Crash Reduction Analysis of Friction Improvement Surface Treatments in Georgia

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TABLE OF CONTENTS

[ABSTRACT 3](#_Toc109207260)

[INTRODUCTION 4](#_Toc109207261)

[METHODOLOGY 6](#_Toc109207262)

[Data and Early Spatial Analysis 6](#_Toc109207263)

[Naïve Bayes Approach to Developing CMFs 7](#_Toc109207264)

[Empirical Bayes Method to Developing High Quality CMFs 8](#_Toc109207265)

[Development of Safety Performance Function Prediction Models 8](#_Toc109207266)

[Calculation of the EB CMF 9](#_Toc109207267)

[Modeling naïve CMFs as functions of the roadway environment 9](#_Toc109207268)

[RESULTS 11](#_Toc109207269)

[Naïve Bayes CMFs 11](#_Toc109207270)

[Developed SPFs 11](#_Toc109207271)

[Empirical Bayes CMFs 13](#_Toc109207272)

[Significant Factors of HFST CMFs 13](#_Toc109207273)

[DISCUSSION 16](#_Toc109207274)

[Use of EB method 16](#_Toc109207275)

[Crash Types 16](#_Toc109207276)

[CMF Model 16](#_Toc109207277)

[Different Materials 17](#_Toc109207278)

[COVID-19 Impact on EB CMFs 18](#_Toc109207279)

[CONCLUSION 18](#_Toc109207280)

[ACKNOWLEDGMENTS 18](#_Toc109207281)

[AUTHOR CONTRIBUTIONS 18](#_Toc109207282)

[REFERENCES 19](#_Toc109207283)

# ABSTRACT

# INTRODUCTION

Curve related crashes are one of the main causes of fatalities in transportation in the US. Out of 37,206 total annual highway crash fatalities in the US, 8,767 are associated with roadway departures on horizontal curves (ref). A preventative measure against these roadway departures is the use of friction improvement surface treatments (FISTs). This study in particular focuses on the three FISTs implemented in Georgia: phonolite, lightweight aggregate (LWA), and high friction surface treatment (HFST). While all three FISTs work towards the same goal of improving friction on road surfaces in order to reduce the chances of roadway departures, the three FISTs are intrinsically different in material makeup, durability, and cost. Phonolite is an alternative epoxy-based friction improvement and has been implemented in Wyoming, earning it the moniker of Wyoming bauxite (ref HFST report). Light weight aggregate is an alternative aggregate that does not require the use of a binding epoxy and is used as a resurfacing material (ref HFST report). Lastly, HFST is comprised of rough aggregates bonded to a roadway surface with an epoxy known as calcined bauxite. HFST is a proven safety counter measure (ref FHWA), and it is usually implemented alongside other safety treatments such as signage and rumble strips. HFST and other friction improvements have been implemented in hundreds of sites in Georgia (ref HFST report GA).

To help mitigate curve crashes, these three types of FISTs were implemented in Georgia, starting with HFST back in 2014. Throughout 2014 to 2017, the Georgia Department of Transportation (GDOT) implemented HFST in 342 sites among districts 3, 4, 5 and 6, making Georgia the leading state in the nation for HFST usage by volume. Furthermore, in 2017, phonolite was installed at 69 sites in district 1 and LWA was installed at 10 sites in district 2. Figure # is a demonstration of the locations and times these FISTs were implemented. These HFST locations are identified from a concurrent project \_\_\_\_\_\_\_\_\_\_\_\_.

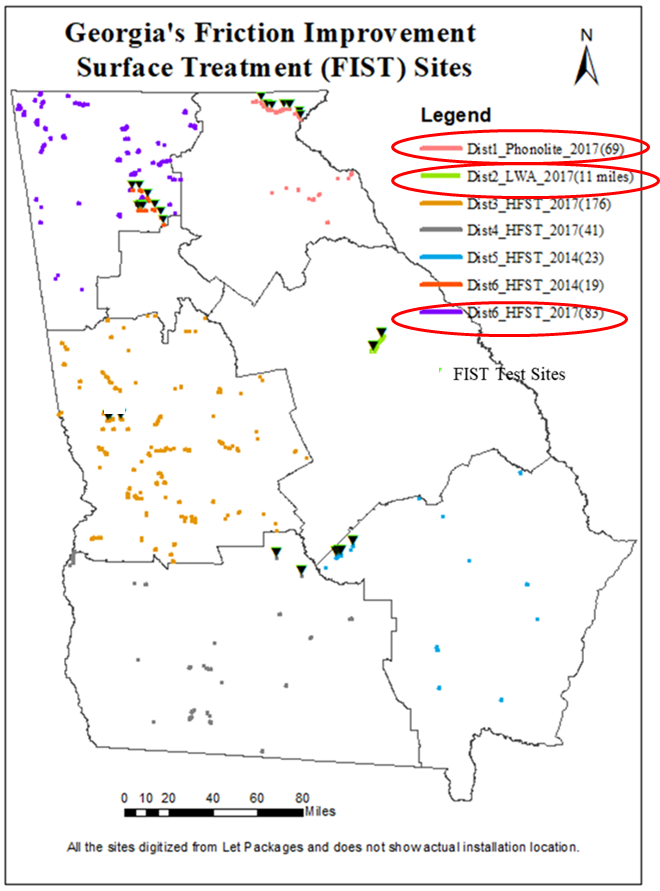


Figure # [description]

In another study which collected data using a dynamic friction tester (DFT), it was discovered that HFST, currently the most used FIST in Georgia, has the best overall performance as it has the highest friction improvement at time of installation and least percentage of friction drop compared to the other two FISTs in both long-term and short-term observation periods (ref). However, HFST is comprised of rarer components, which makes it more expensive compared to the other locally made FISTs (ref). LWA was found to provide a lower level of friction improvement at time of installation (about 80% that of HFST) and had similar initial friction drops (within 3 months after installation) to HFST, but had larger friction drops in long term. Lastly, phonolite was found to provide the least amount of friction improvement (about 60% that of HFST) and showed rapid initial fiction drop but a more stable long term deterioration level like that of HFST. These differences in cost and friction performance over time will lead to different performances in crash reduction and returns on investment, and thus it is crucial to observe and understand the characteristics of these FISTs under different roadway environments to create an optimized strategy that can maximize their crash reduction efficacy while minimizing the cost.

An available way to quantify the crash reduction efficacy of each FIST is through the calculation of a crash modification factor (CMF). CMFs are used to assess the efficacy of different FISTs in terms of the proportion of the crash frequency after FIST implementation to the crash frequency before FIST implementation. For example, a CMF of 0.75 means that the FIST reduces crashes by 25% at a given location, and a CMF greater than 1.0 means this FIST is increasing the number of crashes at a given location. There are multiple methods of calculating a CMF for a FIST, and in this study the two methods used are the naïve Bayes method and the empirical Bayes (EB) method. The difference between the two methods is that the empirical Bayes method provides a higher-quality CMF which accounts for the effect of variations in other roadway features before and after FIST implementation, such as the traffic volume. This method was proven to be effective by David Merritt in his paper *Empirical Bayes Before-After Study to Develop Crash Modification Factors and Functions for High Friction Surface Treatments on Curves and Ramps*, where he calculated empirical Bayes CMFs for curves and ramps in West Virginia, Pennsylvania, Kentucky, and Arkansas. Thus far no CMFs have been developed for HFST implementations in Georgia specifically, and so it is critical to develop CMFs for Georgia-specific conditions because the roadway environment and implementation strategies in other states are not necessarily the same as that of Georgia. Similarly, no published CMFs have been developed for LWA and phonolite in Georgia.

Therefore, the objective of this study is to analyze the effectiveness of phonolite, LWA, and HFST in reducing horizontal curve road departure crashes in Georgia by using naive Bayes and empirical Bayes methods to develop CMFs. Using the calculated CMFs, the three FISTs are to be compared, the crash types that HFST reduces the most are assessed, and the roadway characteristics that have the greatest significance on the final calculated CMF are analyzed.

* Note that though friction data was recorded, high quality friction data before and after HFST implementation is not available and is not considered

# METHODOLOGY

## Data and Early Spatial Analysis

In this study, the crash data was provided by the *Numetric* platform maintained by GDOT (ref), and curve data was provided by GDOT’s safety program (ref). The crash data included all crashes in Georgia’s districts 1, 2, and 6 from 2012 to 2020, and was formatted as a collection of points that included information such as the crash location, date of the crash, vehicles involved, and what the vehicles were doing as the collision occurred. The curve data included curve locations that implemented phonolite in district 1, LWA in district 2, and HFST in district 6, and was formatted as a collection of polylines—best described as connected lines that form the approximate shapes of a road curve, and included information such as the curve location, length, radius, deflection angle, ball-bank indicator reading, speed limit, advisory speed, and AADT.

Crashes that occurred on the same year the FIST was implemented were excluded from the CMF calculations, as it was unclear from the crash data whether these crashes occurred before or after the implementation, or even possibly during the construction of the FIST. For example, for district 6, HFST was implemented in 2017, and thus the crashes before HFST implementation included crashes from 2012 to 2016, crashes after HFST implementation included crashes from 2018 to 2020, and crashes in 2017 were ignored.

There were some initial challenges with the identification of curve AADTs, as there were multiple differing reports of AADTs. Initially, there was only one AADT associated with each curve, and therefore yearly AADTs had to be manually joined to each curve through ArcMap. (more from Ron, I’m not sure of the exact details).

Because the crash dataset included all crashes in the studied districts, there was also a need to identify which crashes occurred on curves with FIST and to discard the rest. To do so, a buffer was constructed around each curve in ArcMap—these buffers had a width of 100 ft around the road and extended 500 ft beyond the road polyline to capture all possible curve crashes. Crashes that intersected these buffers were identified as crashes that occurred on the corresponding curves and were then used as part of the CMF calculation.

Figure number: Photo example of buffer

* 1. Describe some of the effort to attribute AADT to the curve. Describe the curve data availability.
  2. Curve data was developed from a Georgia tech application curve finder, which has given this research team a curve inventory on all GA state routes???

## Naïve Bayes Approach to Developing CMFs

The first method used to quantify the crash reduction effects of FISTs in this study is the naïve Bayes approach. The naïve Bayes approach is a straightforward way of calculating CMFs as it simply uses the proportion below in **Equation 1**:

(1)

The naïve CMFs in this study are calculated using the cumulative crash frequencies of all curves which each FIST. These cumulative naïve Bayes CMFs are then used to find which crash types should be used for the calculation of the empirical Bayes CMFs and to conduct an analysis on the significant roadway characteristics that affect the calculated CMFs the most.

* 1. Simple before and after.
  2. This was utilized to get a preliminary look at the crashes and identify which crash types EB CMFs should be developed for

## Empirical Bayes Method to Developing High Quality CMFs

A flaw of the naïve Bayes method is that the effects of external factors such as changes in traffic volume or other time trends on CMFs are not accounted for. The empirical Bayes Method can address these time trend factors in the calculations of CMFs by not just using observed crashes on a curve but by also using the predicted number of crashes generated by a prediction model, also known as a safety performance function (SPF). These predicted numbers of crashes are used to represent the number of crashes that would’ve occurred had the FIST not been applied to the curve, and the observed crashes are weighed against these predictions to adjust the CMF.

For example, a curve that had a FIST implemented but also a significantly higher traffic volume could possibly observe a higher number of crashes after the FIST. Using a naïve Bayes approach, the number of crashes would suggest that the FIST caused an increase in crashes. However, an empirical Bayes approach would weigh the observed crashes against the prediction—which would predict that crashes should increase due to increased traffic and not because of the FIST—and thus decrease the final calculated EB CMF accordingly.

### Development of Safety Performance Function Prediction Models

As noted in the previous section, the safety performance function (SPF) is used to calculate the predicted number of crashes needed in order to calculate the EB CMF. The predicted crashes are calculated based on the curve characteristics, which for this study includes whether the road is divided, the natural log of the curves’ deflection angle, the curve length, the natural log of the AADT of the curve, the natural log of the ball bank indicator (BBI) measurement of the curve, and the speed difference between the posted speed limit and the advisory curve speed limit. The calculation for the predicted number of crashes per year (P) given certain curve characteristics (Cn) and coefficients for those characteristics (Yn) is as follows in **Equation 2**:

(2)

The coefficients are found through (Need help explaining the process of finding model coefficients). The negative binomial model outputs coefficients that are attributed to a curve characteristic. A separate set of coefficients is created for each crash type identified after the calculation of the naïve Bayes CMFs.

* 1. 5 prediction models are developed.
  2. Models assessed based on goodness of fit,p-value of variables, and preliminary basis of a concurrent study to develop high quality SPFs for network screening purposes (reference my paper)
  3. SPFs are developed for rural curves in GDOT districts 1,2, and 6 the dependent variable of the spf is the crash frequency on each curve

### Calculation of the EB CMF

To weigh the observed number of crashes against the predicted number crashes generated by the SPF, the two values are first combined into an expected number of crashes for both before and after implementation of FIST. The expected crashes before FIST implementation (Ebefore) is calculated using the cumulative crash frequency before FIST implementation for all curves (O), the cumulative predicted crash frequency before FIST implementation for all curves (P), and a weight *w* in the following **Equation 3**:

(3)

The weight *w* can be calculated by using *k*, the dispersion of the SPF prediction model, and the following **Equation 4**:

(4)

The expected number of crashes after the FIST is found using the following **Equation 5**:

(5)

The variance (*V*) of the expected crashes after is then found using the following **Equation 6**:

(6)

Using these values, the final EB CMF is calculated using **Equation 7**:

(7)

The calculation of the standard deviation of the EB CMF is as follows in **Equation 8**:

(8)

Multiple CMFs are calculated for each FIST using the crash types found in the naïve Bayes CMF crash type analysis.

## Modeling naïve CMFs as functions of the roadway environment

After the naïve Bayes CMFs are calculated, a regression analysis in R is performed to understand the effect of different roadway features on those CMFs and to propose a potential model for predicting future CMFs given a set of roadway features. In this study, this analysis is limited to CMFs for HFST in district 6. The roadway features used for this analysis are selected on the basis that these features should be accessible to engineers before implementing the FIST. Thus, the roadway features selected for the analysis are the speed limit of the curve, the curve length, the BBI measurement of the curve, the average AADT of the curve before HFST implementation, the intersection-related crash frequency of the before HFST implementation, and the crash frequency of the curve before HFST implementation. A multiple linear regression model that uses the calculated naïve CMFs as the dependent variable and the selected roadway features as the independent variables is generated, and a backward and forward feature selection process is performed to find the significant roadway features. The variables that are found to have significant effect on the calculated EB CMFs are then isolated by grouping curves based on those variables and then calculating separate EB CMFs for each group. For example, if curve length was identified as a significant variable, then the curves would be grouped based on longer or shorter curve lengths, and a separate EB CMF would be calculated for each curve length group.

# RESULTS

## Naïve Bayes CMFs

The preliminary investigations with the naïve Bayes CMFs led to four different crash types to investigate with EB CMFs: a CMF with all crashes, a CMF with only single vehicle crashes, a CMF with only crashes with the “Negotiating a curve” maneuver, and a CMF with only crashes with wet road conditions were calculated. The crash frequency before FIST implementation, crash frequency after FIST implementation, and calculated naïve Bayes CMFs for each FIST are summarized below in table number below.

Table number: Crash Frequencies and Naïve Bayes CMFs of Studied FISTs

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | CMF | Crash frequency before FIST  implementation  (2013-2016) in crashes/year | Crash frequency after FIST implementation  (2018-2020) in crashes/year | CMF Value |
| Phonolite/Wyoming Bauxite | All Crashes | 41.75 | 40.00 | 0.958 |
| Single Vehicle | 27.25 | 24.67 | 0.905 |
| Curve | 27.25 | 20.67 | 0.758 |
| Wet Road | 8.75 | 9.33 | 1.067 |
| LWA | All Crashes | 5 | 6.33 | 1.267 |
| Single Vehicle | 3.75 | 3.67 | 0.978 |
| Curve | 1.00 | 0.33 | 0.333 |
| Wet Road | 0.25 | 1.00 | 4.00 |
| HFST | All Crashes | 167.00 | 113.67 | 0.681 |
| Single Vehicle | 111.50 | 61.33 | 0.550 |
| Curve | 117.00 | 72.00 | 0.615 |
| Wet Road | 56.25 | 26 | 0.462 |

## Developed SPFs

The coefficients of the SPF function for all crashes, single vehicles crashes only, curve crashes only, and wet road crashes only are listed below in tables number to number.

Table number: Total Crashes SPF Coefficients

|  |  |  |  |
| --- | --- | --- | --- |
| Label | Estimate | Divided by number of years | P value |
| Intercept | -4.345000 | -0.543125 | < 2e-16 \*\*\* |
| Divided road | 0.332100 | 0.0415125 | 1.32e-08 \*\*\* |
| Natural log of deflection angle | 0.247400 | 0.030925 | 2.67e-11 \*\*\* |
| Length | 0.000221 | 2.76375E-05 | 1.18e-10 \*\*\* |
| Natural log of AADT | 0.649600 | 0.0812 | < 2e-16 \*\*\* |
| Dispersion | 1.233000 |  | |
| Years | 8 |
| R2 | 0.491146 |

Table number: Single Vehicle Crashes SPF Coefficients

|  |  |  |  |
| --- | --- | --- | --- |
| Label | Estimate | Divided by number of years | P value |
| Intercept | 2.878000 | 0.35975 | < 2e-16 \*\*\* |
| Divided road | -0.270400 | -0.0338 | 3.95e-08 \*\*\* |
| Natural log of deflection angle | 0.141300 | 0.0176625 | 0.000409 \*\*\* |
| Length | 0.000408 | 5.09625E-05 | < 2e-16 \*\*\* |
| Natural log of AADT | 0.378700 | 0.0473375 | < 2e-16 \*\*\* |
| Natural log of BBI | 0.146800 | 0.01835 | 5.22e-07 \*\*\* |
| Speed limit and advisory speed difference | 0.015740 | 0.0019675 | 1.43e-05 \*\*\* |
| Dispersion | 2.604400 |  | |
| Years | 8 |
| R2 | 0.323600 |

Table number: Curve Crashes SPF Coefficients

|  |  |  |  |
| --- | --- | --- | --- |
| Label | Estimate | Divided by number of years | P value |
| Intercept | -5.882000 | -0.73525 | < 2e-16 \*\*\* |
| Divided road | -0.269500 | -0.0336875 | 2.59e-06 \*\*\* |
| Natural log of deflection angle | 0.630000 | 0.07875 | < 2e-16 \*\*\* |
| Length | 0.000093 | 1.16363E-05 | 0.0198 \* |
| Natural log of AADT | 0.497900 | 0.0622375 | < 2e-16 \*\*\* |
| Natural log of BBI | 0.254800 | 0.03185 | 4.94e-14 \*\*\* |
| Speed limit and advisory speed difference | 0.006123 | 0.000765375 | 0.1264 |
| Dispersion | 2.046300 |  | |
| Years | 8 |
| R2 | 0.422435 |

Table number: Wet Road Crashes SPF Coefficients

|  |  |  |  |
| --- | --- | --- | --- |
| Label | Estimate | Divided by number of years | P value |
| Intercept | -5.932000 | -0.7415 | < 2e-16 \*\*\* |
| Natural log of deflection angle | 0.245500 | 0.0306875 | 8.02e-05 \*\*\* |
| Length | 0.000219 | 0.000027425 | 3.33e-05 \*\*\* |
| Natural log of AADT | 0.654000 | 0.08175 | < 2e-16 \*\*\* |
| Speed limit and advisory speed difference | 0.021210 | 0.00265125 | 0.000286 \*\*\* |
| Dispersion | 0.887400 |  | |
| Years | 8 |
| R2 | 0.295964 |

## Empirical Bayes CMFs

The summary of the calculated Empirical Bayes CMFs is shown below in table number. No Empirical Bayes CMFs were calculated for curves in District 2 with LWA FIST due to the lack of sufficient data.

Table number: Summary table of calculated EB CMFs

|  |  |  |  |
| --- | --- | --- | --- |
|  | Filter | Empirical Bayes CMF | Standard Deviation |
| Phonolite/Wyoming bauxite | All crashes | 0.9163 | 0.1427 |
| Single vehicle crashes | 0.8576 | 0.1642 |
| Curve crashes | 0.7172 | 0.1372 |
| Wet surface crashes | 0.8616 | 0.2752 |
| HFST | All crashes | 0.6719 | 0.0521 |
| Single vehicle crashes | 0.5421 | 0.0513 |
| Curve crashes | 0.6065 | 0.0562 |
| Wet surface crashes | 0.4454 | 0.0592 |

## Significant Factors of HFST CMFs

The summary of the found significant road features to the calculated CMFs for HFST are below in table number. Figures number to number are the regression plots made for these significant road features.

Table number: Significance of roadway factors on the calculated EB CMFs

|  |  |  |
| --- | --- | --- |
| Significant Roadway Features | Coefficient | P-Value |
| Average AADT Before FIST | 6.274×10-5 | 0.00026 |
| Intersection Related Crash Frequency Before FIST | 6.865×10-2 | 0.01441 |
| Crash Frequency Before FIST | -1.515×10-1 | 0.00140 |

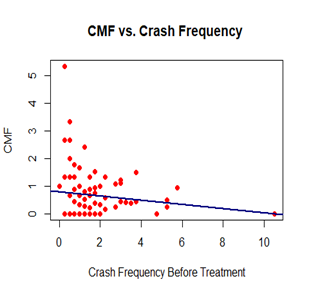


Figure # [desc]

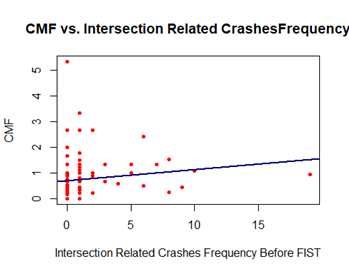


Figure # [desc]

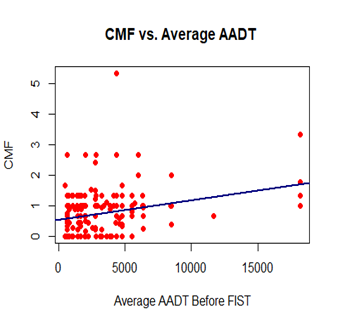


Figure # [desc]

The curves in district 6 were grouped based on the significant variables of crash frequency before FIST implementation and average AADT, and the EB CMFs for each group are listed below in table number.

Table number: District 6 HFST EB CMFs for differing curve characteristics

|  |  |  |
| --- | --- | --- |
|  | CMF (s.e.) | |
|  | AADT ≤ 2000 | AADT > 2000 |
| Crashes Before FIST Implementation ≤ 3 | 0.8679 (0.1614) | 0.9558 (0.2090) |
| Crashes Before FIST Implementation > 3 | 0.4568 (0.1095) | 0.5717 (0.0585) |

* Display Jiashu’s Model of CMF vs roadway environment
* Display R^2
* Display p-values
* Display coefficients
* Covid effects

# DISCUSSION

## Use of EB method

Through the calculations demonstrated in the methodology, the EB method helped account for the correlation between the general increase of traffic and the general increase of crashes on the monitored curves. Thus, the adjusted CMFs were lower than the original naïve Bayes method CMFs, and the EB method realized more benefit of the FISTs. As seen in tables number and number, this trend holds true for all CMFs calculated regardless of FIST or the type of crash filter, and the greatest benefits to CMFs were seen for phonolite—especially in the CMF for wet road crashes, which improved from a naïve CMF of 1.0667 to an EB CMF of 0.8616.

However, the standard deviations for the phonolite EB CMFs are greater than the difference between the EB CMFs and the naïve CMFs in all cases, indicating that the gains made through using the EB method aren’t statistically significant for phonolite. On the other hand, the standard deviations for the HFST EB CMF

## Crash Types

Because not all crashes on curves are necessarily affected by or related to the FIST implemented there—such as head-on collisions, where friction is not a cause—three distinct filters were applied to the crashes for each FIST to gain a clearer perspective of the FISTs effect on crashes where FIST does have relevance. These filters were single vehicle crashes, related crashes (where the vehicle maneuver(s) include a vehicle that is “Negotiating a curve” in the data), and wet road crashes. These filters revealed interesting trends in final calculated CMFs: for example, for HFST, the single vehicle crash CMF and wet road crash CMF are lower than the all crashes CMF, regardless of whether the CMF was calculated using the naïve Bayes or empirical Bayes method. This indicates that HFST is especially effective in reducing single vehicle and wet road crashes on curves. Similar trends are not seen in neither the naïve or the empirical CMFs for phonolite and LWA.

* Discuss the 5 that we moved forward with to make high quality CMFS

## CMF Model

It was found that there are three significant roadway features, which are crash frequency before HFST implementation, intersection-related crash frequency before HFST implementation, and average AADT before HFST implementation, which have coefficients of -1.515×10-1, 6.865×10-2, 6.274×10-5, and P-values of 0.00026, 0.01441, 0.0014, respectively. Other typical roadway features such as curve radius, BBI, speed limit, and curve length were abandoned in the model during the feature selection process as they were found to be uncorrelated and insignificant in predicting a CMF.

The latter two significant factors—average AADT before HFST and intersection-related crash frequency before HFST—are features with positive coefficients, which means that an increase in these factors correlate with an increase of the final calculated CMF. This indicates that HFST might be less effective in curves with high AADT and/or are located near an intersection with a high crash frequency history. This makes sense intuitively, as higher traffic volume and intersection conflict points create more opportunities for crashes that aren’t mitigated by the increased friction from FISTs. Crash frequency before FIST, on the other hand, has a negative coefficient in the multiple linear regression model, indicating that curves that have a higher prior crash frequency tend to result in lower CMFs, or a greater improvement in crash reduction. It is worth noting that this trend might simply be because curves that have small crash frequency have little room for improvement and thus the benefit for implementing HFST might be less visible through the crash data. Future studies can expand upon these findings by locating a threshold for optimizing Cost/Benefit for different types of FISTs implementation based on prior crash frequency or traffic volume.

After finding that prior crash frequency and average AADT were the only significant variables for the EB CMFs, curves in District 1 and District 6 were organized into four groups based on these variables. Each curve was assigned an AADT rating, which would be either low AADT (≤ 2000 vehicles per day) or high AADT (> 2000 vehicles per day), and a prior crash frequency rating, which would be either low prior crash frequency (≤ 3 crashes in the years before FIST) or high prior crash frequency (> 3 crashes in the years before FIST).

The mean number of crashes before FIST implementation was found to be between 3 and 4, and so the curves were grouped in curves with 3 or less crashes or 4 or more crashes before FIST implementation. As for AADT, the GDOT Design Policy Manual designates roads with an AADT less than 2000 vehicles per day as low AADT or something roads, and thus an AADT of 2000 vehicles per day was used as the group divider.

Analysis after tables are updated

* Discussion of the interpretation of the model. Discuss the signs of the coefficients
  + 2 factors were identified as important. Prior crash AADT and prior crash frequency roadways with high aadt and low crash frequency did not realize as much benefit form HFST.
  + The curve characteristics were not significant variables. The only change in the CMF model we could account for was prior crash frequency and traffic volume

## Different Materials

Out of the three materials presented in this report, HFST by far performed the best. The Empirical Bayes CMFs show that HFST reduces crashes of all types by about 33%, and even more significantly, that it reduces wet road crashes by about 55%. Phonolite was significantly less effective, with its Empirical Bayes CMFs suggesting that it reduces crashes of all types by less than 9%. These findings correlate to the friction performance of these materials over time found in that report that was done before this (ref). There were no conclusive findings for the performance of LWA, however, due to the lack of crash data.

## COVID-19 Impact on EB CMFs

There were initial concerns that the decreased traffic volume during the COVID-19 pandemic would cause significant changes to the calculated CMFs. However, after comparing EB CMFs that included data from the year 2020 to EB CMFs that excluded said data, only a minimal difference was noticed, suggesting that the sample size of the data was large enough to mitigate the effect of possible traffic volume variations during the pandemic. Since crashes are rare events, it is more advantageous to utilize more years of data, and thus data from the year 2020 was utilized to increase the sample size of data after FIST implementation to at least three years of data.

# CONCLUSION

Summary:

Limitations:

Future research Needs

# ACKNOWLEDGMENTS

# AUTHOR CONTRIBUTIONS

# REFERENCES

1. Reference 1
2. Reference 2