7	Mill and Fill	In House	441 Type 1 Surface Course	14' by 800'	High: 3-4 yr, med.:3-5 yr., light: 5-7 yr.	traffic volume & load, winter seasons	Some counties do.	$18,000 per lane mile	No

Dist.	Current Repair Methods/ Equipment	In House or Subcontracted?	Mixture	Max. Width &Length	Service Life	Factors Affecting Performance &Service Life	Compaction Monitored?	Cost of Repair	Amish Routes?
8	Mill 3" and fill with skid steerer 24" planer	Both	448 Type 1 Surface Course	6' by 350'	3-4 yr.	weather, heavy equipment loads	No	N/A	No
9	Mill 1.5- 3" and fill with box attached to skid steerer or grader	In House	448 Type 1 Surface Course	40" width,	2-4 yr.	compaction efforts, traffic volume & load	No	$141/ton	Yes
10	Slot mill and fill with milling machine and paver	Both	441 Type 1 and 2	12' by 500'	As an overlay	roadway and shoulder width, pavement below repairs, drainage and compaction	No	$235/cu.y ard	Yes
11	Mill 2" with sweep and tack before replacement with a box attachment	Both	448 Type 1 Surface Course	42" by 600'	4-7 yr.	base course	No	$183/ton but varies significant ly	Yes
12	Remove with jack hammers and track hoes, clean and add surface mix	In House	404,442 and 448	N/A	3-5 yr.	traffic volume, longitudinal joint repairs s	No	$900 per repair	No

Table A.2 Summary of Survey Response to Questions on Partial Depth Repairs on Amish Buggy Routes

Dist.	Current Repair Methods	Service Life	Mixture	Factors Affecting Performance	SMA Used?	Problems with Repairs	Efforts Made to Reduce Damage	Changes of Horseshoe Considered?
3	Drag Paver in buggy lanes	High:2yr, other: 4-5 yr.	448 Type 1	Joint deterioration from buggy wheels in longitudinal joints	Yes	Yes	Drag Paving	No
4	Same as non-Amish routes	depends on buggy traffic	448 Type 1	pavement conditions outside of repairs and location of repairs	Yes	Not substantial	More frequent repairs	No
5	Mill &Fill with Durapatcher	3-4 yr.	448 Type 1	buggy volume	No	No	Yes	No
9	Same as non-Amish repairs	2-4 yr.	448 Type 1	Buggy wheels cracking the aggregate, water damage	No	No	No	No
10	Same as non-Amish routes		441 Type 1 and 2	Density and material selection	No	Yes, little	Used 442 mix in overlay	Yes (internally)
11	Same, except grinding done to smooth road profile	high: 3 yr. medium: 4- 5 yr.; low: 6+yr.	448 Type 1	buggy volume, grade of road, compaction efforts and mix design	Yes	Yes	This study	No
12	Skid steerer with milling attachment	1-2 years	301 agg. Size #4	Traffic, weather	No	No	Utilizing PCR to determine repairs	No

Table A.3 Summary of Survey Responses from Counties that has Routes with Medium/ Heavy Amish Buggy Traffic

County	D	Specific Routes	Service Life	Mixture	Factors Affecting Performance	SMA Used?	Problems with Repairs	Efforts Made to Reduce Damage	Changes of Horseshoe Considered?
Wayne	3	US 250, SR 241 , SR 94, SR 301	For heavy traffic drag paving, 2 years. For Mill and paver, 4-5 years.	448 Type 1 Medium	Sub base quality and buggy traffic	Yes, US 250 used SMA but it did not last as long.	The joint between the existing pavement and repairs ravels out due to buggy wheel riding in the joint	Frequent repairs, drag paving	No
Ashtabula	4	They have not done any partial depth repairs in these areas							
Trumbull and Stark	4	n/a	Varies based on buggy traffic, materials and current pavement conditions.	448 surface mixes, either limestone or gravel aggregate using medium traffic design	The condition of the pavement before the repairs. Repairs do not last as long when they are done near the edge of a longitudinal joint.	Yes for a resurfacing project. Not for patching.	No	Properly maintain repairs	No
Licking	5	SR 586 (Medium Buggy Trafic)	3-4 Years for Medium Traffic	448 Type 1 Medium	Rutting from horseshoes	No	No	Future resurfacing techniques are being discussed	No
Morrow	6	Rt. 314 (Medium)	5+ years	448 Type 1	Buggy traffic and wheel type	No	n/a	n/a	n/a

Appendix B Literature Review

Ohio has the largest Amish population in the nation. Traditional Amish means of travel consists of a steel wheeled buggy pulled by horses. Although the most significant pavement damage is caused by motor vehicle stresses, horse and buggy travel has proven to show costly damage to asphalt pavements. It was commonly thought that the buggy wheel was the main cause for damaging pavements, since it is a rigid wheel with a small contact area. However, the findings of previous studies indicated that horseshoes (Figure B.1) are the cause damage (Stoffels et al.,1995; Hare, 1990). Particularly, the calks, or cleat like welds, that are typically placed by the Amish on the horseshoes to provide adequate traction for their horses. These calks vary from one region to another and also depend on the personal preference of local blacksmiths within those regions. Some calks are more damaging than others, but the cause of damage is the same regardless of the design of the calks. The material that composes these calks is a much harder than the aggregates and the binder in asphalt mixtures. Furthermore, the calks have a small contact area with the pavement, resulting in high stresses that cause rutting. In some cases, the stresses are high enough to fracture the aggregates in the asphalt mixtures. When horse and buggies travel on high roadway grades, the calks of the horseshoe drive harder into the pavement to counteract the large driving weight of the combined horse and buggy. This adds additional stresses to the pavement and create many potential problems such as scarring and rutting. These problems typically occur at the right center of the travel lane, since this is where the buggies typically travel, which can be very hazardous for two-wheeled vehicles. This is also a cause of vehicles to get drawn into this rut outside of the typical wheel path (Hare, 1990). From the study reported by Hare (1990), a significant amount of surface material was lost right after construction from certain test sections opened from the chiseling action of the calked horseshoes on the new pavement.

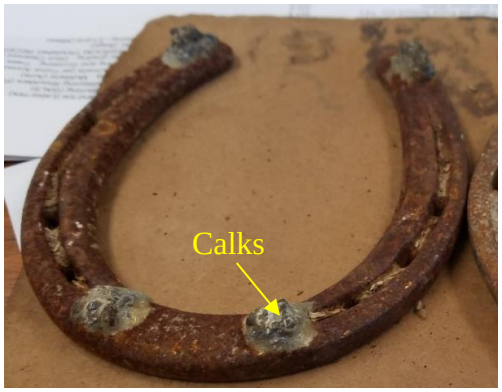

Figure B.1. Horseshoes Typically Used by the Amish

B.1 Alternative Repair Methods and Materials

Few studies have been conducted during the past decades to evaluate different techniques and materials that can enhance the performance of repairs performed on roads with Amish buggy traffic. Stoffels et al. (1995) reported the results of a study funded by the Pennsylvania DOT that included evaluating three methods for repairing Amish buggy routes: continuous paving repair, spot patching repair, and horsetrack chip seal. The continuous paving repair method used a drag box to spread asphalt into a 3 foot wide rutting strip in the road from the horse track path. 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. Stoffels et al. (1995) conducted a life cycle cost analysis to evaluate the cost-effectiveness of the considered methods. The results of this analysis indicated that the continuous paving repair method was the most cost effective method when used on roads with heavy buggy traffic. The spot patching repair method was cost effective when used on moderate traffic roads. The chip seal method had the lowest initial cost but was not recommended due to the excessive loss of aggregate under heavy buggy traffic. Finally, this study also suggested that transferring the buggy traffic to a gravel buggy lane had the best potential savings.

Hare (1990) evaluated four different repair methods and materials on roadways with heavy buggy traffic. The first method involved milling the rutted area of the pavement then placing an ID-2 special blend mix. The second method included the placement of Ralumac, which is a cold-applied overlay material containing latex-modified emulsion, on rutted areas without milling. The third method involved placement of a full width overlay using a wearing course mix with 100 percent steel slag aggregate. Finally, an ID-2 fine binder mix was used to repair the rutting. The performance of these mixes was monitored for 5 years. Based on the results of this study, the first method that used ID-2 special blend was found to have best performance but it was the most expensive. This ID-2 special blend mix is a wearing course of laytex-modified cold emulsion binder that is placed as a surface, or topcoat, on a binder course. This emulsified binder fills the pores of the exposed surface and creates a homogeneous, smooth surface. The mixture has a nominal aggregate size of ½" with a lower binder content. No other information on this mixture was provided in Hare (1990) report.

Recently, the Indiana DOT used steel furnace slag in an asphalt mixture overlay to repair two miles of Indiana State Route 5 that had 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).

In 2014, the Missouri DOT implemented an innovative approach called scratch and seal to repair Amish buggy routes on low volume roads (Miller, 2015). This approach involved using two different processes in the same repair project. The first included applying a leveling (scratch) course of a PG 64-22 asphalt mix with only a 0.25 inch thickness to correct any rutting or cracks in existing pavement. The second process is performed after 10 days and consists of applying a high-quality limestone chip seal. This technique was found to be very effective when used on Amish routes on low-volume roads with significant pavement damage and was much more economical than a typical course repair project (Miller, 2015). Aggregates with sizes larger than the lift thickness may not be fully coated with the binder as part of the chip seal operation, which may create potential problems.

Another important property that must be carefully monitored during partial depth repairs and paving on Amish routes is in-field compaction. When improperly compacted, the pavement will have decreased stiffness that accelerates aging, reduces durability and increases rutting. Compaction reduces the amount of air voids in the mix from placement and increases the density

of the mix, which in turn decreases the amount of future potential densification of the mix causing rutting (Heydorn, 2013). Using proper vibratory equipment and compacting while the mix is hot, roughly 275°F to 300°F, are considered two of the most important compaction controlling parameters when the mix is placed (Sherocman, 2013). According to Sherocman (2013), the mix will contain about 20% air voids in the screed and 30% air void directly after leaving the paver. If the mix is properly compacted, there will be an approximate 8% reduction of air voids to acquire closer density requirements (Sherocman, 2013). The optimal consideration comes in when the line between good mix densification and not as compacted mats is crossed, because a higher density means more material for the same volume of road for the contractors, which is not as efficient as a less densely placed mix. This is a primary reason for setting density requirements in the field. For a pavement to show good rutting performance, compaction should be monitored at the time of placement (Sherocman, 2013).

B.2 Alternative HorseShoes Materials and Designs

Some studies have also explored using alternative horseshoes materials and design to mitigate the damage in roads with heavy buggy traffic. Softer horseshoes will induce lower stresses to the underlying pavement from the horse loads. 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. Some horseshoes have been constructed using recycled scrap tire rubber. This study also investigated various synthetic horseshoes. The first was the Slypner Athletic shoe. This 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. The Unishoe, Inc. Horseshoe is similar to the Slypner shoe, except the plastic sole needs to be bolted to the base plate and metal studs can be attached to the shoe to provide traction in winter months. Some alternative horseshoes use aluminum material as part of the composition. The Perfect Stride Horseshoe inserts a thin aluminum separation plate between the hoof and the plastic sole that comes in three separate pieces, providing a uniform, flexible surface to integrate the aluminum and plastic through stress transitions. This is a luxury when needing to trim the horse, as the composition can easily be detached and reused. The mechanism is very interchangeable and adaptive to the environmental conditions. Some shoes such as the Mustad "Nail-Shu" Horseshoe uses an aluminum shoe coated in polyurethane to provide high shock absorption and longer wearing life. The last alternative horseshoe discussed in this study was the Z&G Roaring Spring Horseshoe, which is steel horseshoe encased in a black rubber material. This is a harder shoe than most alternatives but does not require detailed installation and has a lifespan of about 4 to 5 weeks. Stoffels et al. (1995) conducted a cost analysis to compare the different horseshoes alternatives. Based on the results, the Slypner Athletic shoes were the most cost effective and the Z&G Roaring Spring shoes were the least. Finally, Stoffels et al. (1995) indicated that all alternative shoes might reduce the pavement damage but it won't eliminate it.

Stoffels et al. (1995) evaluated using horseshoes without calks as well as horseshoes with calks made from Borium, Drillex, E.M.E CW and E-Bor. This was done by mounting the horseshoes on a wheel and driving it over a pavement structure. The total volume of pavement damage was recorded for each horseshoes/cleat type. The results of that study showed that

horseshoes without cleats had the minimal damage, followed by those with E.M.E CW, E-Bor, Borium and Drillex calks.

In summary, some new methods and special asphalt mixtures have been used and evaluated to repair Amish buggy routes in different states. In addition, the use of alternative horseshoes materials and designs was also investigated to reduce the stress intensity on pavement structures. However, the performance of these horseshoes on a paved roadway has not yet been examined.

Appendix C Analyses of Partial Depth Repairs on Amish Buggy Routes

C.1 Evaluation Of Repairs On Amish Buggy Routes

The partial depth repairs that were performed on Amish buggy routes in Holmes County during the past three years were evaluated. Pictures were taken during the evaluation to document and record distresses in these repairs. Figure C.1 shows some of the pictures taken during the evaluation. It is noted that the main distress in those repairs was rutting. Rutting results from densification and plastic movement in the repaired surface mixture as well as in underlying existing pavement layers and subgrade soil. Therefore, full depth core samples were obtained from different locations of repaired roadways with heavy Amish buggy traffic to determine the cause of the rutting problem in these roadways. Figure C.2 presents pictures that were taken of some of the obtained core samples. By examining the obtained core samples, it was found that the rutting was mainly in the surface layer(s) and was not due to deficiency in the underlying pavement structure or subgrade soil. In addition, as can be noticed in Figure C.2, there is a clear evidence that the some aggregates within depth of 1.75 inch to 2.5 inch from surface were cracked.

Analysis was conducted using KENLAYER software to determine the distribution of stresses that develop within the pavement structure due to the Amish buggy traffic. In this analysis, it was assumed that the standard horse weighs 1,000 pounds and that the horse is pulling a 1,000 pound buggy behind it up a road with a 10% grade. The contact area between the horse and pavement surface used in this analysis was 2.17 in^2, which was the computed area of calks (or cleats) that are typically welded on the horseshoes to provide adequate traction. The analysis was performed on a pavement structure consisting of asphalt concrete layers with a total thickness of 8 inches and a granular base layer 6 inches thick. The main materials properties used in this analysis are summarized Table C.1. Stress analysis was also performed to determine the stress distribution that develops from an 18 kip Equivalent single axle wheel loads (ESAL), which is the standard axle wheel load used in designing pavements. Figure C.3 shows the vertical stress distribution with depth due to loading from Amish Buggy as well as from an 18-kip ESAL. It is clear that the vertical stresses at the pavement surface layers from the Amish buggy loads are more 160% greater than those from the 18-kip ESAL. The stresses from Amish buggy are much higher than those from 18-ESAL within the top 2.5 inches, but it becomes lower below that depth. This result may explain the previous observation that the rutting in Amish buggy routes occur due to permanent deformation in the surface asphalt layer.

C.2 Cost Analysis of Partial Depth Repair

All available information on partial depth repairs for Amish buggy routes as well as several routes that do not have any Amish buggy traffic but had similar traffic volumes were obtained from ODOT Holmes County garage. Based on the information provided, it was determined that routes with heavy Amish buggy traffic have been repaired about four times in the 12 years' service period, while routes without any Amish buggy traffic have been repaired, on average, every six years. All available costs of repairs that were conducted by ODOT Holmes county garage on Amish and no-Amish buggy routes were obtained. Tables C.2 and C.3 presents a summary of obtained repair costs. To normalize the obtained cost, the total costs were divided by the repaired roadway miles in each job to obtain the cost per mile.

Figure C.1 Pictures of Damage in partial depth repair on Amish Buggy Routes

Figure C.2 Pictures of Cores Obtained from the Repairs on Amish Buggy Routes

Table C.1: Structural Composition of Roadway used in KENPAVE Analysis

Layer	Thickness (in)	Modulus of Elasticity (psi)	Poisson's Ratio
Asphalt Concrete	8	500,000	0.35
Base Course	6	40,000	0.35
Subgrade	-	8,500	0.35

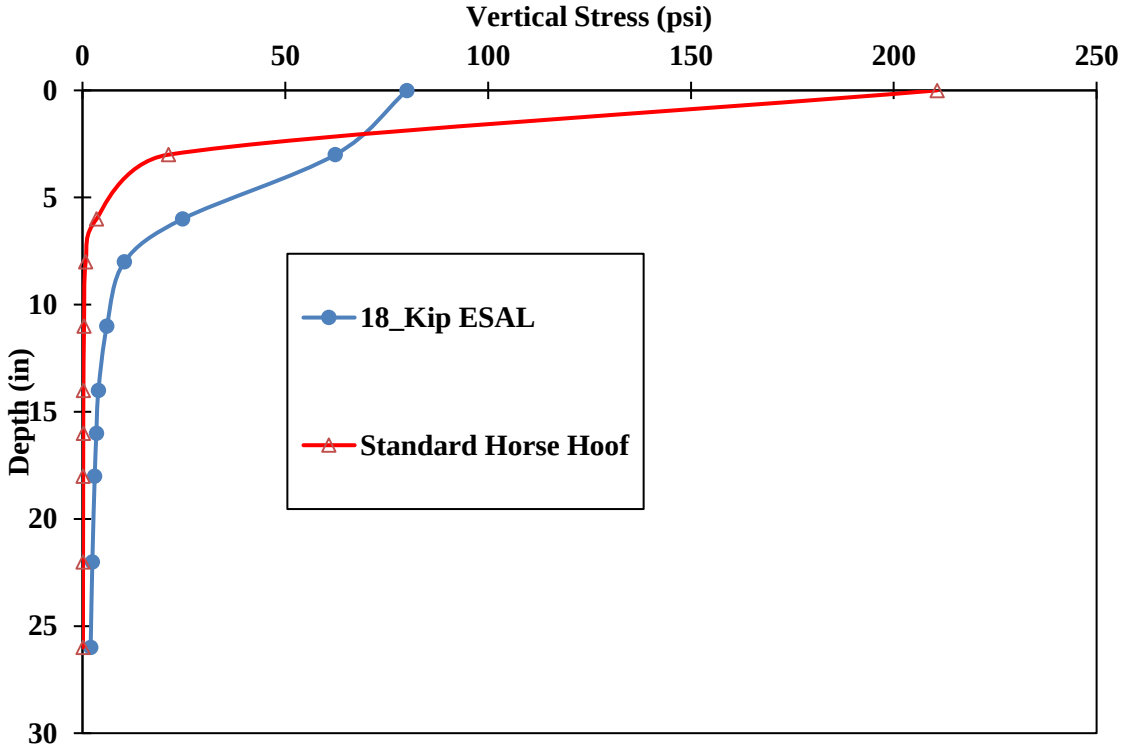

Figure C.3 Vertical Stress Distribution

Table C.2 Cost Repairs Performed for Non-Amish Buggy Routes

Project Road	Equipment Total Cost	Material Total Cost	Labor Total Cost	Total cost	Cost/mile
SR 39	$16,591.3	$16,920.7	$48,763.1	$82,275.1	$13,712.5
SR 60	$2,283.9	$2,608.2	$6,650.9	$11,543.0	$1,846.9
SR 60	$4,399.5	$3,822.7	$10,980.1	$19,202.3	$5,486.4
US 62	$8,781.1	$6,665.5	$17,351.3	$32,797.9	$14,576.9
US 62	$26,905.9	$36,141.2	$44,042.8	$107,089.9	$21,418.0
US 62	$20,918.5	$44,432.1	$42,753.9	$108,104.5	$54,052.3
US 62	$15,793.3	$28,487.1	$32,636.7	$76,917.0	$18,445.3
SR 179	$ 26,581.3	$39,060.1	$ 55,563.7	$ 121,205.0	$ 30,301.3
Average	$15,281.85	$22,267.19	$32,342.82	$69,891.87	**$19,979.93**

Table C.3: Cost Repairs Performed for Amish Buggy Routes

Project Road	Equipment Total Cost	Material Total Cost	Labor Total Cost	Total cost	Cost/mile
SR 241	$ 2,587.9	$ 3,757.2	$ 8,074.4	$ 14,419.6	$ 48,065.2
SR 241	$ 4,892.0	$16,392.6	$ 10,921.4	$ 32,206.0	$ 27,526.5
SR 241	$ 4,796.9	$12,244.1	$ 9,495.3	$ 26,536.3	$ 22,113.6
SR 241	$ 2,348.8	$ 4,049.9	$ 5,670.3	$ 12,068.9	$ 26,819.7
SR 557	$ 10,362.0	$22,301.7	$ 15,793.1	$ 48,456.8	$ 17,947.0
SR 557	$ 7,646.9	$28,466.4	$ 22,586.6	$ 58,699.8	$ 13,651.1
SR 643	$ 5,880.0	$12,019.5	$ 13,612.7	$ 31,512.2	$ 31,512.2
Average	$ 5,502.1	$14,175.9	$ 12,307.7	$ 31,985.7	**$ 26,805.0**

The average cost per mile was computed for Amish and non-Amish buggy routes. It is clear that the average cost of partial depth repairs in Amish buggy routes was higher than those for routes without Amish buggy traffic. This mainly attributed to the much larger repaired areas per mile in Amish buggy routes, which required higher quantity of asphalt mixture to be used in the repair.

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 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 2. It is noted that an analyses period of 12 years and a discount rate of 4% were used in this study. Figure C.4 compares EUAC for Amish buggy routes and routes without Amish buggy traffic. 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.

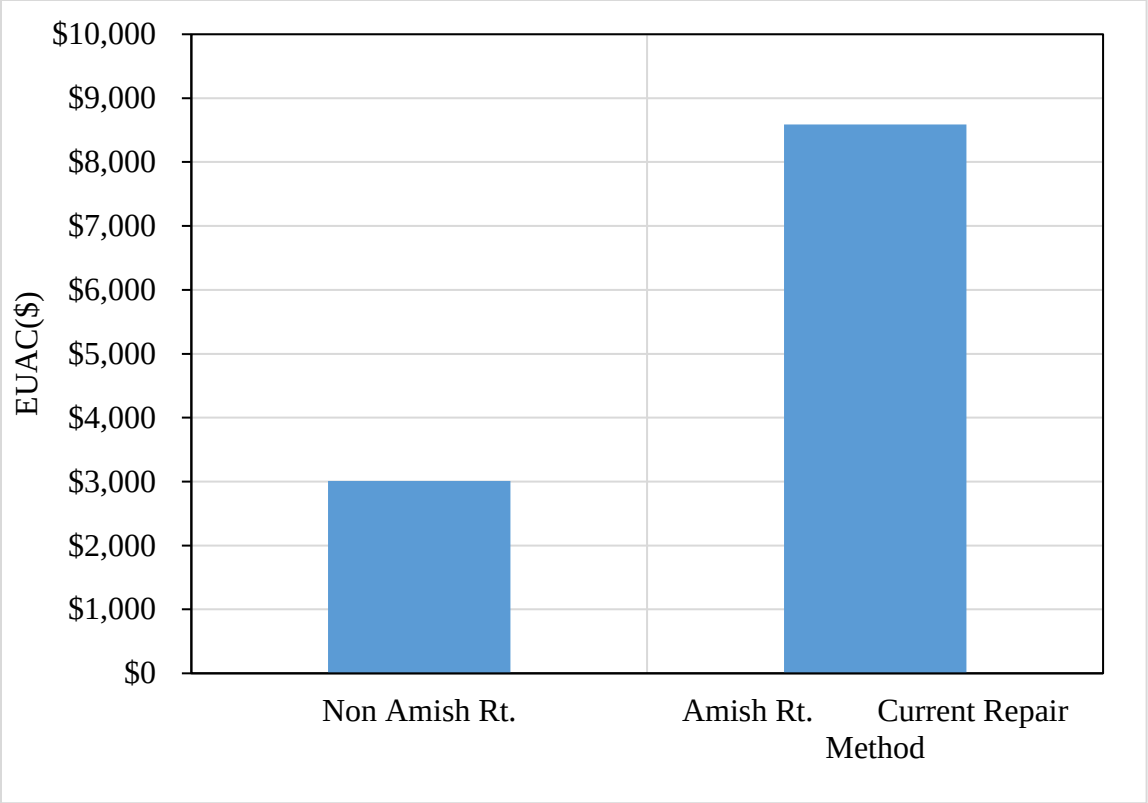

Figure C.4 EUAC For Routes With And Without Amish Buggy Traffic

C.3 Alternative Materials/Methods

The results of the analyses conducted in this study indicated that the main problem in partial depth repair on Amish buggy routes is due in rutting in the surface asphalt layer. Therefore, the mixtures that have been used in resurfacing and repair of those routes were obtained and evaluated. Based on that, different alternatives were identified and evaluated to improve the rutting resistance of mixes used in these repairs, which included:

- Alternative mix design procedure
- Alternative asphalt binder
- Alternative aggregate structure
- Alternative aggregate material

The following sections provide details about each of those alternatives.

C.3.1 Alternative Mix design

In general, mixes used in partial depth repairs had a ½ inch (12.5) or 3/8 inch (9.5 mm) nominal maximum aggregate size (NMAS) and were designed to meet the ODOT specifications for Item 441 for medium traffic surface mixtures. In addition, mixes meeting ODOT specifications for Item 442 (dense grade Superpave mixes) and Item 443 (Stone Matrix Asphalt (SMA)) were used in resurfacing projects. By evaluating parameters used in ODOT Construction and Material Specifications (CMS) for designing Superpave mixes, it was found that the number of gyrations used was set to 65 gyrations. The CMS books of other states were reviewed for comparison. Table C.4 shows the number of gyration used for designing asphalt mixes for routes with heavy traffic in some states. It is clear that the number of gyrations used by ODOT is much lower than those

used by other states. Increasing the number of gyration can help enhance the rutting resistance; however, it might also affect the durability and cracking resistance of mixtures if it is too high. Therefore, it is recommended to design repair mixtures on Amish buggy routes using 95 gyrations and air void of 3.5% and evaluate the rutting resistance and durability of the designed mixes. Asphalt mixture used for the surface course layer in airport pavements are designed to sustain very high loading from aircrafts. By reviewing the design procedures for these mixes, it was found that mix design parameters (please see Table C.5) are different from those used by ODOT, but still those mixes could be produced by any asphalt plant. Therefore, airport mixes might be good alternatives to improve performance of repairs on Amish buggy routes.

Table C.4: Design Number of Gyration Used by Some States for High Volume Traffic

State	N_{Design}
Ohio	65
Indiana	125
Pennsylvania	100
Louisiana	100

Table C.5: Design Parameters for Airport Mixes

Test Property	Value
Number of blows	75
Stability, pounds minimum	2150
Flow, 0.01 in.	10-14
Air voids (%)	2.8-4.2
VFA	65-78
VMA	14-16%

C.3.2 Alternative Asphalt Binders

The binder used in partial depth repair mixes was PG 64-22, in addition for resurfacing project on these routes binders meeting PG 70-22 was used. Therefore, using stiffer binders in the repair mixes should improve their rutting resistance. ODOT CSM book has different stiffer binders that can be used, which include:

- Polymer modified binders meeting specifications for PG 76-22
- High polymer modified binders meeting specification for PG 88-22.
- Ground tire rubber (GTR) modified binder meeting specification PG 76-22

Since the partial depth repair is typically done over a period of two weeks, GTR binders might not be used as ODOT supplement specification 887 allows asphalt plants to store the binder for 48 hours only. However, such binders might be used in resurfacing project on Amish buggy routes. It is noted that the use of the above binders will increase the initial cost of the repairs; however, it might reduce the life cycle cost of these repair as it discussed later in this report.

C.3.3 Alternative Aggregate Structure

Aggregate selection is one of the most critical design in asphalt pavement mixtures, as the type, shape, and gradation of the aggregates selected significantly impact rutting performance of these mixes. One of the most important aggregate characteristics that determines the rutting

resistance and support of an asphalt mix is the aggregate particles packing and interlocking. The mix design methods (i.e. Superpave and Marshall) do not clearly specify lab procedures to characterize the aggregate interlocking. One of the methods that emerged to address this issue and can be used in this study is the Bailey method. This method looks at particle packing based on particle size. It can be used to design the aggregate structure to be strong against rutting and still be easy to compact. The New Hampshire DOT conducted a research study that evaluated the use of the Bailey method to improve the rutting resistance of surface asphalt mixes (Daniel et. al 2009). The study included obtaining different mixture designs from the NHDOT and evaluating them in accordance with the Bailey Method, while also using a Model Mobile Load Simulator (MMLS) to evaluate rutting resistance of each material tested. These mixes were redesigned using the Bailey Method for the aggregates and an optimal asphalt content was determined using Superpave guidelines. The results of this study showed the surface mixtures that were redesigned using the Bailey method provided significantly better rutting performance than the original mixes. The mixtures that were redesigned using the bailey Method needed about three times the number of gyrations during compaction to reach the same target density, which confirmed the Bailey Method prediction.

DOTs have also evaluated mixtures with different aggregate gradations to resist rutting at heavily stressed areas. Hajj et al. (2005) analyzed the rutting performance of different asphalt mixtures at 13 intersections in Nevada by evaluating field cores and their volumetrics, as well as gradation properties. Based on this evaluation, Hajj et al. (2005) identified the no-rut aggregate gradation (NRM) shown in Table C.6, which covered all the extracted aggregate gradations of the mixtures that experienced no rutting. Hajj et al. (2005) and Tannoury (2007) also evaluated the mixtures with the NRM aggregate gradation and compared to other another aggregate gradation used by Caltrans Gradation (CT) for intersections. The results of their evaluation showed the NRM mixture showed the highest rutting resistance and stiffness values. However, the CT mixture had better fatigue cracking resistance.

Table C.6 NRM Blend Gradation (Hajj et al., 2005)

Sieve Size		**Blend**	**Control Points**	
No	**mm**		**Lower**	**Upper**
1"	25.00	100.0	100.0	100.0
3/4"	19.00	92.4	92.0	99.7
1/2"	12.50	75.0	69.8	84.4
3/8"	9.50	62.5	56.0	72.9
#4	4.75	45.7	38.2	54.1
#8	2.36	36.4	25.3	35.3
#10	2.00	33.4	23.8	31.9
#16	1.180	26.2	19.1	23.9
#30	0.6	19.0	13.6	20.7
#40	0.425	16.1	11.9	19.6
#50	0.300	13.5	10.6	18.3
#100	0.150	9.0	8.7	11.4
#200	0.075	6.8	4.4	8.0

C.3.4 Alternative Aggregate Source

The properties of aggregates used in asphalt mixtures have a significant effect on their rutting performance. Aggregate should be angular, sound, tough, and durable and free from films of matter that would prevent thorough coating and bonding with the asphalt binder. Currently, there is no requirement for the aggregates of asphalt mixes used in partial depth repair on Amish routes. Good quality crushed limestone has been used in resurfacing of Amish buggy routes. Results of previous studies proved that, of all the properties of the coarse aggregate materials, the angularity is the most significant factor affecting both the strength and stability of asphalt mixes (Kandhal and Cooley, 2001). One of the aggregate types that has high angularity, excellent strength as well as high skid and abrasion resistance is steel slag. Several DOTs including Illinois and Indiana have used steel slag in surface course mixtures at highly stressed areas. The use of steel slag will help in increasing resistance to wear, rutting, and thermal cracking. In Ohio, Basic Oxygen Furnace (BOF) steel slag is available in the Cleveland area and can be hauled to asphalt plants in Holmes County. This will affect the asphalt mix price as discussed in the next section.

C.3.4 Alternative Repair Method

Compaction is an important factor that affects the rutting performance of mixtures used in partial depth repairs. For ODOT Holmes county garage as well as for other ODOT county garages, small light weight static rollers are typically used in compaction of asphalt mixtures in partial depth repairs on Amish routes. Such equipment applies low compaction effort that results in inadequate density of asphalt mixture. This leads to higher rutting due to densification of mixes under high stresses from Amish buggies. Vibratory steel wheel rollers are much more powerful than static ones and require considerably less passes than static rollers. Vibration allows aggregate particles to move into final positions that result in higher density and greater friction and interlock. Vibration frequency and amplitude significantly affect compactive effort. The ideal vibratory frequency and amplitude settings depends on lift thickness as well as mixture characteristics. Table C.7 presents the recommended vibratory settings for different lift thickness. The rolling speed also affects the compaction. In general, higher frequencies and lower roller speeds are recommended because they increase the compactive effort and enhances mat smoothness. Typically roller speed should be 2.8 – 3.4 mph (4.5 – 5.5 km/hour).

Table C.7 Typical Vibratory Settings (TRB, 2000)

Layer Characteristic	Frequency	Amplitude
Thin Lifts (< about 1.25 inches (30mm))	Operate in static mode. Under vibratory mode, as the pavement increases in density the drums may begin to bounce, which may cause the HMA to shove and become less dense. Also, some of the aggregates may be crushed.	
Lifts between 1.25 and 2.5 inches (30 mm and 65 mm	High Frequency	Low Amplitude
Lifts beyond 2.5 inches (65 mm)	High Frequency	Higher Amplitude
Stiff (more viscous) HMA	High Frequency	Higher Amplitude

The results of the survey that was conducted in this study indicated that ODOT county garages do not monitor compaction during partial depth repair. As mentioned before, compaction can have a significant impact on rutting development, particularly in high-stressed roadway areas

such as Amish buggy routes. Therefore, compaction should be monitored during placement of asphalt mixtures in partial depth repair. Density may be measured PQI 380 non-nuclear density gauge.

C.4 Cost Analyses of Alternatives

Table C.8 presents the estimated costs of mixes with the different alternative binder and aggregate types and their combinations. It is noted that the prices of the alternative binder and aggregate types were obtained from asphalt contractors working in District 11. The design procedure and aggregate gradation used for repair mixes do not typically affect their cost. Such that mixes designed using Airport mix design procedure or using Superpave and Baily's method will have the same cost as along as the aggregate and binder types are the same. Table C.8 also shows the increase in the cost for each mix, which was computed with respect to the control repair mix (i.e. Type 1 mixes) that is typically used in partial depth repairs on Amish buggy routes. Contractors that have asphalt plants in Holmes County indicated that if a special mix will be used, about 20 tons will be wasted every day and will be included in the price of the mix. Therefore, assuming that Holmes county garage uses 100 to 120 tons for partial depth repairs in a day, the increase in the price was computed to account for the waste material as shown in Table C.8.

Table C.8 Prices of Different Alternative Mixture

Mix	Price ($/ton)	Price Increase without waste material (%)	Price Increase with waste material (%)
Type 1 mix (control)	$54.00	0.0%	0.0%
Mixes with PG 70-22	$59.95	11.0%	33.2%
Mixes with PG 76-22	$61.18	13.3%	35.9%
Mixes with PG 88-22	$82.46	52.7%	83.2%
Mixes with PG 76-22 & Steel slag	$64.56	19.5%	43.4%
Mixes with PG 88-22 &Steel slag	$85.46	58.2%	89.9%

As indicated before, vibratory steel roller should be used for compaction of asphalt mixes in partial depth repair. Such equipment is not available at Holmes County garage, and therefore it will be rented. The cost of rental is estimated to be $570 per mile. This amount will be used in the life cycle cost analysis of different alternative repair materials.

LCCA analysis was performed to evaluate the cost effectiveness of the identified alternatives to repair Amish buggy routes and compare them to current repair method and materials. In this analysis, it was assumed that using the alternative repair materials/method will result in repairing the Amish buggy routes only once during the analysis period of 12 years. EUAC was computed for all alternative repair method/materials, as well as the one currently being used by ODOT for Amish buggy routes. Figure C.5 presents the computed EUAC value. Although the initial price of all alternative repair materials/method was higher than the one currently being used for Amish buggy routes, the EUAC of all alternative repair materials/methods was much lower. For each of the identified repair alternatives, the net benefit (ΔEUAC), as well as cost ratio relative to the methods/materials currently used by ODOT for partial depth repair of Amish Routes, were computed using Equations 3 and 4, respectively. Table C.8 presents the computed values. All

alternative mixes are cost effective and will result in reducing the annual repair costs up to 46%. The mixes that use PG 76-22 binder has the greatest cost benefits. It is noted that lab tests should be conducted to verify the rutting performance of these mixes.

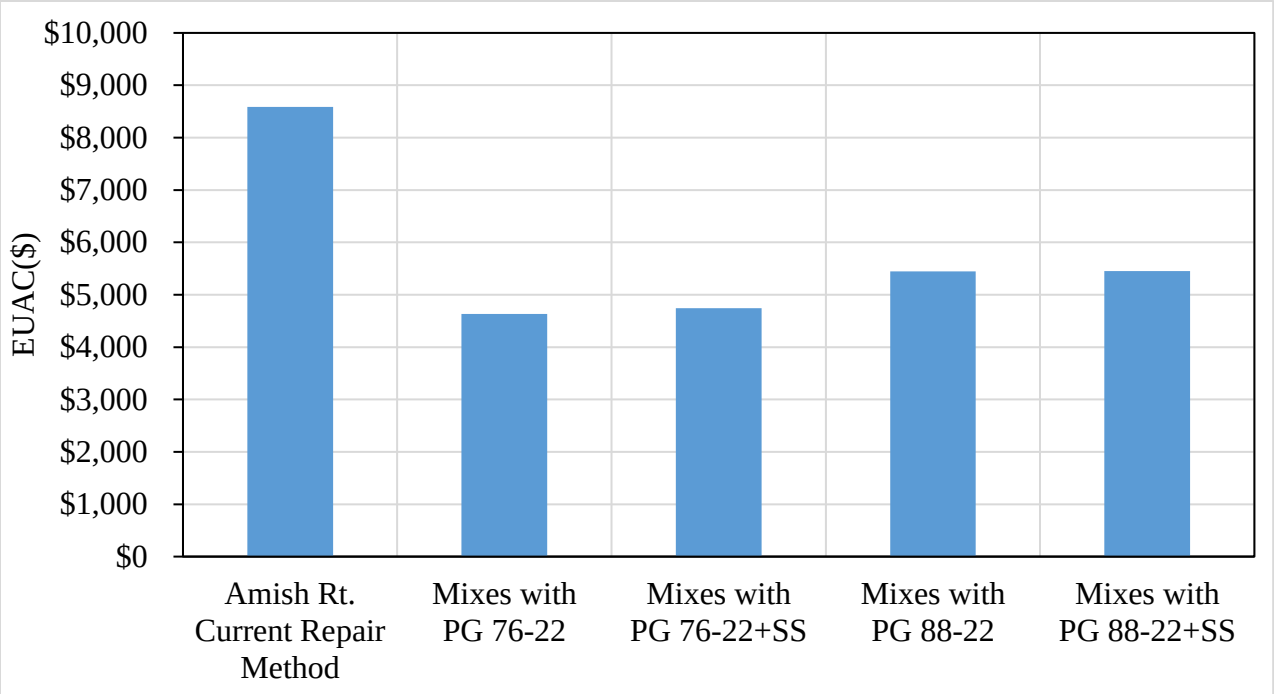

Figure C.5 Life Cycle Costs of Different Alternative Repair Mixtures/Method

Figure C.9 Cost Benefits of the Different Alternative Mixtures

Mixture	Cost Ratio	ΔEUAC
Mixes with PG 76-22	53.9%	$3,956.56
Mixes with PG 76-22+SS	55.3%	$3,842.49
Mixes with PG 88-22	63.4%	$3,140.83
Mixes with PG 88-22+SS	63.5%	$3,136.13

C.5 Changes for Horseshoes

Prevoius studies concluded that using alteranative horseshoes were expensive and will not signficantly reduce the damage to the pavement, since it is the calks or cleats welded to those shoes that damages the pavement. The calk material as well as its contact area are the two main factors affecting the amount of damage to pavement. One solution is to use studs instead of calks that can be attached by screwing them into drilled holes in the horseshoe. Different types of screw-in studs are commercially available as shown in Figure C.6, depending on the type of surface the horse is riding on. The screw-in stud can be made from hard polymer material instead borium or drilex that Amish use for their calk. Polyurethane is polymer that provides great elastic recovery, while maintaining relatively high rigidity. It is also very impermeable to water. Polyurethane studs would provide a better stress-transition to the pavement surface as the quick hoof load is applied. The contact area of the studs plays a critical role in the damage it can cause to asphalt pavement. Smaller contact areas will result in a much higher applied stresses, which will dig harder into the

pavement and cause scarring and rutting. An optimally large contact area should be designed to ensure a minimal damage to the underlying pavement, while driving enough to gain adequate traction for the traveling horse.

Figure C.6 Screw-In Studs

The screw-in studs have several advantages including:

- Screw-in studs do not require a full horseshoe replacement like the caulkin shoe. This is cost effective and requires less maintenance hours. The cost of individual studs are around $1.25 to $3 a piece. However, they have life spans of around 15 years and are relatively universal. A typical farrier may charge around $10 to $15 to drill adequate holes in the horseshoes to screw in the studs.
- Studs can be designed very specifically to each horse, allow for optimal performance.
- The studs provide adequate traction in both soft (soil) and hard (pavement) surfaces and increase the horse travel effectiveness.
- As compared to traditional welded cleats, the studs can be removed when the horse is not traveling, reducing the risk of injury from a kick or being stepped on while the sharp stud is attached.

The screw-in studs also have disadvantages, which include:

- Studs that are not properly suitable for the horse can cause the horse's stride to be out of sorts and will affect travel performance.
- The screw-in studs can come off as compared to an integral horseshoe, often times before its lifespan.
- Studs can be easily stripped if overly tightened by a wrench in alternative horseshoe materials such as aluminum or plastic.
- Sharper studs can cause more damage to paved roadways when used by Amish horse and buggy travel.

Another change to the Amish buggy that might reduce their damage to pavements is the use of horse boots instead of the horseshoes. Horse boots (Figure C.7) are plastic covers that are placed over the entirety of a horse hoof. They are generally made of polyurethane, which prevent snow and ice building up on the bottom as the horse travels in the winter. The horse boots provides adequate traction and wall support and has rotatable connections for ease of horse hoof movement while traveling. The part of the boot that is in contact with the pavement is normally a medium soft, synthetic plastic material that has much higher absorbent energy than a steel caulking horseshoe. This means that when the horse must suddenly come to a halting stop, the shear elastic deformation of the boot sole material will overpower the tendency for a kinetic friction force higher than a static friction force. For steel horseshoes, this outcome would normally be reversed because the stiffness of the steel material would be so high the kinetic friction force would cause the interface surface between the boot and the pavement to slide. The boots typically have strong treads on the bottom of the soles to increase the traction against the pavement surface.

Figure C.7 Standard Horse Boot

Some hoof boots may wear quicker than shoes. However, most hoof boots are surprisingly tough and can last several shoeing periods. The typical boot lasts between 300 to 500 miles of horse travel. Some horse owners have reported use up to 1,000 miles. Some boot companies guarantee a 90 day lifespan. Hoof boots have higher initial price ranging from $50 to $150, depending on the quality. However, the costs of the most expensive set of hoof boots is about the same or less than the cost of a year's worth of shoeing; so they might be more cost effective than regular horseshoes. Horse boots are an effective way to protect the health and lifespan of a horse's hoof, as it is easy to medicate the hoof with the horse boot. They are also ideal for horses that are experiencing problems with their hooves and cannot afford a nailed on horseshoe (Ramey, 2010). The soft, expansive surrounding material allows for expansion and contraction while circulating blood flow through the horse hoof. Horse boots work very well for laminitic horses that have weak hoof-bone connection. The horse boot adds wall support to the load bearing hoof and reduces the applied stress from the weight of the horse. Perhaps one of the most discouraging factors to horse-owners regarding hoof boots is having to put them on and take them off every day. However, the alternative to this is the inconvenience involved when horse loses a shoe and the farrier cannot come out, or even in making sure the farrier comes regularly enough, which is significant.

The ODOT Holmes county garage organized a meeting on January 5th, 2017, with the Amish community representatives. In this meeting, the Amish community representatives were provided with an overview of this study. In addition, possible use of screw-in studs and horse boots

to reduce the pavement damage due to the Amish buggies was discussed. During this meeting, Amish community representatives were receptive to idea of trying the screw-in studs and horse boots and using them in the future, if they are proven to be cost effective and are not rejected by their horses.