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A fully Bayesian before–after analysis of permeable friction course (PFC) pavement wet weather safety

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ABSTRACT

Permeable friction course (PFC), a porous hot-mix asphalt, is typically applied to improve wet weather safety on high-speed roadways in Texas. In order to warrant expensive PFC construction, a statistical evaluation of its safety benefits is essential. Generally, the literature on the effectiveness of porous mixes in reducing wet-weather crashes is limited and often inconclusive. In this study, the safety effectiveness of PFC was evaluated using a fully Bayesian before–after safety analysis. First, two groups of road segments overlaid with PFC and non-PFC material were identified across Texas; the non-PFC or reference road segments selected were similar to their PFC counterparts in terms of site specific features. Second, a negative binomial data generating process was assumed to model the underlying distribution of crash counts of PFC and reference road segments to perform Bayesian inference on the safety effectiveness. A data-augmentation based computationally efficient algorithm was employed for a fully Bayesian estimation. The statistical analysis shows that PFC is not effective in reducing wet weather crashes. It should be noted that the findings of this study are in agreement with the existing literature, although these studies were not based on a fully Bayesian statistical analysis. Our study suggests that the safety effectiveness of PFC road surfaces, or any other safety infrastructure, largely relies on its interrelationship with the road user. The results suggest that the safety infrastructure must be properly used to reap the benefits of the substantial investments.

1. Introduction

The Texas Department of Transportation (TxDOT) is currently using permeable friction course pavements (PFC) to functionally improve structurally sound impermeable pre-existing pavements. Being the second largest state highway system, TxDOT annually maintains approximately 194,000 road lane miles. A review of asphalt mixture construction quantities over recent years indicates that the use of PFC has increased significantly and now makes up about 5% of the total tonnage paved. PFC is an open-graded asphalt concrete mixture predominantly comprising large single-sized aggregate and high air void content (about 20–25%) and is typically constructed in thin pavement lifts. PFC is a hot mix suitable for pavement maintenance with significant safety and environmental benefits. PFC has become popular since it drains water off the roadway quicker, reduces the risk of hydroplaning and minimizes splash/spray from vehicles traveling at highway speeds. For example, Nicholls and Daines (1992), Nicholls (1997) reported 90–95% reduction in splash and spray on porous asphalt surfaces. Furthermore, PFC reduces glare and improves the visibility of traffic markings. The porous structure of PFC potentially reduces tire-pavement noise, which is a main concern in urban neighborhoods. Earlier studies reported relatively higher skid resistance on PFCs in general compared to dense graded mixtures (Kandhal, 2002; Flintch, 2004; McGhee et al., 2009). The enhanced frictional characteristics of PFC road surfaces are arguably due to the coarse macro-texture of the porous skeletal structure.

A vast body of literature has demonstrated that vehicle crashes are more likely to occur under wet conditions. Given the wet weather benefits and adequate skid resistance of PFCs, their application offers the potential for safety improvement. However, the safety benefits of porous asphalt surfaces have not been adequately studied. Elvik and Greibe (2005) performed a meta-analysis of different safety studies to determine the safety benefits of porous asphalt mixes in European countries. Interestingly, their analysis

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observed no clear effect of porous asphalt. Estimates of safety effectiveness were very small and rarely statistically significant across the studies analyzed. Based on twelve safety effectiveness estimates, porous mixes did not tend to be favorable under wet conditions relative to dry conditions. Note that these studies were thoroughly evaluated for reliability and validity prior to their incorporation into the meta-analysis. Elvik and Greibe (2005) reported that "the research that has been reported so far regarding road safety effects of porous asphalt is inconclusive". Elvik and Greibe (2005) attributed the unexpected results to the adapting behavior (by driving faster under wet conditions) of the road users which may offset the favorable impacts and nullify the potential wet weather benefits of porous pavements.

Furthermore, there is a multitude of risk factors that govern the overall safety of PFC surfaces. The interaction of these risk factors may either improve the overall safety of PFC or reduce the existing safety level. For instance, a reduction in crash numbers during a rainy season may be offset by the potential hazards of increased ice formation in porous asphalt mixes. On the other hand, DPS of Travis County, Texas, reported that the number of wet weather accidents on a FM road facility dropped by more than 90% after the road was overlaid with PFC, despite almost twice as many rain days (Dale, 2012). Such project specific studies lack statistical justification but rather rely largely on raw crash numbers. In summary, these findings (Elvik and Greibe, 2005; Dale, 2012) cast doubts on the safety benefits of porous asphalt mixes and emphasize the need for further rigorous investigations in order to warrant these mixes for safety improvement. In addition, PFC is considerably more expensive per tonnage (between 20 and 50 percent) than typical dense-graded hot-mix alternatives. To warrant the extra cost of PFC, particularly in terms of its safety effectiveness, requires a thorough statistical evaluation of the underlying safety benefits.

To truly understand the wet weather crash reduction benefits of PFC requires a before–after safety analysis. This analysis ensures that the crash reduction is not due to other natural reasons such as regression to the mean (RTM) bias or to seasonal/random fluctuations, but to the presence of a PFC treatment. Using probability theory, a time period with a large crash frequency is followed by another period with a lower crash frequency (Hauer, 1986). Furthermore, a before–after safety analysis allows for incorporating any site specific factors that influence the crash frequency into the safety effectiveness evaluation. Empirical Bayes (EB) and Fully Bayes (FB) approaches are the most commonly used techniques for performing before–after safety analysis (Hauer, 1986; Persaud et al., 1997; Persaud and Lyon, 2007). The objective of these approaches is to evaluate the average reduction in crashes solely caused by the treatment (PFC) while excluding the reduction in crashes due to other factors. Reference or comparison sites (non PFC sites) are typically incorporated into before–after safety analyses to model the crash trends in the absence of treatments; any further crash reduction in addition to that observed at reference sites is regarded as the safety effectiveness of the treatment. An empirical Bayes approach includes developing Safety Performance Functions (SPF) to predict the crash counts using site specific features (such as traffic, etc.); SPFs are typically based on data from reference sites. SPF is essentially the expected value or mean of the respective crash counts and expressed as a function of site characteristics. Highway Safety Manual recommends using negative binomial specifications to construct SPFs. The expected crash count of a treatment site is calculated as a weighted combination of the observed crash count (after the PFC application) and the estimated crash count (or the general trend) using the respective SPF. On the other hand, a fully Bayesian approach avoids including noisy observed data in the before-and-after analysis; rather it uses the estimated before and after crash counts. A fully Bayesian approach incorporates into the analysis both before and after crash data from reference as well as treatment (or PFC) sites. Fully Bayesian methods offer a greater flexibility in specifying the underlying crash count model and facilitate detailed causal inferences (Lan et al., 2009). Persaud et al. (2010) reported that EB and FB methods are comparable with large sample of reference sites. We opted to use a fully Bayesian approach to evaluate the safety effectiveness of the PFC application.

In summary, to the author's knowledge, safety effectiveness evaluation studies on PFC are limited. This paper adds to the literature by quantifying the wet weather crash reduction benefits of PFC using a fully Bayesian before–after analysis. We identified a number of PFC overlaid road segments across Texas dating back to 2003; we also identified reference or non-PFC sites that are generally similar to the PFC sites in terms of site specific features. Subsequently, using Bayesian techniques we constructed the empirical distribution of an estimate of PFC safety effectiveness or ratio of the expected crash counts corresponding to after and before the PFC installation periods (relative to that of reference sites). This paper describes the dataset development process for a fully Bayesian before–after safety analysis of PFC treatment as well as the salient features of the dataset. Next, a negative binomial count specification is constructed to model the underlying reference population of crash counts; crash counts on PFC sites are assumed to be generated from a similar population but differed by a mean shift. Subsequently, we describe a computationally efficient procedure for fully Bayesian estimation of the proposed crash count model and for construction of the posterior distribution of the safety effectiveness. Finally, we discuss the posterior estimation results and comment on the PFC effectiveness in reducing wet weather crashes. The paper concludes with recommendations on the use of PFC for reducing wet weather crashes.

2. Data description

First, we identified several PFC projects that were constructed as main lanes since 2003. PFC installation project locations were extracted across the Texas road network using TxDOT's HMA project database. Note that this sample does not include PFC overlays constructed on service or frontage roads, on- and off-ramps or connectors and flyovers. The construction year of the PFC projects is different from site to site as indicated in Table 1. The difference in the construction years of the individual PFC treatment sites has been incorporated into the before–after safety analysis. The study period corresponding to individual sites was divided into before and after periods using the respective construction year. The PFC installed road segments varied between 1.1 and 19.6 miles in total length with 2–8 lanes (both traffic direction). PFC sections were selected from different facility types (see Table 1 for categorized proportions) to account for the influence of facility type on the PFC effectiveness evaluation. PFC is generally used for resurfacing Interstate Highways (IH) and used only on higher volume farm- or ranch-to-market (FM/RM) roads, national (US) and state highways (SH). The imposed speed limits of the identified PFC sections varied from 40 to 75 miles per hour. To incorporate the climatic effects into the analysis, PFC projects spanning across the five typical Texas climatic zones were included. Generally, PFC is no longer used in very cold/wet regions where the possibility of "black-ice" conditions severely impacts the safety performance of these mixes. The descriptive statistics show that PFC is favored in wet and warm climates. In Texas, PFC mixes are manufactured using either polymer modified Performance Grade (PG) or Asphalt Rubber (AR) binders. PFCs containing AR binders tend to clog faster than the PFCs manufactured using regular binder, which may in turn affect safety effectiveness. On the other hand, asphalt rubber based PFC surfaces tend to offer better dry skid resistance than do conventional PFCs. We included both types of PFCs in the analysis; however, the