Managing Pavement Friction of Wyoming's Roads Considering Safety

By

Marwan Hafez, Ph.D., P.E.
Postdoctoral Research Associate, Wyoming Technology Transfer Center,
University of Wyoming, Laramie, WY 82071, mhafez@uwyo.edu

Ahmed Farid, Ph.D.
Postdoctoral Research Associate, Wyoming Technology Transfer Center,
University of Wyoming, Laramie, WY 82071, afarid@uwyo.edu

Khaled Ksaibati, Ph.D., P.E.
Director, Wyoming Technology Transfer Center, University of Wyoming,
WY 82071, Tel: (307) 766-6230; khaled@uwyo.edu

Sponsored By

Sarah Rickgauer, P.E.
Pavement Management Engineer
Wyoming Department of Transportation

Matt Carlson, P.E.
State Highway Safety Engineer
Wyoming Department of Transportation

Submitted To

Wyoming Department of Transportation

September, 2020

1 INTRODUCTION

Achieving adequate levels of pavement friction enhances road safety in terms of reducing proportions of certain crash types. Although pavement friction is considered in managing maintenance plans of roadways, most state departments of transportation (DOTs) consider simple friction criteria, such as the friction number (FN), for selecting treatments. The Wyoming Department of Transportation (WYDOT) categorizes its road network in excellent condition (greater than 55 FN), good condition (greater than 40 FN but less than or equal to 55 FN), fair condition (greater than 35 FN but less than or equal to 40 FN), and poor condition (less than or equal to 35 FN). The FN values aid in the determination of construction and maintenance treatment activities on a contract level and internal WYDOT crew level. As a result, the impact of various conditions on pavement friction and the relationship between skid resistance and traffic safety are not well investigated.

In 2016 and 2017, Wyoming experienced 27,984 crashes of which 205 (0.7 percent) were fatal and 4,955 (17.7 percent) were injury crashes. Wyoming is characterized by a high percentage of truck traffic along its highways. Some of the high traffic volumes are due to industrial activities in the state. The Wyoming I-80 corridor serves an average annual daily traffic (AADT) volume ranging from 12,000 to 17,000 vehicles per day (vpd) with a percentage of trucks estimated at up to 51 percent. In addition, Wyoming experiences substantial precipitation rates. A considerable proportion of the statewide crashes (31.2 percent) occurred on non-dry road surfaces (e.g., wet, icy, snowy or slushy surfaces). Figure 1 depicts the severity proportions of crashes that occurred on non-dry surfaces in 2016 and 2017. Note that the proportion of fatal crashes that occurred on such surfaces was 0.4 percent. With all these facts, certain crash types such as lane departure and rear-end crashes are expected to be strongly influenced by pavement friction levels in Wyoming. Other factors may have the potential to impact the occurrences of skid related crashes including vertical profile, horizontal profile, operating speeds, surface type (e.g., asphalt or concrete), and road functional classification. Pavement friction is currently treated in Wyoming using thin layers of bonded aggregates. Yet, the effectiveness of each of the different treatments is not covered. These challenges require additional research needs to interpret the association between traffic safety and skid resistance properties to arrive at better informed decisions regarding pavement maintenance.

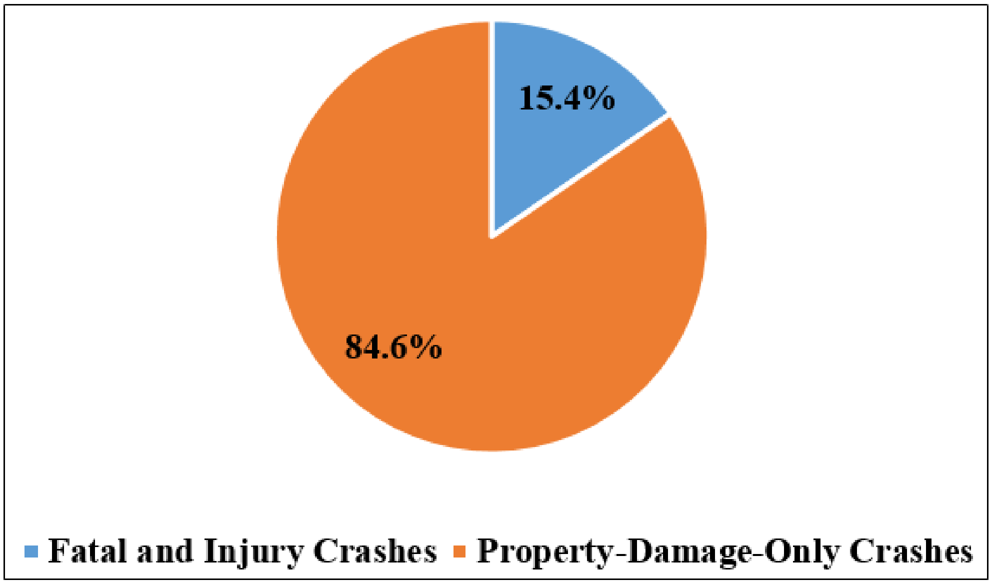


Figure 1: Severity proportions of crashes on wet, icy, snowy and slushy road surfaces in Wyoming in 2016 and 2017.

In terms of traffic safety, drivers' ability to accelerate, brake, and steer the vehicle is significantly affected by pavement friction and skid resistance (McCarthy et al., 2016). The friction properties of the pavement play a key role in the skid resistance across the pavement surface. Vehicles tend to have different friction demands, which are levels of skid resistance needed to execute safe driving maneuvers (Najafi et al., 2017). The highway engineering literature shows that there are different factors affecting friction demands including roadway geometries, operating speeds, weather conditions, traffic volumes and vehicle mix compositions, among other factors. Higher friction values are commonly required at horizontal curves, steep grades and areas in which vehicles are required to stop or slow down (e.g. intersections and roundabouts). Friction demands could be more important on roads encountering higher rates of precipitation. A research study conducted by the National Transportation Safety Board shows that improving pavement friction can mitigate wet road crashes by 70 percent (McGovern et al., 2011). According to the National Highway Traffic Safety Administration (NHTSA), more than 19,000 fatalities resulted from roadway departure crashes from 2016 to 2018 (Federal Highway Administration [FHWA], 2020). The road departure crashes represents 51 percent of the nationwide fatality toll. Pavement friction can contribute to lane departure crashes in areas where friction demands are high.

This proposal identifies the relationship between pavement performance in terms of skid resistance and the probability of skid-related crashes. The study expands these relationships to manage the pavement maintenance plans considering the long-term friction performance of surface treatments, costs, and safety performance targets.

2 OBJECTIVE

The main goal of this study is to enhance road safety in Wyoming by integrating a crash risk mitigation approach into the pavement friction management program. This goal can be accomplished by performing the following tasks:

- Investigate the relationship between pavement surface friction and friction-related crashes in Wyoming.
- Define the best practices of maintaining pavement friction levels using bonded aggregates and surface treatments.
- Implement a data-driven approach to select friction related maintenance strategies.
- Estimate the potential reduction in friction related crashes due to the enhanced maintenance activities, which consider the restoration of adequate pavement friction levels.
- Develop a detailed methodological framework for implementing pavement friction treatments for WYDOT considering safety implications.
- Determine the cost-effectiveness of the proposed pavement friction management plans in terms of crash reduction benefits and associated maintenance costs.
- Propose an enhanced pavement management policy for WYDOT considering friction treatment plans to ensure safe traffic operations.

3 EXPECTED BENEFITS

The findings of this study will aid WYDOT and other transportation agencies in the state to enhance their pavement maintenance programs. Those programs account for the risks of encountering friction-related crashes under various traffic, geometric and environmental conditions. The primary benefits include:

- Restore safe levels of pavement friction on roads at locations requiring higher friction demands.
- Enhance driving conditions of vehicles, especially heavy trucks, on Wyoming's highways during high precipitation rates.
- Reduce fatalities and injuries of skid-related roadway departure and rear-end crashes in Wyoming.
- Support WYDOT and other agencies in the state with a skid resistance policy that maximizes the benefits of friction surface treatments within defined budgets and resources.

4 BACKGROUND

4.1 Pavement Friction Characteristics

Pavement friction is an important resisting force that eliminates the relative motion between the vehicle tires and the pavement surface (Hall et al. 2009b). The frictional force between the tires and the surface is generated in two main directions, namely the longitudinal and lateral directions. These forces are greatly affected by the pavement texture which can be classified according to the texture's wavelength (Henry, 2000). As shown in Figure 2, the microtexture and the macrotexture are two critical characteristics affecting the skid resistance of the pavement. The term microtexture refers to the small-scale of the pavement aggregate surfaces and is responsible for achieving adequate adhesion between the tires and the pavement surface in dry conditions. However, this adhesion is reduced when the pavement is wet. On the other hand, the macrotexture is the large-scale texture of the pavement surface due to the aggregate particle arrangement. The higher wavelengths entailed in macrotexture materials are essential to provide paths for water drainage from beneath the tire such that the adhesive component of the friction provided by microtexture is reestablished.

Microtexture is affected by the properties of the surface coarse aggregates used in asphalt pavements while fine aggregates and cement paste provide the required micotexture adhesions for concrete pavements. On the other hand, the pavement-tire friction of macrotexture asphalt surfaces is formed from the size of the aggregate particles, shape of the aggregate particles and porosity of the surfaces. The pavement-tire friction of macrotexture concrete surfaces is shaped by grooving as shown in Figure 3.

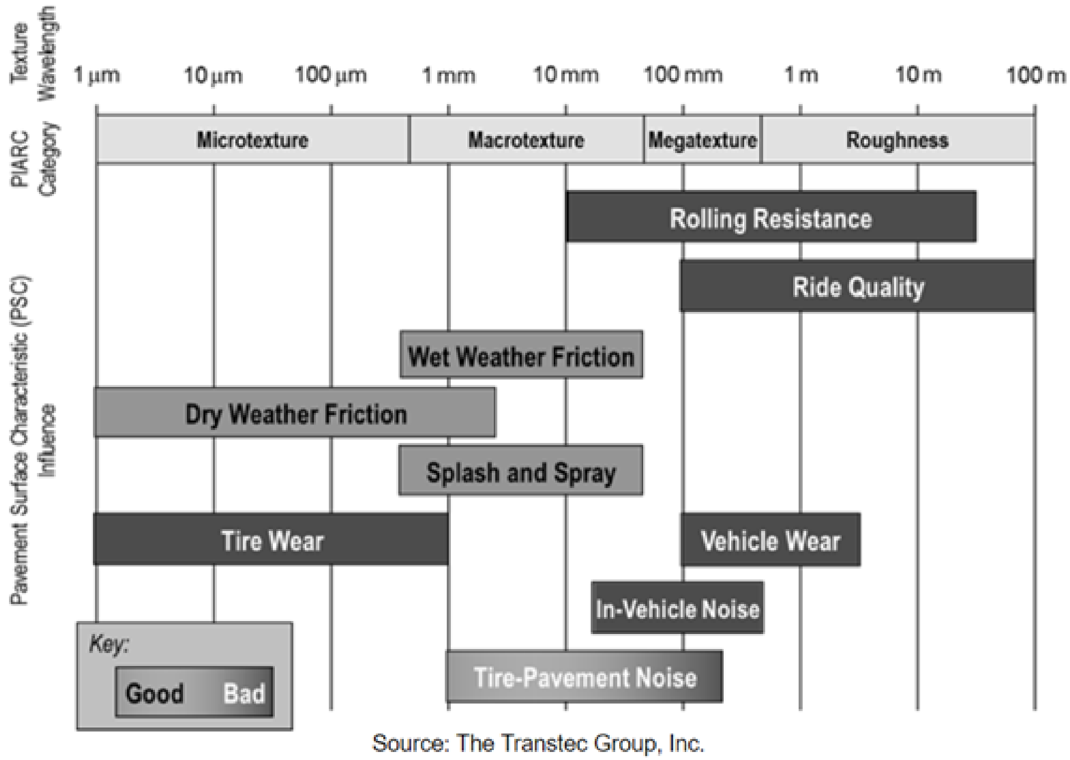
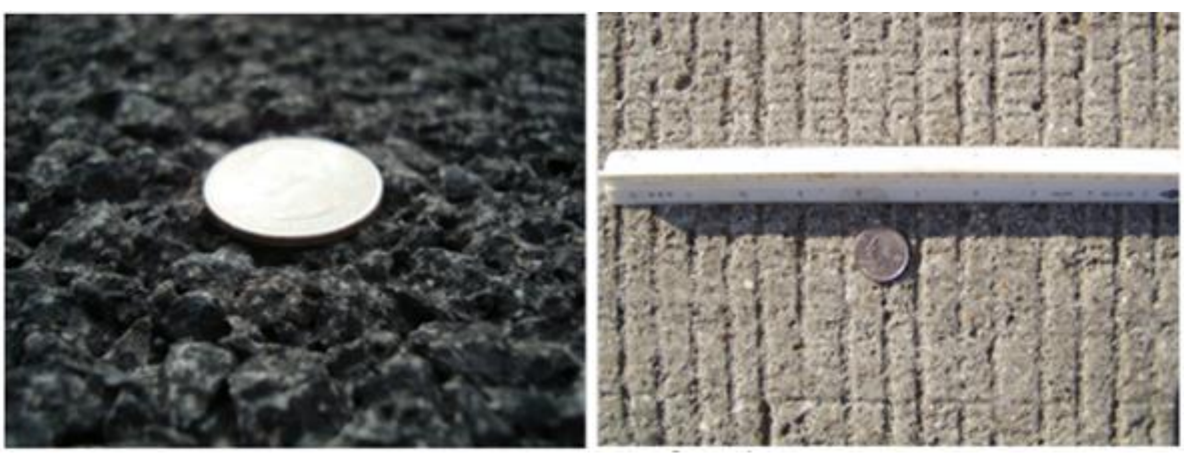


Figure 2: Effect of pavement texture on road surface friction.

Source: Merritt et al. (2015).



(a) **(b)**

Figure 3: Macrotexture of pavement surfaces: (a) asphalt; (b) concrete tining.

Source: Merritt et al. (2015).

Pavement friction levels reduce over time as a result of traffic volumes which polish the surface texture of aggregates. Thus, it is highly recommended that state DOTs and transportation agencies monitor the skid resistance of pavement surfaces using quantifiable friction measurements. Among these measurements, the coefficient of friction (μ) represents the ratio of the frictional resistance force (F) to the longitudinal moving force (W). It is used to determine the friction number (FN) which represents the resulting friction ratio, multiplied by 100. The frictional forces are determined on the road using locked-wheel friction testers (American Society for Testing and Materials [ASTM] E 274) and these values mainly depend on the velocity of the test tire. Hence, friction numbers are reported with the applied testing speed (V, mi/hr; e.g. FN(V) = 100 (F/W)}.

4.2 Pavement Surface Treatments

Most surface treatments are typically used for pavement preservation to extend the service life of an existing pavement. Roadway friction levels are enhanced via surface treatments since most of these treatments improve the quality of the macrotexture to increase the skid resistance. Several treatments are used throughout the U.S. to enhance pavement friction as listed in Table 1 (Merritt et al., 2015). In terms of skid resistance and safety, the application of these treatments differs among agencies depending on costs, expertise, and the potential hazards of skid-related (also known as friction related) crashes. Some of these treatments may be used as spot applications to increase friction levels at horizontal curves, bridges, steep grades and intersections where higher friction demands are required to reduce skid-related crashes.

Table 1: Common surface treatments to increase skid resistance.

Asphalt Pavement	Concrete Pavement
Chip Seal	Grooving
Micro-Milling	Diamond Grinding
Thin Hot-Mix Asphalt (HMA) Overlay	Thin HMA Overlay
Open Graded Friction Course (OGFC)	Open Graded Friction Course (OGFC)
Ultra-Thin Bonded Wearing Course (UTBWC)	Ultra-Thin Bonded Wearing Course (UTBWC)
Microsurfacing	Microsurfacing
Texturing: Shot Blasting /Abrading	Texturing: Shot Blasting /Abrading
High Friction Surfacing (HFS)	High Friction Surfacing (HFS)
Cape Seal	Epoxy Overlay (Bridge Deck)
Scrub Seal	
Slurry Seal	

4.3 Importance of Pavement Safety

The importance of maintaining adequate pavement friction cannot be overstressed. The friction resulting from the interaction between the tires and the pavement plays a critical role in highway safety. It inhibits drivers from executing unsafe maneuvers involving veering off their intended travel trajectories. It is also needed for highway geometric design when it comes to determining minimum stopping distances (Hall et al., 2009b). In addition, the pavement friction ought to be adequate for skid resistance purposes when having wet, icy, snowy or slushy road surfaces. At the national level, roughly, 25 percent of total crashes and 13.5 percent of fatal crashes occur on wet roads (Hall et al., 2009b; Kuemmel et al., 2000). The following content is composed of discussions of research studies about the relationship between pavement friction and safety.

Rizenbergs et al. (1972) found that the rates of crashes that occurred on wet road surfaces were higher for conditions in which the SN40R were lower than 40. That was for roads with light and medium traffic volumes. The SN40R is the ASTM designation for the friction number measured using a test vehicle with grooved tires traveling 40 mi/hr over the pavement under study. The American Association of State Highway and Transportation Officials' (AASHTO's) designation for this measure is FN40R (Hall et al., 2009a). Giles et al. (1962), Cairney (1997) and Gothie (1996) confirmed that FN values under 50 indicated hazardous conditions whereas those higher than 60 indicated a reduced likelihood of pavement friction related crashes. McCullough and Hankins (1966) suggested a friction coefficient that is not less than 0.4. This value was ascertained based on tests of which the test vehicle was driven at 30 mph. Miller and Johnson (1973), Kamel and Gartshore (1982) and Bray (2002) discovered that maintaining the pavement such that its friction is at an appropriate level reduces wet surface related crashes. McLean (1995) inferred that crash rates may rise for rural highway sites that were upgraded to have higher friction numbers. This was possibly because drivers were likely to use lower friction roads and to travel faster.

In a more recent study, Noyce et al. (2007) investigated the association between pavement skid resistance and crash count. The research team did not conclude that a correlation exists between both parameters based on their statistical analyses. However, the data showed that lower friction numbers corresponded to unsafe road surface conditions. Also, it was recommended that the roads be maintained such that their FN40R's do not drop to 35 or lower. Mayora and Piña (2009) also maintained that higher friction numbers translated to safer roads for wet road surface conditions. Note that the authors used skid resistance data collected from the Sideway Force Coefficient Routine Investigation Machine (SCRIM). Other notable relevant studies are those of the Organization for Economic Cooperation and Development (1984), Wallman and Astrom (2001), Gandhi et al. (1991), Craus et al. (1991), Larson (1999), Xiao et al. (2000) and Schulze et al. (1976). The previously discussed studies show that the likelihood of wet surface related crashes reduce with the enhancement of pavement friction levels. Also, surfaces with friction numbers less than particular values, depending on the site, represent hazardous conditions (Kuttesch, 2004). Yet, the occurrences of wet surface related crashes are not only attributed to the pavement friction but also to other crash contributing factors. Hence, the relationship between the risk of wet surface related crashes and pavement friction, whether linear or not, is dependent on the roadway facility under study (Hall et al., 2009b).

4.4 Friction Management System

As per the Highway Safety Improvement Program (HSIP), each state shall incorporate a process for analyzing traffic safety data that identifies highway safety improvement projects (Federal Highway Administration [FHWA], 2019). Hence, state DOTs can prioritize and manage the use of resources to reduce friction-related vehicle crashes using a network-level friction management program. In this program, pavement friction characteristics are periodically collected on road segments to find sections which have intolerable rates of friction-related crashes. Processed pavement friction management data aids DOTs in arriving at better informed decisions to enhance skid resistance at high crash risk locations, or hot-spots, to reduce expected fatalities and injuries in the state. The FHWA issued guidelines for the implementation of pavement friction management (PFM) programs which cover several topics including (Federal Highway Administration [FHWA], 2017):

- Measuring pavement friction,
- Identifying and classifying road network hot-spots,
- Prioritizing projects for improving pavement friction levels, and
- Determining the effectiveness of developed friction management programs.

5 STUDY TASKS

This study's goals can be achieved by performing the following tasks:

5.1 Literature Review

Conduct an extensive literature review to examine the relationship between pavement friction and traffic safety across the nation. Also, as part of the review, the best maintenance practices that lead to acceptable road surface friction will be investigated for both asphalt and concrete pavements.

5.2 Data Collection

Secure friction and crash data in collaboration with WYDOT. The data comprises friction numbers of road segments and historical maintenance records of surface treatments. These records include types and costs of applied treatments and aggregates. In addition, detailed safety data and other relevant data will be collected. They include crash data, geometric characteristics, traffic, weather conditions and other related data.

5.3 Data Processing

Process the secured data to gain insights on the contributing factors of friction-related crashes in Wyoming. Correlations between the performances of pavement friction levels and crash rates will be inferred as well. ***The data processing results will be presented at the network level and no segment-specific friction data will be reported or presented by the researchers.***

5.4 Skid Resistance Safety Performance Functions

Formulate crash count prediction models, also known as safety performance functions (SPFs), for predicting friction related crashes. Extensive crash, traffic, road geometry, pavement conditions, and environmental data of Wyoming will be utilized to develop the SPFs. That is, such crashes are modeled as functions of the characteristics of the aforementioned data. SPFs are of great value for road network screening analysis. Road network screening, also known as hot-spot identification, involves the implementation of methods to pinpoint high crash risk locations by crash type and/or severity (AASHTO, 2010).

5.5 Examining the Effectiveness of Pavement Friction Treatments in Wyoming

Investigate the effectiveness of Wyoming's pavement friction treatments. There exist various aggregate and surface treatments applied on Wyoming's roads during pavement preservation. The historical performance of skid resistance will be modeled as functions of aggregate/ treatment type, pavement type, and friction levels. These models are expected to account for the long-term friction performance of the pavement.

5.6 Developing a Methodology to Incorporate Friction Management into Safety Analysis

Develop a methodology to incorporate friction management into safety analysis. In this task, the contribution from pavement friction to vehicle crashes will be evaluated while controlling the other factors known to impact safety performance. First, crash sites with distinctive road classification, traffic, and environmental characteristics will be identified. Then, a quantitative approach will be developed to classify the crash risk and associated critical skid resistance threshold levels.

5.7 Evaluating the Friction Requirements of Wyoming's Roads

Evaluate the friction requirements of Wyoming's roads for each functional classification, pavement type, and specific locations such as horizontal curves and steep grades. Potential methods of defining friction demand will be developed for WYDOT to provide an assessment of friction measurement and how it relates to friction demand, especially at critical locations. Other innovative treatments can be investigated such as high friction surface treatments (HFSTs) according to data availability. The effectiveness can be evaluated using common metrics such as friction numbers.

5.8 Correlating the Impact of Proposed Friction Treatments with the Associated Safety Enhancements

Correlate the impact of proposed friction treatments with the associated safety enhancements. The expected reductions in crashes can be estimated using methods prescribed in the Highway Safety Manual (AASHTO, 2010) for each treatment type.

5.9 Prioritizing Pavement Maintenance Activities to Account for Skid Resistance

Prioritize a pavement maintenance management program to account for skid resistance. Safety satisfaction levels will be considered in order to select the pavement friction treatment strategies for each road network in the state. In this task, the safety ranks of each road segment, in terms of pavement friction, will be outlined at the network level.

5.10 Benefit-Cost Analysis

Conduct a benefit-cost analysis to evaluate the consequences of considering safety improvements in the enhanced maintenance strategies. The benefits represent the expected reduction in friction-related crash rates after implementing the proposed management strategies.

5.11 Pavement Friction Management Policy

Develop a comprehensive policy for WYDOT to manage the pavement friction of Wyoming's roads considering guidelines derived from the findings of this study. The policy will consider roadway features such as geometric conditions, traffic volumes, functional classification, and etc.

All findings including guidelines and the proposed policy will be compiled into a comprehensive final report.

5.12 Summary

This project is aimed at improving pavement maintenance practices in Wyoming to enhance skid resistance and hence prevent friction related crashes. This involves conducting a literature review of the relationship between pavement friction and road safety. A review of the pavement maintenance practices, in which adequate pavement friction levels are considered, will be conducted. Subsequently, pavement friction and road safety data of Wyoming will be secured with the aid of WYDOT. The data will be analyzed to interpret how the precursors of pavement friction related crashes give rise to the occurrences of such crashes. Also, SPFs will be developed to predict the count of pavement friction related crashes in the state. The SPFs are beneficial for network screening analyses. Furthermore, the past pavement friction performance of Wyoming's roads will be modeled. Afterwards, a methodology will be developed to incorporate pavement management practices, where adequate friction supply levels are restored, in road safety analysis. The expected crash reductions, resulting from maintained pavements in which safe friction levels are preserved, will be estimated. Note that pavement management activities will be prioritized to take into account locations requiring restoration of adequate friction levels. A benefit-cost analysis will also be carried out to assess whether incorporating the safety aspect (i.e. maintaining acceptable friction levels) into the pavement management process is economical. With that, adequate pavement friction levels of Wyoming's roads are supplied by road functional classification, pavement type and geometric conditions. All the project's efforts culminate in the proposition of a fully-fledged pavement management policy for WYDOT.

6 TIMELINE

This study is expected to be completed in 2 years and 3 months. The expected timeline of the research tasks is shown in Figure 4.

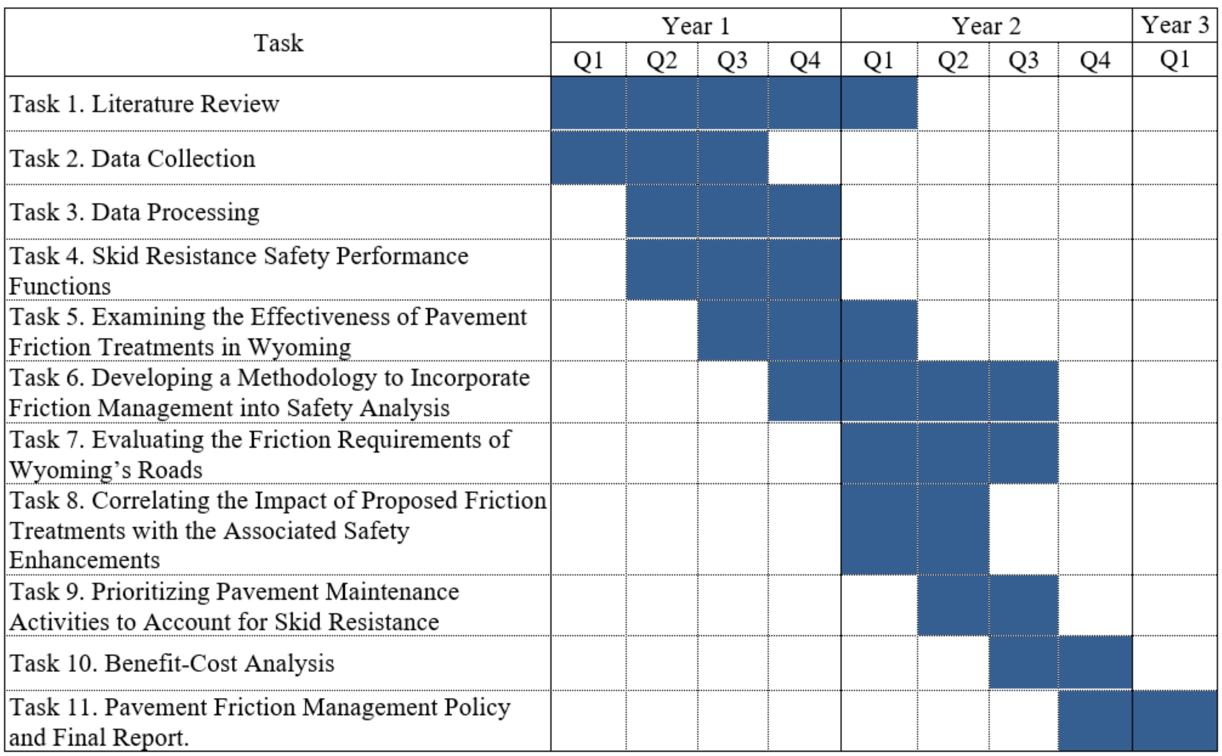


Figure 4: Proposed timeline.

7 BUDGET

The tasks of this research require the contributions of two postdoctoral research associates, a Ph.D. student and a faculty member. Table 2 summarizes the budget of this study.

Table 2: Budget of the project.

Categories	Cost	Explanatory Notes
Engineer/ Post Doc Salaries	$28,800	
Faculty Salaries	$18,100	
Administrative Staff Salaries		
Staff Fringe Benefits	20,308	
Student Salaries	$38,800	
Student Fringe Benefits	$1,513	
Total Personnel Salaries	$85,700	
Total Fringe Benefits	$21,821	
TOTAL Salaries & Fringe Be	**$107,521**	
Travel	$4,000	
Equipment	$0	
Supplies	$3,500	Reports and etc.
Contractual	$0	
Construction	$0	
Other Direct Costs (Specify)*	$16,000	
TOTAL Direct Costs	$131,021	
F&A (Indirect) Costs[$]	$23,004	
TOTAL COSTS	**$154,025**	

REFERENCES

American Association of State Highway and Transportation Officials, 2010. *Highway Safety Manual.* American Association of State Highway and Transportation Officials, Washington, D.C.

Bray, J., 2002. The Role of Crash Surveillance and Program Evaluation: New York State Department of Transportation's Skid Accident Reduction Program (SKARP). Presented at 28th International Forum on Traffic Records and Highway Information Systems, Orlando, Florida.

Cairney, P., 1997. *Skid Resistance and Crashes – A Review of the Literature*. Research Report Number 311. Australian Road Research Board Transport Research Ltd., Vermont South, Victoria, Australia.

Craus, J., Livneh, M., Ishai, I., 1991. Effect of Pavement and Shoulder Condition on Highway Accidents. *Transportation Research Record: Journal of the Transportation Research Board* 1318, 51-57.

Federal Highway Administration, 2017. Friction Management Program. Federal Highway Administration, U.S. Department of Transportation. https://safety.fhwa.dot.gov/roadway_dept/pavement_friction/friction_management/. Accessed September 21, 2020.

Federal Highway Administration, 2019. Highway Safety Improvement Program (HSIP). Federal Highway Administration, U.S. Department of Transportation. https://safety.fhwa.dot.gov/hsip/hsip.cfm. Accessed September 21, 2020.

Federal Highway Administration, 2020. Roadway Departure Safety. Federal Highway Administration, U.S. Department of Transportation. https://safety.fhwa.dot.gov/roadway_dept/#:~:text=From%202016%20to%202018%20an, fatalities%20in%20the%20United%20States. Accessed September 14, 2020.

Gandhi, P., Colucci, B., Gandhi, S., 1991. Polishing of Aggregates and Wet-Weather Accident Rates for Flexible Pavements. *Transportation Research Record: Journal of the Transportation Research Board* 1300, 71-79.

Giles, C., Sabey, B., Cardew, K., 1962. *Development and Performance of the Portable Skid Resistance Tester*. American Standards of Testing and Materials Special Technical Publication Number 326. American Society of Testing and Materials, Philadelphia, Pennsylvania.

Gothie, M., 1996. Relationship between Surface Characteristics and Accidents. Proceedings of 3rd International Symposium on Pavement Surface Characteristics. Christchurch, New Zealand.

Hall, J., Smith, K., Littleton, P., 2009. *National Cooperative Highway Research Program Report 634: Texturing of Concrete Pavements*. Project Number 10-67. National Cooperative Highway Research Program, Transportation Research Board of the National Academies, Washington, D.C.

Hall, J., Smith, K., Titus-Glover, L., Wambold, J., Yager, T., Rado, Z., 2009. *National Cooperative Highway Research Program Project 01-43: Guide for Pavement Friction*. Web-Only Document 108. National Cooperative Highway Research Program, Transportation Research Board of the National Academies, Washington, D.C.

Henry, J., 2000. *National Cooperative Highway Research Program Synthesis 291: Evaluation of Pavement Friction Characteristics*. National Cooperative Highway Research Program Synthesis of Highway Practice 291. National Cooperative Highway Research Program, Transportation Research Board of the National Academies, Washington, D.C.

Kamel, N., Gartshore, T., 1982. Ontario's Wet Pavement Accident Reduction Program. *American Standards of Testing and Materials Special Technical Publication 763.* American Society of Testing and Materials, Philadelphia, Pennsylvania.

Kuemmel, D., Jaeckel, J., Satanovsky, A., 2000. *Investigative Study of the Italgrip System: Noise Analysis*. Report Number WI/SPR-02-00. Wisconsin Department of Transportation, Madison, Wisconsin.

Kuttesch, J., 2004. Quantifying the Relationship between Skid Resistance and Wet Weather Accidents for Virginia Data. Master's Thesis. Department of Civil Engineering, Virginia Polytechnic Institute and State University, Blacksburg, Virginia.

Larson, R., 1999. Consideration of Tire/Pavement Friction/Texture Effects on Pavement Structural Design and Materials Mix Design. Federal Highway Administration, Washington, D.C.

Mayora, J., Piña, R., 2009. An Assessment of the Skid Resistance Effect on Traffic Safety Under Wet Pavement Conditions. *Accident Analysis & Prevention* 41 (4), 881-886. https://doi.org/10.1016/j.aap.2009.05.004.

McCarthy, R., Flintsch, G., Katicha, S., McGhee, K., Medina-Flintsch, A., 2016. New Approach for Managing Pavement Friction and Reducing Road Crashes. *Transportation Research Record: Journal of the Transportation Research Board* 2591 (1), 23-32. https://doi.org/10.3141/2591-04.

McCullough, B., Hankins, K., 1966. Skid Resistance Guidelines for Surface Improvements on Texas Highways. *Transportation Research Record: Journal of the Transportation Research Board* 131, 204-217.

McGovern, C., Rusch, P., Noyce, D., 2011. *State Practices to Reduce Wet Weather Skidding Crashes.* Report Number FHWA-SA-11-21. Federal Highway Administration, U.S. Department of Transportation, Washington, D.C.

McLean, J., 1995. The Relationship between Pavement Condition and Road Safety. Presented at Load-Pavement Interaction Workshop, Newcastle, England.

Miller, M., Johnson, H., 1973. *Effects of Resistance to Skidding on Accidents: Surface Dressing on an Elevated Section of the M4 Motorway*. Report Number LR 542. Transport and Road Research Laboratory, Berkshire, United Kingdom.

Najafi, S., Flintsch, G., Medina, A., 2017. Linking Roadway Crashes and Tire–Pavement Friction: A Case Study. *International Journal of Pavement Engineering* 18 (2), 119-127. https://doi.org/10.1080/10298436.2015.1039005.

Noyce, D., Bahia, H., Yambo, J., Chapman, J., Bill, A., 2007. *Incorporating Road Safety into Pavement Management: Maximizing Surface Friction for Road Safety Improvements*. Report Number MRUTC 04-04. Wisconsin Department of Transportation, Madison, Wisconsin.

Organization for Economic Cooperation and Development, 1984. Road Surface Characteristics – their Interaction and their Optimisation. Organization for Economic Cooperation and Development Scientific Expert Group, Road Transport Research, Paris, France.

Rizenbergs, R., Burchett, J., Napier, C., 1972. *Skid Resistance of Pavements*. Report Number KYHPR-64-24 Part II. Kentucky Department of Highways, Lexington, Kentucky.

Schulze, K., Gerbaldi, A., Chavet, J., 1976. Skidding Accidents, Friction Numbers, and the Legal Aspects Involved. *Transportation Research Record: Journal of the Transportation Research Board* 623, 1-10.

Wallman, C., Astrom, H., 2001. *Friction Measurement Methods and the Correlation between Road Friction and Traffic Safety*. Swedish National Road and Transport Research Institute, Linkoping, Sweden.

Xiao, J., Kulakowski, B., El-Gindy, M., 2000. Prediction of Risk of Wet-Pavement Accidents: Fuzzy Logic Model. *Transportation Research Record: Journal of the Transportation Research Board* 1717 (1), 28-36. https://doi.org/10.3141/1717-05.