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Frequency Analysis of Equivalent Property-Damage-Only (EPDO) Crashes at Intersections

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Abstract: Traffic crashes are burdening societies with severe costs in terms of public health and economic loss. Intersection-related crashes are responsible for a large proportion of these losses due to their higher frequency and severity. Understanding the factors contributing to intersection crash frequency and severity is essential to mitigate their grave consequences. This study covered the analysis of roadway risk factors, influencing the frequency of equivalent property-damage-only (EPDO) crashes at intersections. The study included developing a negative binomial modeling framework to examine nine years of intersection crash records in the state of Wyoming. The modeling results revealed the key role of pavement friction in intersection safety and EPDO frequency. The findings also demonstrated that intersection location, grade, road functional classification, road surface type, the presence of guardrails, right shoulder type, and horizontal curvature all influence the EPDO crash frequency at intersections.

Keywords: EPDO crashes; pavement friction; intersection safety; intersection crash analysis; roadway geometric characteristics; roadway functional classification

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1. Introduction

The estimated annual economic cost for motor vehicle crashes in the state of Wyoming is USD 788 million [1]. This figure reflects the financial burden of traffic crashes on the state of Wyoming and the well-being of its residents. Intersections are recognized among the most high-risk locations in roadway networks. Intersections are considered crash-prone locations due to the interaction between different transportation models and complex traffic movements. Crashes occurring at intersections are responsible for over 20% and 40% of traffic-related fatalities and injuries, respectively. The study of crash economic burden requires combining the effects of crash frequency and crash severity. Therefore, transportation professionals commonly use equivalent property-damage-only (EPDO) crashes, which are crash counts magnified by crash costs according to their severity [2–9]. EPDO crash analysis is also used for network screening and crash blackspot identification [10,11].

Traffic crashes are affected by the driver, vehicle, environmental, and roadway attributes. Intersection characteristics such as traffic control, type, location, roadway classification, median and shoulder attributes, grade, and curvature influence the crash frequency and severity. The impact of roadway geometric attributes on crash count and severity has been widely studied. However, other roadway characteristics related to the pavement are yet to be fully examined. Pavement friction is rarely considered in traffic safety studies and its influence on roadway safety is yet to be thoroughly explained. The studies which examined pavement friction demonstrated that friction can be a significant risk factor affecting the severity and frequency of certain crash types [12–18]. Pavement friction, also commonly known as skid resistance, is the resisting force to relative motion between traveling vehicle tires and the pavement surface. This force is essential for vehicle maneuvering and stopping, which directly affects the crash frequency and severity [19,20].

The pavement friction supply tends to decline over time due to the aggregate polishing in the surface layer under moving traffic. Therefore, consistent monitoring of friction levels is needed to ensure the sufficiency of pavement friction supply. Friction monitoring can be even more significant at special roadway locations with higher friction demand and rapid friction deterioration rates, such as curves, ramps, and intersections. A limited number of agencies would collect friction data at such locations with the need to investigate safety concerns, usually involving the increase of wet crashes [21–23]. Maintaining adequate friction levels can be achieved by applying pavement surface treatments, particularly at special locations in the network. These treatments include chip seals, hot-mix asphalt (HMA) overlays, open-graded friction courses (OGFC), micro-milling, and high-friction surface treatments (HFST), which are ideal for spot applications [19,24,25].

As Federal and state departments are working to mitigate the severe impacts of traffic crashes on society, further investigation is needed to examine the factors contributing to traffic crashes. The objective of this study was to further investigate the geometric and roadway characteristics, including pavement friction, that contribute to crash frequency and severity at intersections. The study included developing a negative binomial model to explore the influence of intersection attributes on the EPDO crash frequency at intersections in the state of Wyoming.

2. Literature Review

This section reviews multiple studies relevant to EPDO crash analysis and the pavement friction impact on intersection safety. The limitations of the reviewed studies are identified and the research contribution to the literature is discussed.

Son et al. [26] proposed new performance measures to identify high-risk urban intersections using data from South Korea. The study utilized random forest and extreme gradient boosting (XGB) approaches to estimate the severity factor weights. The authors used the estimated factor weights to develop safety performance functions (SPFs) following Poisson and negative binomial techniques. The study included crash, vehicle, driver, and environmental characteristics as potential risk factors. Even though the study considered the road surface condition (dry, wet, etc.), the authors did not include roadway geometric attributes or pavement friction in the model.

Roshandeh et al. [27] utilized a random-parameter Poisson model to investigate the factors contributing to crash frequency at signalized intersections in Chicago, Illinois. The study examined the impact of traffic, geometric, and environmental characteristics. The study included the pavement condition as a potential influencing factor. The results identified the main factors influencing crash frequency as traffic volume at evening peak, intersection lighting, and pavement condition. The findings highlighted the strong correlation between deteriorated pavement conditions and increased crash frequency at intersections. However, the authors did not incorporate the crash severity and did not consider pavement friction in the analysis.

Poch and Mannering [28] developed a negative binomial model to analyze the factors contributing to intersection crash frequency in Bellevue, Washington. The results identified several traffic-related and geometric attributes influencing the frequency of different types of intersection crashes. However, the study did not consider crash injury severity and did not include any of the pavement characteristics in the model.

Sharafeldin et al. [29] utilized a Bayesian ordered probit model to examine the factors influencing the injury severity of intersection crashes. The analysis incorporated crash, driver, environmental, and roadway risk factors, including pavement friction. The findings showed that pavement friction is a significant contributing factor to crash severity and that lower friction numbers are associated with increasing severity levels. Even though the study incorporated pavement friction in the analysis, the study examined a limited dataset, did not include other roadway characteristics, and did not consider crash frequency.

Claros et al. [30] investigated the challenges of traffic safety management in small jurisdictions and small agencies. The study developed local crash prediction models for intersections in the Madison metropolitan area, Wisconsin. The authors utilized performance measures including EPDO crash frequency and level of service of safety (LOSS) to screen the network and rank the examined sites. The benefit–cost ratio was estimated for intersections using potential treatments. Sites with the highest safety benefit were selected for implementation. The study considered traffic volume, intersection type, and traffic control as risk factors for crash severity and frequency. However, the study did not include other intersection attributes or pavement friction in the analysis.

Afghari et al. [31] employed a joint model of crash count and crash severity to identify the high-risk crash spots on the roadway network in Queensland, Australia. The study examined several traffic characteristics and roadway geometric attributes. The analysis included pavement seal condition and pavement roughness as independent variables. The results showed that unsealed pavements and higher pavement roughness increased crash counts and crash severity. The results also showed that sharper horizontal curves and urban roads were associated with less severe crashes. In addition, rolling terrain was linked to a decreased crash count. However, the study did not include pavement friction in the analysis and did not examine intersection crashes.

Sharafeldin et al. [32] developed an ordinal probit model to examine the roadway attributes contributing to the injury severity of intersection crashes. The study investigated the influence of environmental conditions and a set of roadway characteristics, including pavement friction. The results demonstrated that pavement friction significantly influences intersection crash severity. The study also identified other significant roadway attributes, including location, functional classification, and right shoulder width. However, the study did not consider crash frequency nor the financial burden of crashes.

Roy et al. [33] developed safety performance functions (SPFs) for different classes of roads in Wyoming. The authors examined the effect of traffic, roadway, environmental, and vehicle characteristics on total crashes and EPDO crash frequencies. Pavement friction was investigated in this study. The findings demonstrated that pavement friction is a significant factor, as lower friction numbers increased the frequency of total and EPDO crashes at most of the examined roadway functional classes. The study also identified several significant factors, including traffic volume, grade, horizontal curvature, and road surface condition. This study did not examine crashes at intersections and only examined crashes at road segments.

While there is a growing interest in exploring the relationship between pavement surface friction and roadway safety, the knowledge of pavement friction's impact on intersection safety is insufficient. To the best of the authors' knowledge, this is the first study to explore the influence of pavement friction on crash frequency and severity considering the financial burden of crashes. This work included developing a negative binomial modeling framework to investigate the influence of roadway geometric elements and intersection attributes on the EPDO crash frequency at intersections.

3. Research Methodology

This study developed a negative binomial (NB) model to explain the influence of intersection attributes, as independent variables, and EPDO crash count as the response, which is a non-negative integer. The NB modeling framework was utilized instead of Poisson as the NB model assumptions allow for overdispersion, unlike the Poisson model. The response variable, EPDO, was over-dispersed. Overdispersion is when the variance of the count variable is greater than its mean.

Following the NB model, the risk, P_i, of observing y_i EPDO crashes on a specific intersection, i, is computed as follows [34]:

$$P_i(y_i) = \frac{\Gamma\left(y_i + \frac{1}{k_i}\right)}{y_i! * \Gamma\left(\frac{1}{k_i}\right)} \times \left(\frac{\frac{1}{k_i}}{\frac{1}{k_i} + \lambda_i}\right)^{\frac{1}{k_i}} \times \left(\frac{\lambda_i}{\frac{1}{k_i} + \lambda_i}\right)^{y_i} \quad (1)$$

where λ_i and k_i represent the mean EPDO frequency and dispersion parameter, while $\Gamma(.)$ is the gamma function. Dispersion parameters measure the sample fluctuation around the mean value. The Gamma function is typically used as an extension of the factorial function to complex numbers [33]. The variance function of the NB model is expressed as follows [35]:

$$\text{Var}(y_i) = \lambda_i(1 + \lambda_i k_i) \tag{2}$$

The mean EPDO frequency is a function of the intersection characteristics, x_i, and is expressed as follows [35]:

$$\lambda_i = \exp(\beta_0 + \beta_1 X_1 + \beta_2 X_2 + \ldots + \beta_p X_p + \theta_i) \tag{3}$$

The regression coefficients, β's, are obtained by using the maximum likelihood estimation and are known as MLE estimates. The parameter, θ_i, is expressed as $\exp(\theta_i) \sim \Gamma(1, k_i)$ [35]. The crash injury severity was included in the analysis to properly reflect the impact of the intersection attributes, which could not be captured by considering only the crash counts. The study implemented the EPDO approach to combine the crash severity with the crash count.

The EPDO crash frequencies are estimated by taking the ratio of crash cost to property-damage-only (PDO) crash cost, according to WYDOT crash cost estimates. The crash costs include medical costs, legal expenses, property damage costs, etc. The EPDO crash frequencies were calculated as follows for each crash severity level:

- 277 for fatal crashes
- 13 for suspected serious injury crashes
- 4 for suspected minor injury, possible injury, or unknown severity crashes
- 1 for PDO crashes

4. Data Preparation

The crash data analyzed in this study were obtained from the Critical Analysis Reporting Environment (CARE) package. The CARE package is supported by the Wyoming Department of Transportation (WYDOT). The dataset is developed by collecting the crash records details from the police crash reports.

The data included EPDO crash frequency at 359 intersections in Wyoming from January 2007 through December 2017, except for the years 2010 and 2011 due to the unavailability of friction data. The examined intersections were mapped, and the crashes that occurred within a 250 feet buffer (76.2 m) from the center of the intersection were considered intersection crashes. This approach follows the guidelines of the American Association of State Highway and Transportation Officials [36]. The data were prepared such that each observation represented the EPDO crash frequency at an intersection in one year. The dataset comprised 1594 observations. EPDO crash frequencies were estimated as follows [37]:

$$\begin{gathered}\text{EPDO count} = 277 \times \text{fatal crashes} + 13 \times \text{suspected serious injury} + \\ 4 \times \text{suspected minor injury} + 4 \times \text{possible injury} + 4 \times \text{unknown severity} + \text{PDO}\end{gathered} \tag{4}$$

Table 1 presents the number of crashes, crash costs, and EPDO counts per crash severity level for the examined dataset.

Each observation included EPDO crash count as the response and the intersection characteristics as the independent variables, including pavement friction measured in that year at the intersection location. The examined intersection attributes were pavement friction, intersection type, and location, traffic control, grade, horizontal curvature, road functional classification, number of lanes, type of road surface, median type and width, right shoulder type and width, and guardrail presence. No multicollinearity was detected between the independent variables. Table 2 presents a summary of the data.

Table 1. Summary of crash counts, costs, and EPDO frequency.

Crash Severity	Number of Crashes	Crash Costs (USD)	EPDO Counts
Property-damage-only (PDO)	6807	$306,315,000	6807
Suspected minor injury/possible injury/unknown	2140	$385,200,000	8560
Suspected serious injury	144	$84,240,000	1872
Fatal injury	17	$211,905,000	4709

Table 2. Descriptive data statistics.

Continuous Variables				
	Mean	**Standard Deviation**	**Minimum**	**Maximum**
EPDO crash count (response)	13.77	30.271	1	314
Pavement friction	41.48	9.186	18.65	71
Number of lanes	3.481	0.877	2	4
Median width	13.87	21.078	0	120
Right shoulder width	5.296	2.908	0	10
Binary Variable			**Count**	**Percentage**
Type: Four legs or more (1 if yes or 0 otherwise)			1270	79.7
Location: Urban (1 if yes or 0 otherwise)			1319	82.7
Traffic control: Signalized (1 if yes or 0 otherwise)			1298	81.4
Grade: Uphill or downhill (1 if yes or 0 otherwise)			170	10.7
Functional classification: Interstate (1 if yes or 0 otherwise)			22	1.4
Functional classification: Principal arterial (1 if yes or 0 otherwise)			1204	75.5
Functional classification: Minor arterial (1 if yes or 0 otherwise)			180	11.3
Functional classification: Collector (1 if yes or 0 otherwise)			31	1.9
Road surface: Concrete (1 if yes or 0 otherwise)			654	41.0
Guardrail (1 if yes or 0 otherwise)			30	1.9
Median: Depressed (1 if yes or 0 otherwise)			169	10.6
Median: Raised (1 if yes or 0 otherwise)			973	61.0
Paved right shoulder (1 if yes or 0 otherwise)			1450	91.0
Slight horizontal curve (>1500 ft radius) (1 if yes or 0 otherwise)			245	15.4
Heavy horizontal curve (<1500 ft radius) (1 if yes or 0 otherwise)			195	12.2

Table 2 demonstrates the overdispersion of the EPDO crash count across the observations. The pavement friction values ranged from 19 to 71, with a mean of 41. The location of each intersection was identified as urban or rural following the US Census Bureau maps [38]. The examined attributes included the functional classification of the major roadway at the intersection. The category "Interstate" referred to the intersections at the interstate interchange, with on/off ramps.

WYDOT collected pavement friction data using the locked-wheel testing device. The locked-wheel tester is a two-wheel trailer fitted with two standard tires, which can be either smooth or ribbed. To measure the longitudinal pavement friction, one or both wheels are locked to achieve the fully locked state with 100% slip and report the average sliding force. Accordingly, the friction can be measured using the locked-wheel tester only at regular intervals to meet the full-lock requirement [39]. It is recommended by the Federal Highway

Administration (FHWA) to use continuous pavement friction measurement (CPFM) for continuous friction data collection for road segments and special locations, such as curves and intersections [40].

The collected friction data were then calibrated in the WYDOT regional calibration center. For this study, the friction data were allocated to the intersections based on the milepost of the intersections and the recorded measurements. When not directly available, the two nearest measurements (before and after the intersection milepost) were averaged to estimate pavement friction at the intersection. For years with missing friction data, friction numbers were estimated by averaging the measurements from previous and subsequent years for the same location. This approach was followed only for locations with decreasing friction numbers, which indicates the absence of maintenance work for this period. This approach assumed a consistent deterioration rate for pavement friction over three years for the same location. The friction number (FN) is recorded as FN40R, which represents measuring friction using a standard ribbed tire on a locked wheel device, at a testing speed of 40 miles per hour.

5. Empirical Analysis

Negative binomial modeling results of intersection crashes are presented in Table 3. All explanatory variables from Table 2 were included in the model. The statistically insignificant predictors at the 95th percentile confidence level were excluded using backward elimination.

Table 3. Negative binomial model results.

Coefficients	Estimate	Standard Error	*p*-Value
Constant	2.803	0.194	<0.001
Pavement friction	−0.015	0.003	<0.001
Location: Urban	−0.231	0.081	<0.001
Grade: Uphill or downhill	−0.465	0.091	<0.001
Functional classification: Interstate	1.031	0.239	<0.001
Functional classification: Principal arterial	0.397	0.068	<0.001
Functional classification: Collector	−0.936	0.229	<0.001
Road surface: Concrete	0.287	0.057	<0.001
Guardrail	−0.483	0.215	0.025
Paved right shoulder	0.234	0.096	0.015
Slight horizontal curve (>1500 ft radius)	0.179	0.076	0.019
Heavy horizontal curve (<1500 ft radius)	−0.241	0.085	0.004
Log-likelihood		−11,438.892	
Log-likelihood of constant-only model		−17,558.649	
ρ^2		0.349	

The modeling results demonstrated that several risk factors, including pavement friction, significantly influenced the EPDO crash frequency at intersections. The marginal effects of the significant influencing factors are presented in Table 4.

Table 4. Marginal effects of EPDO crash frequency factors.

Marginal Effects	Estimate	Standard Error	*p*-Value
Pavement friction	−0.199	0.042	<0.001
Location: Urban	−3.286	1.214	0.007
Grade: Uphill or downhill	−5.096	0.821	<0.001
Functional classification: Interstate	23.137	8.513	0.007
Functional classification: Principal arterial	4.611	0.727	<0.001
Functional classification: Collector	−7.881	1.226	<0.001
Road surface: Concrete	3.737	0.775	<0.001
Guardrail	−5.044	1.715	0.003
Paved right shoulder	2.629	1.024	0.010
Slight horizontal curve (>1500 ft radius)	5.417	1.819	0.003
Heavy horizontal curve (<1500 ft radius)	−2.228	1.056	0.035

6. Discussion

As per the modeling results, pavement friction was a significant factor in reducing the EPDO crash frequency at intersections. Increasing friction numbers (FN40R) by one unit is predicted to reduce EPDO crashes in a given year by 0.199, while controlling for all other parameters. This finding emphasized the key role of friction in intersection safety and the importance of maintaining adequate friction supply on roads, particularly in locations with a higher friction demand and a higher crash risk. This finding can be related to the key role of pavement friction in safe vehicle maneuvering and stopping. Insufficient friction levels increase the crash frequency and the chances of crashing at higher speeds, which results in more severe injuries and higher EPDO frequencies. Several studies have reported relevant findings [29,32,33]. This finding also highlighted the safety benefit of improving pavement friction from an economic perspective, as the cost of one PDO crash in Wyoming is estimated as USD 45,000 [33], while the cost of applying a skid-resistant surface for the intersection is between USD 20,000 and 50,000 [30].

The following is an example of a four-legged, urban intersection on a principal arterial road and a level grade. The intersection is on a slight horizontal curve, the road surface is concrete, and it has a paved right shoulder with no installed guardrails. In a given year, this intersection experienced 73 EPDO, while pavement friction at the intersection was measured at 32.

Assuming application of a Chip Seal treatment at the intersection influence area (250 ft from the center of the intersection) with a service life of 5 years, the estimated annual cost of the treatment will be approximately USD 10,000 [41]. The friction provided by the treatment is expected to decline over its service life and the friction number is expected to be 60 (FN40R) for the newly applied treatment [42]. As per the modeling results, increasing the pavement friction at this intersection from 32 to 60 would reduce the EPDO crashes by 5.57 for the first year. This EPDO cost reduction is estimated to be over USD 250,000, which will result in a benefit–cost ratio for friction improvement of approximately 25.

Urban intersections were found to experience fewer EPDO crashes. An intersection in an urban area would have 3.286 fewer EPDO crashes per year, compared to a rural intersection, while controlling for all other characteristics. This finding can be attributed to the higher traveling speeds on rural roads, driver's susceptibility to distraction, and higher chances of driver fatigue due to longer travel distances. This result emphasized the additional attention needed for rural intersections as they experience higher-severity crashes and a higher EPDO frequency [43,44]. This is particularly important to the state of Wyoming since it has a high number of intersections in rural and semi-rural areas. Intersections on non-level grades were found to witness less frequent EPDO crashes. An uphill or downhill intersection would experience 5.096 fewer EPDO crashes per year, compared to intersections on a level grade, while controlling for all other variables. This finding can be related to the fact that drivers are more cautious while traveling on rolling terrains [31].

Two functional classes of the roadway were found to be associated with a higher EPDO frequency. Intersections linked to interstates and principal arterial roads would experience 23.137 and 4.611 more EPDO crashes per year, compared to local roads, assuming all other factors are controlled. These findings can be attributed to the larger traffic volumes, higher speeds, higher percentage of trucks, and more complex traffic movements on these higher-class roads compared to local roads. On the contrary, intersections on collector roads would have 7.881 fewer EPDO crashes per year, compared to local roads, while controlling for all other parameters. This interesting finding can be related to several reasons. Non-compliance with safety measures and traffic control rules is more common on local roads compared to collectors. Speeding and driving under the influence can be more dangerous on narrower local roads. Driver distraction and overconfidence can be observed more on local roads with lower traffic volumes and lower speed limits.

Intersections on concrete roads would have 3.737 more EPDO crashes per year, compared to asphalt roads, while controlling for all other characteristics. This result can be related to the fact that most concrete road segments in Wyoming are higher-class roads with higher posted speeds and traffic volumes. Installing guardrails at intersections was found to significantly affect the EPDO crash frequency. Installing guardrails would reduce EPDO crashes at an intersection by 5.044 per year, assuming all other factors are controlled. This finding would emphasize the role of guardrails in mitigating crash severity at intersections. Intersections with a paved right shoulder would experience 2.629 more EPDO crashes per year, compared to intersections with no right shoulder, while controlling for all other variables. This finding can be attributed to the improper use of the paved and wide shoulder for overtaking or making a right turn, which increases the risk of sideswiping and rear-end crashes [45].

Intersections on slight horizontal curves (>1500 ft radius) would have 5.417 more EPDO crashes per year, compared to an intersection at non-curved segments, while controlling for all other variables. On the contrary, intersections on heavy horizontal curves (<1500 ft radius) would have 2.228 fewer EPDO crashes per year, compared to an intersection at non-curved segments, assuming all other factors are controlled. These findings are related to cautious driving behavior under complex road geometry and the fact that sharper horizontal curves will require the drivers to travel at lower speeds. Afghari reported similar conclusions [31]. Several studies suggested the use of perceptual measures, and delineation treatments to warn drivers of the presence of curves, which will impact their behavior and improve traffic safety at such locations [46–48].

7. Conclusions and Recommendations

This study presented a negative binomial model of intersection crashes to investigate the factors contributing to the EPDO crash frequency at intersections. The study explored the role of pavement friction, intersection attributes, and roadway characteristics. The analysis results revealed that several factors significantly influence the EPDO frequency. Pavement friction was found to be a significant parameter as increasing friction numbers reduced the EPDO crash frequency at intersections. Intersections in urban areas, or on uphill/downhill grades, were found to experience fewer EPDO crashes. The number of EPDO crashes at intersections linked to interstates or principal arterial roads was higher than those local road intersections, while the EPDO crash frequency was lower for intersections on collector roads. The presence of a paved right shoulder or concrete roadway surface was associated with higher EPDO counts. Guardrails were found to reduce EPDO counts at intersections. Horizontal curvature was found to influence EPDO differently according to its radius. Intersections on slight horizontal curves (>1500 ft radius) would experience higher EPDO counts, while the EPDO frequency would be lower on intersections on heavy horizontal curves (<1500 ft radius).

This study intended to examine the role of pavement friction on intersection crashes, incorporating both crash count and severity by analyzing the EPDO crash frequency. The findings of this work would help to define desirable friction thresholds for roadway intersections, considering other intersection attributes and geometric elements. Additionally, these conclusions can be used during the planning stage for intersection construction or rebuilding, and they can also be applied while reviewing high-risk intersections. The findings of this study can be used in support of road safety assessments and Safety Index (SI) validation, as the findings identified roadway risk factors impacting the EPDO crash frequency at intersections [49].

8. Study Limitations and Future Research

Underreporting of PDO crashes may affect the estimation accuracy. This study examined data only from the state of Wyoming, which may limit the transferability of the findings to other states with different related conditions.

Future research may focus on developing economical solutions and spot applications for improving pavement friction.

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